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Vpliv implantov na porazdelitev elektromagnetnega polja v človeku

Doktorska disertacija

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Zahvala

Za svoje raziskovalno delo in dosežke se lahko v prvi vrsti zahvalim predvsem mentorju profesorju Damijanu Miklavčiču. V celotnem času podiplomskega študija je bil kot mentor vedno pozoren do mojih potreb, znal me je spodbujati in svetovati, a hkrati puščati tudi dovolj ustvarjalne svobode.

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Geometrija modela človeškega telesa je bila narejena na osnovi slik iz baze Visible Human Dataset (National Library of Medicine, National Institute of Health, Združene države Amerike).

Kazalo

Povzetek

Implant je instrument, aparatura, naprava ali material, ki se v človeku uporablja posamezno ali v kombinaciji s še kakšnim dodatkom ali programom. Namenjen je za diagnostiko, preprečevanje, merjenje, zdravljenje ali lajšanje bolezni ali poškodb ter preiskavo, nadomestilo ali spremembo anatomije ali fiziološkega procesa. Implanti svojega glavnega učinka ne dosega s pomočjo farmakoloških, kemičnih, imunoloških ali metabolnih učinkov. Vsajeni implanti povzročijo spremembo porazdelitve elektromagnetnega polja, saj so navadno zgrajeni iz snovi z dielektričnimi lastnostmi, ki so bistveno različne od človeškega tkiva.

Elektromagnetno polje v okolju je omejeno z Uredbo o elektromagnetnem sevanju v naravnem in življenjskem okolju [Uradni list RS, 70/96]. Obstajajo tudi drugi dokumenti, ki priporočajo mejne vrednosti elektromagnetnega polja. Med njimi so najpomembnejše Smernice o omejevanju izpostavljenosti elektromagnetnemu sevanju *Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)* [ICNIRP, 1998]. Pri nastajanju Smernic ICNIRP so upoštevali zdravo človeško telo brez implanta, saj piše: »*Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document but is available elsewhere (UNEP/WHO/IRPA 1993)*« [ICNIRP, 1998]. V citatu so omenjena Okoljska zdravstvena merila UNEP/WHO/IRPA »*Environmental health criteria 137 Electromagnetic fields (300 Hz to 300 GHz)*« [UNEP/WHO/IRPA, 1993], kjer naj bi bilo več napisanega o vplivu na implante, a tudi v njih so implanti le bežno omenjeni, pa še to le srčni spodbujevalniki.

Da bi preverili vpliv implantov na porazdelitev elektromagnetnega polja v človeku smo s pomočjo numeričnega modeliranja izračunali porazdelitev elektromagnetnega polja v človeku z implantom, izpostavljenem polju nizkih (50 Hz), srednjih (27 MHz) in visokih (900 MHz) frekvenc. Geometrija modela človeškega telesa je bila zgrajena na osnovi slik iz baze Visible Human Data Set (VHDS). Baza je po predhodnem dovoljenju s strani Nacionalne medicinske knjižnice ZDA (National Libraty of Medicine, National Institutes of Health, United States) prosto dostopna, v njej pa so slike prerezov zmrznjenega ženskega in moškega kadavra. Odločili smo se uporabiti slike ženskega kadavra, ki so posnete v korakih 0.33 mm z enako razločljivostjo kot je korak, to je 0.33 mm. V model nizkih frekvenc smo vključili tudi implant, in sicer intramedularni žebelj, ki se uporablja za fiksacijo zlomov votlih kosti v modelu nizkih frekvenc. Geometrijo intramedularnega žeblja smo določili s pomočjo rentgenskih slik bolnice z zlomom desne stegnenice po fiksaciji z intramedularnim žebljem.

Preden smo lahko intramedularni žebelj vključili v model, je bilo potrebno rentgenske slike postaviti v enako orientacijo kakor model, narejen na osnovi VHDS slik. V model smo poleg implanta vključili tudi vse kosti tiste noge, v kateri je implant: stegnenico, pogačico, golenico in mečnico. V model srednjih in visokih frekvenc smo vključili srčni spodbujevalnik z elektrodami. Geometrijo srčnega spodbujevalnika in elektrod smo določili na podlagi CT slik bolnice. V model smo poleg implanta vključili še pljuča, ker imajo različne dielektrične lastnosti od okoliškega tkiva. Lastnosti snovi smo določili s pomočjo literature, vendar smo se zaradi razpršenosti vrednosti v literaturi pri nizkih frekvencah odločili za parametrizacijo izračuna glede na vrednosti prevodnosti in dielektričnosti mehkega tkiva in kosti. V modelih smo določili takšne robne pogoje, da je bila jakost elektromagnetnega polja v modelih enaka mejnim vrednostim Uredbe za II. območje. Zaradi lažjega ovrednotenja vpliva implantov na porazdelitev elektromagnetnega polja smo izračunali tudi enake modele brez implanta.

Iz rezultatov je razvidno, da intramedularni žebelj povzroči povečanje gostote toka na mestu, kjer izstopa iz kosti. Povečanje je tako veliko, da kljub izpolnjenim mejnim vrednostim Uredbe za II. območje gostota toka preseže mejne vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo. Po drugi strani je področje, kjer pride do izrazitega povečanja gostote toka omejeno na nekaj kubičnih centimetrov. Razen v tisti nogi, v kateri je implant sicer ni opaznih sprememb v porazdelitvi gostote toka v drugih delih telesa.

Podobno velja tudi za srčni spodbujevalnik, kjer je iz rezultatov za frekvenčno območje 27 MHz razvidno, da je SAR in s tem posledično segrevanje tkiva znatno povečano ob koncu elektrod. Na drugem koncu elektrod, na samem spodbujevalniku pa je zaradi velike stične površine le to komaj opazno. V elektromagnetnem polju 900 MHz je prav tako zaznati povečanje SAR ob koncu elektrod, le da je to nekajkrat manjše, saj je vdorna globina elektromagnetnega polja pri 900 MHz manjša kot pri 27 MHz.

Na podlagi rezultatov modela lahko zaključimo, da kovinski implanti pomembno vplivajo na porazdelitev elektromagnetnega polja v človeku. Kljub izpolnjenim mejnim vrednostim Uredbe so lahko presežene mejne vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo. Razumevanje vpliva prevodnih implantov na porazdelitev elektromagnetnega polja v človeku je kompleksno in vsekakor ni namenjeno širšemu prebivalstvu, vendar bi bilo potrebno in primerno tako za zdravnike, ki se ukvarjajo z vstavljanjem takšnih implantov, kakor tudi za bolnike, ki jih prejmejo, ponuditi informacijo o tem vplivu. V primeru srčnih spodbujevalnikov so bolniki o vplivu elektromagnetnih polj informirani, predvsem zaradi preprečevanja elektromagnetnih motenj in zagotavljanja elektromagnetne kompatibilnosti srčnega spodbujevalnika. V primeru drugih kovinskih implantov bolniki običajno niso informirani o njihovem vplivu na porazdelitev elektromagnetnega polja ter možnem lokalnem preseganju mejnih vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo.

Abstract

Implant is any instrument, apparatus, appliance, material or other article, used for human beings whether alone or in combination, together with any accessories or software. It is intended to be used for the diagnosis, prevention, monitoring, treatment or alleviation of disease or injury, investigation, replacement or modification of the anatomy. An implant does not achieve its principal intended action by pharmacological, chemical, immunological or metabolic means. In a human bearing an implant, electromagnetic field distribution is altered due to markedly different dielectric properties of the implant in comparison to the properties of human tissue.

Electromagnetic field in the area with public access is regulated by Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju [Uradni list RS, 70/96]. There are also other documents, giving limit values for electromagnetic field. Among others, the most important document is the Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz) [ICNIRP, 1998]. When preparing ICNIRP Guidelines the authors focused on normal healthy human being without an implant: »Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document but is available elsewhere (UNEP/WHO/IRPA 1993)« [ICNIRP, 1998]. Environmental health criteria 137 Electromagnetic fields (300 Hz to 300 GHz) [UNEP/WHO/IRPA, 1993] is mentioned, where the problem of implants should be discussed, but only cardiac pacemakers are briefly mentioned.

To determine the influence of an implant on electromagnetic field distribution inside a human we used numerical modeling to calculate electromagnetic field distribution in a human with implant in the low frequency (50 Hz), mid-frequency (27 MHz) and high frequency (900 MHz) electromagnetic field. The geometry of the model is based on images from Visible-Human Data Set (VHDS). This Data Set consisting of images of male and female frozen cadaver is available for free after the registration from National Libraty of Medicine, National Institutes of Health, United States. We used female cadaver, which has 0.33 mm resolution. In the model of low frequency also intramedular nail was included, which is used to fix broken cancelous bones. The geometry of the intramedular nail was based on X-ray images of a woman with broken right femur, taken after the fixation with intramedular nail. Before we were able to include the nail in the model we had to orient X-ray images with respect to the model, based on VHDS images. Beside intramedular nail, also bones of the right leg were

included: femur, patella, fibula and tibia. In models of mid- and high frequency a cardiac pacemaker was included. The geometry of the cardiac pacemaker and lead was defined based on the CT scans of female patient with implanted cardiac pacemaker. Beside cardiac pacemaker and leads also lungs were modeled, since their specific conductivity differ significantly from the surrounding tissue. Material properties were derived from the literature. Since the data were dispersed, we performed parameterization of the calculation with respect to the specific conductivity and permittivity of the soft tissue and bones. Boundary conditions were defined in such a way that electromagnetic field intensity was near the reference levels, defined in Uredba. For comparison of the result and the influence of the implant on electromagnetic field distribution also models without the implant were calculated.

From the result it can be seen that intramedular nail increase current density in the region, where intramedular nail is partially outside the bone. The increase is significant, since in spite meeting that reference levels, defined in Uredba, basic restrictions on current density for general public defined in ICNIRP Guidelines are exceeded. On the other hand, the region, where significant increase in the current density is observed, is limited to few cubic centimeters only. Except in the leg, where intramedular nail is implanted there is no observable difference in current density distribution in other parts of the body.

Similarly we obtained for cardiac pacemaker, that SAR and consequentially tissue heating is significantly increased at the lead tips in the 27 MHz model. At the other end of the lead, where the lead is connected to the pacemaker, there is only a minor increase in SAR due to the large contact surface between the pacemaker and surrounding tissue. In the 900 MHz model, the increase of the SAR is similar to the one of 27 MHz, but substantially lower increase in SAR is observed at the tip of the lead due to the lower penetration depth of the electromagnetic field at 900 MHz in comparison to 27 MHz.

Based on these results we can conclude that significant change in electromagnetic field distribution for low frequency field (50 Hz) when metallic implants are present in the human body is observed. In spite that reference levels defined in Uredba are met, it is possible to exceed basic restrictions for general public, defined in ICNIRP Guidelines. The understanding of the change in electromagnetic field distribution inside the human due to conducting implants is out of the scope for general public. But cardiologists, traumatologists or other physicians who are implanting such implants or patients receiving them should be informed. For pacemakers there are instructions given to the patients, primarily because of electromagnetic interference and electromagnetic compatibility problems. For other conducting implants the patients are not informed about their influence on electromagnetic field distribution and possible local excess of basic restrictions for general public, defined in ICNIRP Guidelines.

1 Uvod

Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju [Uradni list RS, 70/96] določa, kakšne smejo biti vrednosti elektromagnetnega polja v območju, kjer se lahko giblje človek. Ker so tako porazdelitev elektromagnetnega polja kakor tudi njegovi biološki učinki zelo odvisni od njegove frekvence, so tudi mejne vrednosti v Uredbi določene s pomočjo frekvenčnih območij. Podobna priporočila za jakost elektromagnetnega polja so podana tudi v Priporočilih Sveta Evrope »*Council recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)*« [Official Journal of the Europena Communities, 59/1999]. Nastala so na osnovi Smernic ICNIRP (*International Commision on Non-Ionizing Radiation Protection*) »*Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)*« [ICNIRP, 1998] in uporabljajo enako terminologijo ter mejne vrednosti. Tako v Smernicah ICNIRP kot Priporočilih 1999/519/EC sta podani dve vrsti omejitev. Mejne vrednosti (*basic restrictions*) temeljijo na bioloških učinkih elektromagnetnega polja, zato so veličine, ki jih omejujejo, gostota električnega toka, gostota pretoka moči in SAR. Zaradi lažje uporabe so dodali še omejitve na lažje merljivih veličinah, in sicer na električni poljski jakosti, magnetni poljski jakosti, gostoti magnetnega pretoka in gostoti pretoka moči. Te omejitve imenujemo izvedene mejne vrednosti (*reference levels*). Velja, da mejne vrednosti niso presežene niti v najslabši možni kombinaciji izvedenih mejnih vrednosti. Mejne vrednosti so bile določene glede na do sedaj znane podatke o škodljivih učinkih elektromagnetnega polja na človekovo zdravje z upoštevanjem varnostnega faktorja. Pri nastajanju teh omejitev so upoštevali zdravo človeško telo brez implanta, saj v Smernicah ICNIRP piše: »*Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document but is available elsewhere (UNEP/WHO/IRPA 1993)*« [ICNIRP, 1998]. V citatu so omenjena Okoljska zdravstvena merila UNEP/WHO/IRPA »*Environmental health criteria 137 Electromagnetic fields (300 Hz to 300 GHz)*« [UNEP/WHO/IRPA, 1993], kjer naj bi bilo več napisanega o medsebojnem vplivu implantov in elektromagnetnega polja. Vendar tudi Okoljska zdravstvena merila UNEP/WHO/IRPA bežno omenjajo le srčne spodbujevalnike, ostalih implantov pa ne.

Število ljudi z vsajenimi implanti je vedno večje, zato je tudi poznavanje medsebojnih vplivov impantov in elektromagnetnega polja vedno pomembnejše. Glede na način delovanja se implanti delijo na aktivne in pasivne. Aktivni so implanti, ki za svoje delovanje uporabljajo lasten vir električne ali kakšne druge energije. Najbolj znani predstavniki aktivnih implantov so srčni spodbujevalnik, defibrilator, kohlearni implant in inzulinska črpalka. Vsi ostali implanti, ki za svoje delovanje ne potrebujejo vira energije, se imenujejo pasivni implanti. Glede na vpliv na porazdelitev elektromagnetnega polja so zanimivi predvsem kovinski implanti, ki imajo bistveno večjo električno prevodnost od biološkega tkiva ali implanti z bistveno nižjo prevodnostjo, izdelani iz keramike ali različnih plastik. Takšni implanti povzročijo spremembo porazdelitve elektromagnetnega polja v telesu. Tako v statičnem električnem polju kot tudi v elektromagnetnem polju se spremeni porazdelitev električnega polja in posledično tudi porazdelitev tokovnega polja in SAR, kar pomeni, da se lahko spremenijo tudi biološki učinki elektromagnetnega polja. V primeru kovinskih implantov je pri višjih frekvencah pomembno segrevanje, ki se pojavi zaradi induciranega toka, na kar kažejo tudi številne raziskave o varnosti uporabe MRI tehnike pri uporabnikih z vsajenimi kovinskimi implanti [Chou, 2000; Shellock, 2001; Finelli *et al.*, 2002; Shellock *et al.*, 2005; Luechinger *et al.*, 2005].

Pri aktivnih implantih je poleg vpliva na porazdelitev elektromagnetnega polja v telesu pomembna tudi elektromagnetna kompatibilnost implantov. Zaradi elektromagnetnega polja lahko pride do motenj v delovanju aktivnega implanta. Ponavadi so motnje prehodnega značaja, saj se aktivni implant potem, ko ni več izpostavljen elektromagnetnemu polju, povrne v normalno delovanje. Lahko se zgodi, da aktivni implant v času izpostavljenosti elektromagnetnemu polju sploh ne deluje, a se po prenehanju izpostavljenosti elektromagnetnemu polju povrne v normalno delovanje. Pri večji izpostavljenosti je možna tudi trajna okvara aktivnega implanta, kar pa lahko ima škodljive posledice za osebo, ki ima tak aktivni implant vsajen. Da je to področje aktualno, kažejo številne raziskave o elektromagnetni kompatibilnosti aktivnih implantov ter njihovi varnosti, ki se pojavljajo v zadnjem času [Kainz *et al.*, 2001; Kolb, 2003; Wackym, 2004; Kainz *et al.*, 2005; Trigano *et al.*, 2005]. Vendar se z elektromagnetno kompatibilnostjo implantov v tem delu ne bomo ukvarjali.

Zaradi vse večje razširjenosti in množične uporabe mobilnih telekomunikacijskih naprav, večje uporabe elektromagnetnih polj v medicinske namene ter večjemu zanimanju javnosti za vprašanje vplivov elektromagnetnega polja na človeka so raziskave na tem področju številne. Vendar so raziskave, ki vključujejo tudi implante, omejene predvsem na ugotavljanje elektromagnetne kompatibilnosti implantov [Kainz *et al.*, 2003, Kainz *et al.*, 2005] ali možnega prekomernega segrevanja implantov med postopkom slikanja z magnetno resonanco [Chou, 2000; Shellock, 2001; Finelli *et al.*, 2002; Shellock *et al.*, 2005; Luechinger *et al.*, 2005]. Manj pa se raziskovalci ukvarjajo z vplivom implantov na samo porazdelitev elektromagnetnega polja v človeškem organizmu. V vseh omenjenih raziskavah se poslužujejo treh načinov določanja elektromagnetnega polja v človeškem telesu: z uporabo fantomov [Chou, 2000; Shellock, 2001; Finelli *et al.*, 2002; Kainz *et al.*, 2003; Shellock *et al.*, 2005], živalskih modelov [Luechinger *et al.*, 2005] in numeričnih modelov [Braire in Frijans 2000; Virtanen *et al.*, 2005, Ilvonen *et at*, 2005], manj pa analitično, saj je le to zelo omejeno in težavno [Vatta *et al.*, 2005].

V naši raziskavi, ki bo temeljila na uporabi numeričnih modelov, bomo določili, kolikšen je vpliv implantov na porazdelitev elektromagnetnega polja v delu človeškega telesa pri različnih frekvencah. Zanimale nas bodo tiste frekvence, ki se pojavljajo kot vir elektromagnetnega polja v okolju, kot je na primer frekvenca visokonapetostnega energetskega distribucijskega omrežja (50 Hz), ali frekvence, ki se uporabljajo pri dielektričnem sušenju lesa ali v druge industrijske namene (27 MHz) in pri mobilni telefoniji (900 MHz). S primerjavo rezultatov modelov z implanti in brez implantov bomo ovrednotili, kolikšno je povečanje veličin elektromagnetnega polja v okolici implanta ter ocenili, ali je to povečanje tako visoko, da bi glede na Smernice ICNIRP in Priporočila 1999/519/EC lahko bile presežene mejne vrednosti.

2 Elektromagnetno polje

Splošne Maxwellove enačbe: razširjen Amperov zakon, Faradayev zakon indukcije, Gaussov stavek za magnetno polje ter Gaussov stavek za električno polje se glasijo:

$$\nabla\times\vec{B}-\mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}=\mu_0\vec{J}\,, \tag{2.1}$$

$$\nabla\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0\,, \tag{2.2}$$

$$\nabla\cdot\vec{B}=0\,, \tag{2.3}$$

$$\nabla\cdot\vec{E}=\frac{\rho}{\varepsilon_0}\,. \tag{2.4}$$

$\vec{B}$ je gostota magnetnega pretoka, μ_0 in ε_0 permeabilnost in dielektričnost praznega prostora, $\vec{E}$ električna poljska jakost, $\vec{J}$ volumska gostota električnega toka ter ρ prostorska gostota naboja. V elektrotehniki se pogosteje uporabljajo Maxwellove enačbe, ki upoštevajo polarizacijo in magnetizacijo snovi. Tako dobimo dve novi spremenljivki, gostoto električnega pretoka $\vec{D}$ in magnetno poljsko jakost $\vec{H}$:

$$\vec{H}=\frac{\vec{B}}{\mu_r\mu_0}\,, \tag{2.5}$$

$$\vec{D}=\varepsilon_r\varepsilon_0\vec{E}\,. \tag{2.6}$$

μ_r in ε_r sta relativna permeabilnost in dielektričnost snovi. Maxwellove enačbe se glasijo:

$$\nabla\times\vec{H}-\frac{\partial\vec{D}}{\partial t}=\vec{J}_{prosti}\,, \tag{2.7}$$

$$\nabla\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0\,, \tag{2.8}$$

$$\nabla\cdot\vec{B}=0\,, \tag{2.9}$$

$$\nabla\cdot\vec{D}=\rho_{prosti}\,. \tag{2.10}$$

Z $\vec{J}_{prosti}$ in ρ_{prosti} sta označena volumska gostota toka prostih nabojev in volumska gostota prostih nabojev, to je tistih nabojev v snovi, ki niso vezani in se lahko premikajo.

Poleg Maxwellovih enačb so za poznavanje elektromagnetnega polja pomembni še zakon o ohranitvi nabojev oz. kontinuitetni zakon za električni tok (2.11), enačba, ki definira magnetni vektorski potencial $\vec{A}$ (2.12), enačba, ki povezuje magnetni vektorski potencial $\vec{A}$, električno poljsko jakost $\vec{E}$ in električni potencial V (2.13) in in razširjen Ohmov zakon (2.14):

$$\nabla \cdot \vec{J}_{prosti} + \frac{\partial \rho_{prosti}}{\partial t} = 0, \tag{2.11}$$

$$\vec{B} = \nabla \times \vec{A}, \tag{2.12}$$

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t}, \tag{2.13}$$

$$\vec{J}_{kond} = \gamma \vec{E} + \vec{J}_g, \tag{2.14}$$

pri čemer je $\vec{J}_g$ gostoto toka zaradi virov, specifična električna prevodnost snovi γ pa je v splošnem tenzor:

$$\gamma = \begin{bmatrix} \gamma_{xx} & \gamma_{xy} & \gamma_{xz} \\ \gamma_{yx} & \gamma_{yy} & \gamma_{yz} \\ \gamma_{zx} & \gamma_{zy} & \gamma_{zz} \end{bmatrix}. \tag{2.15}$$

V izotropnih snoveh, ki imajo specifično prevodnost v vseh smereh enako, se matrika poenostavi v en sam element, skalar.

Pri prehajanju elektromagnetnega polja preko meje dveh snovi se nekatere veličine elektromagnetnega polja spremenijo. Z indeksi 1 označimo veličine v prvi snovi in z indeksi 2 veličine v drugi snovi, oznaka t pomeni tangencialno komponento, oznaka n pa normalno komponento veličine glede na ravnino meje. Iz prvih dveh Maxwellovih enačb izhajata prestopna pogoja za poljski jakosti, iz drugih dveh pa za gostoti pretoka:

$$H_{t2} - H_{t1} = K_{prosti}. \tag{2.16}$$

$$E_{t2} - E_{t1} = 0. \tag{2.17}$$

$$B_{n2} - B_{n1} = 0, \tag{2.18}$$

$$D_{n2} - D_{n1} = \sigma_{prosti}. \tag{2.19}$$

K_{prosti} je površinska gostota toka prostih elektronov na meji, σ_{prosti} pa površinska gostota prostih nabojev na meji.

2.1 Tokovno polje

Določanje vseh veličin elektromagnetnega polja je računsko zahtevno in zamudno. Programski paketi za modeliranje in numerično reševanje to omogočajo le deloma, večinoma le za harmonska vzbujanja v stacionarnih razmerah. Velikokrat lahko računanje poenostavimo tako, da namesto vseh veličin določimo le tiste, ki so pomembne. Tako je na primer mogoče stimulacijo bioloških tkiv z enosmernim električnim tokom opisati s tokovnim poljem. Tokovno polje je vezano na prevodne snovi, kjer velja Ohmov zakon (2.14). Od sistema štirih Maxwellovih enačb ostaneta tako le dve poenostavljeni enačbi:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \tag{2.20}$$

$$\nabla \times \vec{E} = 0 \tag{2.21}$$

Poleg tega veljata tudi Ohmov zakon in (2.11) zakon o ohranitvi nabojev oz. kontinuitetni zakon za naboj. Ko v enačbo (2.11) vstavimo enačbi (2.14) ter (2.13), dobimo enačbo:

$$\nabla \cdot (\gamma \cdot (-\nabla V)) = -\frac{\partial \rho}{\partial t}. \tag{2.22}$$

Če velja, da je specifična električna prevodnost snovi γ izotropna in homogena (γ je konstanta), dobimo Poissonovo diferencialno enačbo:

$$\Delta V = \frac{1}{\gamma}\frac{\partial \rho}{\partial t}. \tag{2.23}$$

V stacionarnih razmerah, ko so vrednosti časovnih odvodov enake 0, se enačba poenostavi v homogeno Poissonovo oz. Laplaceovo diferencialno enačbo:

$$\Delta V = 0. \tag{2.24}$$

2.2 Modeliranje in izračun z numeričnimi metodami

Modeliranje je postopek, pri katerem nek sistem nadomestimo z modelom z namenom, da bi s preučevanjem modela bolje spoznali sam sistem in njegovo obnašanje. Danes najpogostejša oblika modeliranja je matematično modeliranje, ko sistem nadomestimo z matematičnim modelom, ki predstavlja sistem v obliki diferencialnih enačb. Kljub temu, da sistem pri zapisu z diferencialnimi enačbami poenostavimo, ponavadi še vedno ni analitično rešljiv. Pred uporabo digitalnih računalnikov so se za reševanje takšnega sistema diferencialnih enačb uporabljali analogni računalniki. Analogni računalniki so vsebovali različne osnovne gradnike, kot na primer različni viri, množilniki, seštevalniki, diferenciatorji, integratorji …, ki jih je bilo potrebno med seboj pravilno povezati glede na diferencialne enačbe [Zupančič *et al.*, 1995]. Danes so analogne računalnike nadomestili digitalni računalniki, ki so postali dovolj zmogljivi, da omogočajo numerično reševanje sistema diferencialnih enačb.

Modeliranje in izračun z numeričnimi metodami prinaša številne prednosti, saj lahko na primer preizkušamo občutljivosti sistemov na posamezne parametre, kar je na samih sistemih ponavadi veliko dražje, mnogokrat pa je to zaradi različnih vzrokov nemogoče (varnost, čas, zdravje …); pri načrtovanju sistema se lahko opiramo na podatke, pridobljene iz odzivov modela, in podobno. Prav zaradi številnih prednosti numeričnega modeliranja, razvoja računskih zmogljivosti računalnikov ter njihovi dostopnosti, po drugi strani pa tudi v večji ponudbi programskih paketov za modeliranje in izračun z numeričnimi metodami ter vse večja uporabnost le-teh se uporaba numeričnega modeliranja veča.

Poznamo različne postopke modeliranja in izračuna z numeričnimi metodami, med najbolj razširjenimi metodami sta metoda končnih elementov in metoda končnih diferenc. Bistvo obeh metod je razdelitev celotne geometrije (območje računanja) na manjše dele, elemente, ki so v primeru končnih diferenc na premici daljice, v ravnini pravokotniki ter v prostoru kvadri, v primeru metode končnih elementov daljice na premici, v ravnini običajno trikotniki, lahko poljubni mnogokotniki ali celo liki z ukrivljenimi stranicami ter v prostoru običajno tetraedri (tristranične piramide), lahko pa poljubna geometrijska telesa, podobno kot v ravnini tudi z ukrivljenimi ploskvami. Takšni delitvi območja pravimo mreža. Vsakemu elementu v mreži nato določimo fizikalne lastnosti snovi. Na podlagi diferencialne enačbe sledi pri metodi končnih diferenc zapis enačb iskane spremenljivke za vsako vozlišče. Nastali sistem enačb pretvorimo v matrični zapis:

$$M \cdot \vec{\vec{V}} = \vec{P}\,, \tag{2.25}$$

kjer je M matrika koeficientov enačb, $\vec{\tilde{V}}$ vektor vrednosti iskane spremenljivke, $\vec{P}$ pa vektor robnih pogojev in virov v modelu. Dobljeni sistem enačb rešimo z eno od numeričnih metod, npr. Gaussovo eliminacijsko metodo in izračunamo vrednost iskane spremenljivke v vozliščih [Sinigoj, 1996]. Pri metodi končnih elementov je pristop k zapisu končne matrične enačbe drugačen. Kot izhodišče služi iskani spremenljivki V prirejen funkcional, iščemo pa njegov minimum. Končna matrična enačba ima enako obliko kot enačba za metodo končnih diferenc (1.1), razlikujejo se le koeficienti v matriki M in vektor robnih pogojev $\vec{P}$.

2.2.1 Metoda končnih diferenc

Metoda končnih elementov je tako za uporabo kot tudi za razumevanje preprosta metoda, še posebej za elektrotehnike, saj ima veliko podobnosti z reševanjem vezij. Za tokovno polje temelji zapis metode na enačbi (2.22)

$$\nabla \cdot (\gamma \cdot (-\nabla V)) = -\frac{\partial \rho}{\partial t},$$

ki se v stacionarnih razmerah poenostavi v enačbo (2.25):

$$\nabla \cdot (\gamma \cdot (-\nabla V)) = 0\,. \qquad (2.26)$$

Za nek majhen volumen W (oz. za zapis v integralski obliki) bo veljalo:

$$\int_W \nabla\left(-\gamma \nabla V\right) dw = 0\,. \qquad (2.27)$$

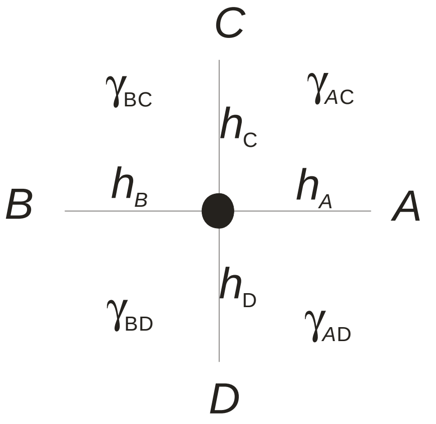
Če uporabimo Gaussov izrek in nadomestimo volumski integral divergence s ploskovnim integralom po sklenjeni ploskvi, dobimo iz enačbe (2.27):

$$-\oint_A \gamma \nabla V \, d\vec{a} = 0 \qquad (2.28)$$

ali drugače zapisano:

$$-\oint_A \gamma \frac{\partial V}{\partial n} da = 0\,. \qquad (2.29)$$

Enačba (2.29) je izhodiščna enačba za računanje porazdelitve električnega potenciala v primeru tokovnega polja z metodo končnih diferenc.



Slika 1: Vozlišče v kvadratni mreži v ravnini. Z *A*, *B*, *C* in *D* so označena sosednja vozlišča v mreži, *h* označuje razdalje do sosednjih vozlišč, γ pa specifične prevodnosti.

Pri izračunu z metodo končnih diferenc je potrebno želeno območje prekriti z daljicami na premici, s pravokotniki v ravnini in kvadri v prostoru. V ravnini nadomestimo integral v enačbi (2.29) za eno vozlišče, predstavljeno na Sliki 1, z vsoto posameznih prispevkov:

$$\begin{aligned}-\oint_A \gamma \frac{\partial V}{\partial n} da = &-\left(\gamma_{AC}\frac{h_C d}{2}+\gamma_{AD}\frac{h_D d}{2}\right)\frac{V_A-V_0}{h_A}-\left(\gamma_{BC}\frac{h_C d}{2}+\gamma_{BD}\frac{h_D d}{2}\right)\frac{V_B-V_0}{h_B}-\\ &-\left(\gamma_{BC}\frac{h_B d}{2}+\gamma_{AC}\frac{h_A d}{2}\right)\frac{V_C-V_0}{h_C}-\left(\gamma_{BD}\frac{h_B d}{2}+\gamma_{AD}\frac{h_A d}{2}\right)\frac{V_D-V_0}{h_D}\end{aligned}, \qquad (2.30)$$

kjer je *d* debelina plasti. Z *A*, *B*, *C* in *D* so označena sosednja vozlišča, *h* pa označuje razdalje do sosednjih vozlišč. Takšno enačbo zapišemo v vseh vozliščih ter iz njih sestavimo matrični zapis (2.25):

$$M \cdot \vec{\vec{V}} = \vec{P}\,,$$

kjer je M matrika koeficientov enačb, $\vec{\vec{V}}$ vektor vrednosti iskane spremenljivke, $\vec{P}$ pa vektor robnih pogojev in virov v modelu. Dobljen sistem enačb rešimo z eno od numeričnih metod in izračunamo vrednost iskane spremenljivke v vozliščih. Podobno enačbo kot (2.30) dobimo tudi v primeru prostora, le da imamo na desni strani enačbe namesto sedanjih štirih šest členov.

2.2.2 Metoda končnih elementov

Kakor smo že prej napisali, je končna matrika za reševanje pri metodi končnih elementov podobna kot pri metodi končnih diferenc, prav tako je osnova obeh metod razdelitev prostora v manjša območja, le da mreža pri metodi končnih diferenc temelji na kvadratnih oblikah, pri metodi končnih elementov pa običajno temelji delitev na trikotnih oblikah, lahko pa na poljubnih mnogokotnikih, celo takšnih z ukrivljenimi robovi ali stranicami. Vendar se metodi razlikujeta po pristopu k zapisu enačb, saj pri metodi končnih diferenc zapis temelji na Poissonovi enačbi in robnih pogojih, pri metodi končnih elementov pa zapis temelji na minimizaciji potencialu prirejenega funkcionala.

Prvi korak pri metodi končnih elementov je razdelitev območja računanja ν v elemente, kar imenujemo tudi gradnja mreže. Na premici predstavljajo posamezne elemente daljice, ki so med seboj lahko različno dolge, ne smejo se prekrivati, hkrati pa morajo pokriti celotno območje računanja ν. Podobno je v ravnini, ki jo ponavadi prekrijemo s trikotniki in prostoru, kjer za elemente ponavadi vzamemo tetraedre. Pomembno je, da elementi s čim manjšim odstopanjem sledijo robovom modela in mejam med različnimi snovmi v modelu ter so obenem tako majhni, da lahko v posameznem elementu lastnosti snovi opišemo kot krajevno neodvisne. Sledi določanje normiranih lokalnih koordinat v vsakem elementu. V primeru tetraedra, katerega oglišča označimo z *A*, *B*, *C* in *D*, uporabimo piramidne koordinate ξ^e_A, ξ^e_B, ξ^e_C in ξ^e_D, ki imajo izhodišča v ogliščih in naraščajo v smeri pravokotnic do nasprotnih trikotnih stranic tetraedra do vrednosti 1. Določanju elementov sledi določanje vozlov. Najpreprostejši je primer, ko so vozli postavljeni le v krajišča daljic oziroma v oglišča trikotnikov ali tetraedrov, lahko pa so tudi na sredini daljic oziroma stranic ali robov. Prvi primer imenujemo linearni elementi, drugega kvadratni, če pa bi uporabili še dodatne vmesne vozle, bi naraščala tudi potenca elementov.

Imejmo na območju računanja ν dano funkcijo $\psi = \psi(x, y, z)$, ki na ogliščih elementa zavzame vrednosti ψ_A, ψ_B, ψ_C in ψ_D. Aproksimacijo funkcije ψ v enem elementu, $\tilde{\psi}^e$ definiramo tako, da v ogliščih zavzame enake vrednosti kot funkcija ψ, kar je najenostavneje doseči z linearno funkcijo $\tilde{\psi}^e = \alpha^e x + \beta^e y + \chi^e z + \delta^e$, ki jo izrazimo kot funkcijo normiranih koordinat elementa *e*:

$$\tilde{\psi}^e(x, y, z) = \tilde{\varphi}^e(\xi^e_A, \xi^e_B, \xi^e_C, \xi^e_D) = \tilde{\varphi}^e \,. \tag{2.31}$$

Od tod tudi ime linearni elementi. Ob uporabi dodatnih vmesnih vozlišč bi namesto linearne funkcije za zapis $\tilde{\psi}^e$ uporabili kvadratno in elemente imenovali kvadratne. Aproksimacijo $\tilde{\varphi}^e$ sestavimo iz vsote štirih linearnih funkcij:

$$\tilde{\varphi}^e = \sum_{T=A}^{D} \psi_T (1-\xi_T^e)\,. \tag{2.32}$$

Taka aproksimativna funkcija $\tilde{\varphi}^e$ v vseh vozliščih zavzame enake vrednosti kot funkcija ψ, kar tudi želimo. Za zapis aproskimacije funkcije ψ v vseh elementih modela, $\tilde{\psi}$ oziroma $\tilde{\varphi}$ definiramo funkcijo

$$\tilde{\varphi}_0^e = \begin{cases} \tilde{\varphi}^e & za\, točke\, v\, elementu \\ 0 & drugje \end{cases} \tag{2.33}$$

ter iz vsote takšnih aproksimacijskih funkcij določimo aproksimacijo celotnega območja računanja

$$\tilde{\varphi} = \sum_{e=1}^{E} \tilde{\varphi}_0^e\,, \tag{2.34}$$

kjer je *E* število vseh elementov. Z indeksom *i* označimo vse vozle v mreži: *i* = 1, 2, …, *n* ter s $\tilde{\psi}_i$ vrednosti funkcije ψ v vozlih in zapišimo $\tilde{\varphi}$ kot dvojno vsoto:

$$\tilde{\varphi} = \sum_{e=1}^{E}\sum_{i=1}^{n} \psi_i u_i^e = \sum_{i=1}^{n} \psi_i \sum_{e=1}^{E} u_i^e = \sum_{i=1}^{n} \psi_i u_i\,, \tag{2.35}$$

kjer je

$$u_i^e = \begin{cases} 1-\xi_i^e & v\, elementu \\ 0 & drugje \end{cases}. \tag{2.36}$$

Zadnji del enačbe, vsota u_i^e po vseh elementih, se v enem vozlu reducira le na tiste elemente, v katerih leži to vozlišče. To vsoto imenujmo u_i, to je vsota vseh tistih funkcij $\{1-\xi^e_i\}$, ki linearno upadajo iz *i*-tega vozlišča proti sosednjim vozliščem.

Ko imamo že določeno mrežo elementov v ν, sledi določanje iskanih veličin, v primeru tokovnega ali elektrostatičnega polja je to električni potencial V. Nastavek za potencial zapišemo v obliki

$$\vec{\tilde{V}} = \sum_i C_i u_i \,, \tag{2.37}$$

torej kot linearno kombinacijo funkcij $\{u_i\}$ s koeficienti $\{C_i\}$, ki jih ne poznamo. Koeficienti C_i zavzamejo v vozliščih aproksimativne vrednosti električnega potenciala, $C_i = \tilde{V}_i$ iz česar sledi:

$$\vec{\tilde{V}} = \sum_i \tilde{V}_i u_i \;. \tag{2.38}$$

Razširimo zadnjo enačbo z vpeljavo Dirichletovih robnih pogojev za tista vozlišča, kjer takšni robni pogoji veljajo, denimo da je m takšnih vozlišč.

$$\vec{\tilde{V}} = \sum_{k=1}^{m} V_{0k} u_{0k} + \sum_{i=1}^{n} \tilde{V}_i u_i \tag{2.39}$$

Funkcije $\{u_{0k}\}$ so definirane enako kot funkcije $\{u_i\}$, $\{V_{0k}\}$ pa so znane vrednosti potencialov v teh vozlih. Z uporabo Rayleigh-Ritzovega postopka [Sinigoj, 1996] za minimizacijo funkcionala iz enačbe (2.38) dobimo za elektrostatično polje enačbo:

$$\sum_{j=1}^{n} \left(\int_{\nu'} \varepsilon \left(\nabla u_i \cdot \nabla u_j \right) \right) \tilde{V}_j = \int_{\nu'} \left(\rho_{prosti} u_i - \varepsilon \sum_{k=1}^{m} \int_{\nu'} V_{0k} \left(\nabla u_i \cdot \nabla u_{0k} \right) \right) dv + \int_{A_N'} \varepsilon u_i h' da \,, \tag{2.40}$$

kjer je ν' območje računanja, ki ga opisujejo elementi in odstopa od ν zaradi oglatosti robov, A_N' je meja ν', ε je relativna dielektričnost snovi, ρ_{prosti} prostorska gostota naboja v snovi ter h' odsekoma konstantna aproksimacija normalnega odvoda. Enačba (2.40) za tokovno polje je podobna, le da relativno dielektričnost snovi ε v enačbah nadomesti specifična prevodnost snovi γ ter prostorsko gostoto naboja ρ_{prosti} nadomesti odvod prostorske gostote naboja po času, ki pa je za stacionarne razmere enak 0:

$$\sum_{j=1}^{n} \left(\int_{\nu'} \gamma \left(\nabla u_i \cdot \nabla u_j \right) \right) \tilde{V}_j = \int_{\nu'} \left(-\gamma \sum_{k=1}^{m} \int_{\nu'} V_{0k} \left(\nabla u_i \cdot \nabla u_{0k} \right) \right) dv + \int_{A_N'} \gamma u_i h' da \,, \tag{2.41}$$

Po reševanju vseh integralov v enačbi (2.40) [Sinigoj, 1996] dobimo sistem enačb za aproksimativni potencial v vsakem elementu $\tilde{V}_i$ v naslednji obliki:

$$\sum_{j=1}^{n} m_{ij}\tilde{V}_j = p_i, \quad i = 1, 2, \dots, n, \tag{2.42}$$

kjer so

$$m_{ij} = \int_{v'} \gamma\left(\nabla u_i \cdot \nabla u_j\right)$$

ter

$$p_i = \int_{v'}\left(-\gamma\sum_{k=1}^{m}\int_{v'} V_{0k}\left(\nabla u_i \cdot \nabla u_{0k}\right)\right)dv + \int_{A_N'} \gamma u_i h' da\,.$$

V matrični obliki bi enačbo (2.42) zapisali kot

$$M \cdot \vec{\tilde{V}} = \vec{P}\,,$$

kar pa je pravzaprav enačba (2.25). Rešitev sistema enačb (2.42) vstavimo v enačbo (2.39) ter tako določimo iskan aproksimativni potencial $\vec{\tilde{V}}$.

2.2.3 Izbor metode in programskega paketa

V okviru Laboratorija z biokibernetiko uporabljamo tri programske pakete za modeliranje in izračun z numeričnimi metodami: Comsol Multiphysics (Comsol, Švedska), ki se je do inačice 3.1 imenoval FEMLAB, MAXWELL (Ansoft, ZDA) in EMAS (Ansoft, ZDA). Vsi trije programski paketi temeljijo na metodi končnih elementov. Ker bomo geometrijo modelov izdelali na podlagi medicinskih slik, bi bila metoda končnih diferenc bolj preprosta za uporabo. Namreč, ta metoda temelji na razdelitvi prostora v enakomerno, ponavadi pravokotno mrežo, ki jo sestavljajo kocke, kar sovpada z slikami, ki so prav tako sestavljene iz točk kvadratne oblike (*pixel*). Vendar bi model z višino dva metra ter širino in dolžino en meter v primeru kock z robom 5 mm vseboval kar 16.000.000 takšnih kock. Za reševanje tako velikih modelov je potrebno imeti programe, ki omogočajo vzporedno računanje na več računalnikih, kar se sicer pogosto uporablja [Mason *et. al.*, 2000, Potter *et. al.*, 2000, Gajsek *et. al.*, 2002], kar pa nam ni bilo dosegljivo. Z metodo končnih elementov je mogoče z dosti manjšim številom elementov doseči dovolj natančne rezultate, hkrati pa celoten model reševati na enem računalniku. Od zgoraj navedenih programskih paketov, ki jih imamo na razpolago, smo uporabili Comsol Multiphysics, saj je do uporabnika sorazmerno prijazen, omogoča izdelavo geometrij na podlagi slik in omogoča računanje elektromagnetnega polja in kvazistatičnega elektromagnetnega polja.

2.2.4 Posebnosti modeliranja v biomedicini

Modeliranje in izračun z numeričnimi metodami v biomedicini je v veliko primerih zahtevno opravilo. Kakor smo že zapisali, moramo vsakemu elementu določiti lastnosti snovi v njem. Modeliranje in izračun z numeričnimi metodami uporabljamo največ na področju tehnike, kjer so lastnosti materialov znane in večinoma linearne ter izotropne, medtem ko so lastnosti tkiv v bioloških organizmih velikokrat nelinearne, anizotropne in v primeru elektromagnetnih lastnosti izrazito frekvenčno odvisne [Foster in Schwan, 1989, Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b, Pavšelj, 2002]. Geometrija je v primeru tehniških problemov večinoma sestavljena iz različnih osnovnih geometrijskih likov in teles, medtem ko so oblike v primeru bioloških modelov nepravilne, posledično je geometrija nesimetrična [Valič *et al.*, 2003, Pucihar *et al.*, 2006]. Poleg tega je v bioloških modelih velikokrat zelo veliko razmerje med najmanjšo ter največjo dimenzijo v geometriji. Kakor bomo videli v naslednjem podpoglavju, predstavlja ravno veliko geometrijsko razmerje pri modeliranju zahteven problem.

2.2.5 Uporaba nelokalnega sklapljanja

V programskih paketih za numerično modeliranje so vgrajeni algoritmi, ki skrbijo za gradnjo mreže - delitev prostora v posamezne elemente. Ponavadi imajo ti algoritmi različne parametre, ki jih lahko uporabnik nastavlja, kot na primer največja velikost elementov, hitrost večanja elementov… Z nastavitvami teh parametrov ima uporabnik možnost vplivati na kvaliteto mreže in na število elementov v njej ter posledično na število prostostnih stopenj modela. Kljub tem nastavitvam je v modelih z velikim geometrijskim razmerjem mreža ponavadi zapletena in velika. Velikokrat se zgodi, da ne glede na nastavljene parametre algoritem v takšnem modelu ne uspe zgraditi mreže in je zato nemogoče izračunati neznane spremenljivke.

Za reševanje takšnih problemov obstajajo različne pristopi, kot na primer razširjena metoda končnih elementov (*extended finite element method*, XFE metoda) [Moes *et al.*, 2003]. Z razliko od FE metode, kjer mora biti v enem elementu le ena snov (povsod v elementu veljajo enake materialne lastnosti), imamo lahko v primeru XFE metode v enem elementu več materialov. Zato ni več potrebno, da mreža sledi mejam materialov in je torej lahko bolj preprosta. Žal veliko programskih paketov za numerično modeliranje XFE metode ne podpira. V primeru FE metode na osnovi digitalnih slik [Hollister in Kikuchi, 1994] vsaka pika v digitalni sliki predstavlja en element v mreži. Tako dobimo preprosto mrežo, ki pa je v primerjavi z drugimi metodami gradnje mreže zelo gosta in vsebuje veliko število elementov. Prav zaradi tega je izračun takšnega modela počasen in se takšna mreža v primeru FE metode uporablja le redko, je pa zelo pogosta v primeru FD metode, saj je ravno zaradi preproste pravokotne mreže zelo prikladna za uporabo. Ponavadi se v FE metodi uporablja adaptivna mreža, to je mreža, ki ima različno velike elemente glede na velikost objektov, ki sestavljajo geometrijo. Adaptivna mreža je lahko narejena ročno [Kopecky *et al.*, 2005] ali avtomatsko s pomočjo algoritmov za gradnjo mreže. Vsi ti principi so nam v pomoč pri reševanju modelov z velikim geometrijskim razmerjem, a samega velikega geometrijskega razmerja ne znižajo. Z uporabo popolnoma prilegajočih plasti (*perfectly matched layers,* PML) [Sebastian *et al.*, 2004] kot robnim pogojem lahko model omejimo le na področje, kjer nas izračun zanima. Popolnoma prilegajoče plasti kot robni pogoji namreč predstavljajo robni pogoj brez odbojev, kar prestavlja neskončni prostor. S to metodo lahko znižamo geometrijsko razmerje modela v modelih z neskončnim prostorom.

Za reševanje modelov v tej nalogi smo uporabili COMSOL Multiphysics, zato smo za reševanje modelov z velikim geometrijskim razmerjem izkoristili nekatere njegove lastnosti. Ena izmed njih je možnost, da lahko v enem modelu zgradimo dve ločeni geometriji. Iz celotne geometrije smo izrezali tisti predel, ki je predstavljal težavo pri gradnji mreže oziroma smo želeli v njem prostorsko bolj podroben ter natančen rezultat. Izrezani del smo vstavili v drugo geometrijo. Tako smo dobili dve geometriji v enem modelu: celotno brez izrezanega dela, poimenovali smo jo velika, ter izrezani del, ki smo ga poimenovali mala geometrija. Obe tako dobljeni geometriji imata nižje geometrijsko razmerje kot osnovna geometrija. Nato pa je potrebno mesta rezanja v eni in drugi geometriji povezati na takšen način, da se obe geometriji obnašata kot ena. COMSOL Multiphysics omogoča reševanje takšnega problema, saj omogoča definiranje več vrst spremenljivk sklapljanja (*coupling variables*) [Comsol AB., 2001]. To so spremenljivke, ki so lahko definirane v eni geometriji in jih uporabimo tako v tej kot tudi v drugi geometriji znotraj istega modela. Omogočajo nam preslikovanje med različnimi dimenzijami v geometriji, na primer integral določene spremenljivke po volumnu v eni geometriji služi kot robni pogoj v drugi geometriji. Z eno od takšnih spremenljivk sklapljanja (*extrusion coupling variable*) smo na meji rezanja določili sklopljen robni pogoj. Na podlagi imena spremenljivke smo tehniko poimenovali nelokalno sklapljanje.

Oglejmo si, kaj mora veljati na mejah rezanja v primeru stacionarnega tokovnega polja. Tako v mali kot v veliki geometriji je potrebno z robnimi pogoji na meji rezanja, ki je postala rob, zagotoviti, da se meja rezanja obnaša kot meja dveh prevodnih medijev. Na meji dveh prevodnih medijev velja za stacionarno tokovno polje zaradi nevrtinčnosti električne poljske jakosti (2.2) in zaradi zakona o ohranitvi nabojev (2.11) naslednji prestopni pogoj za gostoto električnega toka:

$$E_{t\,v} - E_{t\,m} = 0 \tag{2.43}$$

in

$$J_{n\,v} - J_{n\,m} = 0\,, \tag{2.44}$$

kjer z indeksom *v* označujemo veliko geometrijo, z indeksom *m* pa malo geometrijo.
Če upoštevamo Ohmov zakon (2.14) ter upoštevamo, da sta snovi v veliki in mali geometriji na mestu reza enaki (torej imata enako specifično prevodnost), lahko enačbo (2.44) zapišemo kot:

$$E_{n\,v} = \frac{\gamma_m E_{n\,m}}{\gamma_v} = E_{n\,m}\,. \tag{2.45}$$

Enačbi (2.43) in (3.45) predstavljata Neuman-ove robne pogoje, ki določajo vrednost prvega odvoda spremenljivke na meji. Poleg izpolnjevanja le teh pa je potrebno na meji rezanja zagotoviti še zveznost električnega potenciala *V*, kar je v primeru mejnih pogojev samoumevno, v primeru robnih pogojev pa ne. Robni pogoj

$$V_v = V_m \tag{2.46}$$

je Dirichlet-ov robni pogoj, ki določa vrednost spremenljivke na meji. Torej morata na meji veljati tako Neumann-ov kot Dirichlet-ov robni pogoj, kar drugače imenujemo tudi mešani robni pogoj.

V COMSOL Multiphysics-u ni potrebno določiti sestavljenega robnega pogoja na meji rezanja, ampak je potrebno definirati le spremenljivko sklapljanja V_s. Poleg imena je spremenljivki potrebno določiti še tri parametre, in sicer: katero spremenljivko preslikuje (*variable*); od kod (*source*) preslikuje in kam preslikuje (*destination*). Spremenljivki smo določili, da električni potencial v večji geometriji V_v na meji rezanja v veliki geometriji preslika na mejo rezanja v manjši geometriji. Nato je potrebno v manjši geometriji na meji rezanja določiti robni pogoj: $V_m = V_s$, na meji rezanja v večji geometriji pa homogene Neumannove robne pogoje. Spremenljivka V_m predstavlja električni potencial v manjši geometriji. Za algoritem reševanja takšno sklapljanje pomeni, da rob, na katerem je definirana spremenljivka sklapljanja, ter rob, na katerega cilja spremenljivka sklapljanja, ni več rob, ampak meja dveh prevodnikov. Zato algoritem zgradi eno samo matriko za reševanje, ki jo reši enako, kakor da gre za eno geometrijo. Pri tem je potrebno upoštevati še, da je matrika, ki jo je potrebno rešiti, običajno redka. Vrednost nekega vozlišča je namreč odvisna le od vrednosti sosednjih vozlišč, vsi ostali elementi v vrstici matrike pa so enaki nič. Zaradi nelokalnega sklapljanja postane ta matrika vse manj redka, zaradi česar se poveča raba pomnilnika med izračunom ter se podaljša čas reševanja [Comsol AB., 2001]. Podobno kakor v primeru stacionarnega tokovnega polja velja tudi za druga polja, razlika je le v tem, da je potrebno sklapljanje na robovih določiti za vse neodvisne spremenljivke, ki jih v modelu računamo.

3 Regulativa na področju elektromagnetnega sevanja

O elektromagnetnem sevanju obstaja veliko različnih dokumentov, vendar je resnično pomembnih in relevantnih le nekaj. Le-ti se med seboj razlikujejo tako po vsebini kot tudi po njihovem pravnem statusu. V osnovi jih lahko delimo na dve skupini:

- znanstveni dokumenti, kamor sodijo okoljska zdravstvena merila UNEP/WHO/IRPA (United Nations Environment Programme/World Health Organization/ International Radiation Protection Association) in Smernice ICNIRP (International Commission on Non-Ionizing Radiation Protection);
- pravni dokumenti, kamor sodijo Direktiva 2004/40/EC evropskega parlamenta in Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju in
- ostali dokumenti, kamor sodijo Priporočila 1999/519/EC.

V nadaljevanju bodo dokumenti podani v hierarhičnemv vrstnem redu, kajti okoljska merila, ki so nastala prva, so služila za osnovo Smernic ICNIRP in Uredbe, Priporočila 1999/519/EC in Direktiva 2004/40/EC pa temeljijo na Smernicah ICNIRP.

3.1 Okoljska zdravstvena merila UNEP/WHO/IRPA in Smernice ICNIRP

V okviru IRPA (International Radiation Protection Association) se je oblikovala v sedemdesetih letih delovna skupina NIR (non-ionizing radiation) za neionizirno sevanje, kasneje se je preimenovala v komite INIRC (International Non-Ionizing Radiation Committee). V sodelovanju z WHO je pripravila več okoljskih zdravstvenih meril pod pokroviteljstvom UNEP (United Nations Environment Programme):

- UNEP/WHO/IRPA. 1984. Environmental Health Criteria 35 Extremely low frequency (ELF) fields. WHO, Geneva. Dostopno na: http://www.inchem.org/documents/ehc/ehc/ehc35.htm
- UNEP/WHO/IRPA. 1987. Environmental Health Criteria 69 Magnetic fields. WHO, Geneva. Dostopno na: http://www.inchem.org/documents/ehc/ehc/ehc69.htm
- UNEP/WHO/IRPA. 1993. Environmental Health Criteria 137 Electromagnetic fields (300 Hz to 300 GHz). WHO, Geneva. Dostopno na: http://www.inchem.org/documents/ehc/ehc/ehc137.htm

V teh dokumentih je podan obširen pregled literature o vplivih elektromagnetnih sevanj različnih frekvenčnih področij na človeka, podane so ocene tveganja, obenem pa so predstavljene tako značilnosti kot tudi merjenje in viri neionizirnih elektromagnetnih sevanj. Kasneje je INIRC postal neodvisna znanstvena organizacija ICNIRP (International

Commission on Non-Ionizing Radiation Protection), katere naloge so raziskovanje mogočih nevarnosti povezanih z neionizirnimi elektromagnetnimi sevanji, priprava mednarodnih smernic o izpostavljenosti neionizirnim elektromagnetnim sevanjem in zaščita pred neionizirnimi elektromagnetnimi sevanji. Eden izmed najpomembnejših dokumentov, ki jih je ICNIRP pripravil, so Smernice o omejevanju izpostavljenosti elektromagnetnemu sevanju:

- ICNIRP. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74: 494-522.

V tem dokumentu je krajši pregled vplivov neionizirnega elektromagnetnega sevanja, podkrepljen s številnimi citati. Podane so tudi predlagane mejne vrednosti (*basic restrictions*), ki se razlikujejo glede na frekvenčno območje. Pri nizkih frekvencah do 100 kHz so mejne vrednosti podane kot gostota električnega toka v telesu, kar preprečuje vplive na živčni sistem. V frekvenčnem območju od 100 kHz do 10 MHz so mejne vrednosti določene tako za gostoto toka v telesu kakor tudi za SAR. Za SAR so določene dvojne mejne vrednosti, in sicer za celotno telo ter lokalna vrednost SAR (povprečni SAR v 10 g tkiva), kar preprečuje prekomerno gretje tako celotnega telesa kakor tudi dela telesa. Kot sprejemljiva sprememba temperature telesa zaradi elektromagnetnega sevanja je uporabljena vrednost 1˚C. V frekvenčnem območju od 10 MHz do 10 GHz so omejitve določene le za SAR. Med 10 GHz in 300 GHz so mejne vrednosti določene kot gostota pretoka moči, da je preprečeno prekomerno segrevanje tkiva na ali tik pod površino telesa, saj se večina energije elektromagnetnega sevanja zaradi majhne vdorne globine absorbira v zelo tanki plasti. Ker je premalo znanega o bioloških in zdravstvenih učinkih elektromagnetnih sevanj, da bi lahko postavili točno določene meje za celotno frekvenčno območje in različne modulacije elektromagnetnega sevanja, Smernice ICNIRP predlagajo mejne vrednosti za znane biološke in zdravstvene učinke zmanjšane za varnostni faktor 10 za zaposlene ter dodatni varnostni faktor 5 (skupno torej 50) za prebivalstvo. Dodaten varnostni faktor za prebivalstvo je uporabljen zaradi mogočih odstopanj v starosti in zdravstvenem stanju prebivalstva. Mejne vrednosti so podane v Tabeli 1.

Tabela 1: Mejne vrednosti (*basic restrictions*) po Smernicah ICNIRP. Mejne vrednosti so določene za posamezna frekvenčna območja, saj so glede na frekvenčno območje različne tako mejne vrednosti kakor tudi veličine, ki so omejene. Tabelo sestavljata dva dela, saj veljajo za prebivalstvo petkrat nižje mejne vrednosti kot za zaposlene.

	Frekvenčno območje	Gostota toka glava in trup ($\mathrm{mAm^{-2}}$) (rms)	Povp. SAR telo ($\mathrm{Wkg^{-1}}$)	Lokalni SAR glava in trup ($\mathrm{Wkg^{-1}}$)	Lokalni SAR okončine ($\mathrm{Wkg^{-1}}$)	Gostota pretoka moči ($\mathrm{Wm^{-2}}$)
Mejne vrednosti za zaposlene	up to1 Hz	40	—	—	—	—
	1–4 Hz	40/*f*	—	—	—	—
	4 Hz–1 kHz	10	—	—	—	—
	1–100 kHz	*f*/100	—	—	—	—
	100 kHz–10 MHz	*f*/100	0.4	10	20	—
	10 MHz–10 GHz	—	0.4	10	20	—
	10 GHz-300 GHz	—	—	—	—	50
Mejne vrednosti za prebivalstvo	up to1 Hz	8	—	—	—	—
	1–4 Hz	8/*f*	—	—	—	—
	4 Hz–1 kHz	2	—	—	—	—
	1–100 kHz	*f*/500	—	—	—	—
	100 kHz–10 MHz	*f*/500	0.08	2	4	—
	10 MHz–10 GHz	—	0.08	2	4	—
	10 GHz-300 GHz	—	—	—	—	10

Opombe:

- *f* je frekvenca izražena v Hz.
- Gostoto toka je zaradi nehomogenosti telesa potrebno povprečiti na površino 1 cm^2 pravokotno na smer toka.
- Za frekvence do 100 kHz se maksimalne vrednosti gostote toka določi iz vrednosti gostote toka v rms pomnožene z $\sqrt{2}$ (≈1.414). Za pulze dolžine t_p je ekvivalentna frekvenca $f = 1/(2tp)$.
- Za frekvence do 100 kHz v primeru pulzirajočega magnetnega polja se maksimalno gostoto toka izračuna iz dvižnega/vpadnega časa in največje spremembe gostote magnetnega pretoka. Inducirana gostota toka se nato primerja z ustrezno mejno vrednostjo.
- Vrednosti SAR je potrebno povprečiti na 6 minutno periodo.
- Za lokalni SAR je masa za povprečenje 10 g sosednjega tkiva, tako določen maksimalen SAR se uporablja za oceno izpostavljenosti.
- Da bi preprečili slušne efekte zaradi termoelastičnih raztezkov, pa velja za pulze v frekvenčnem območju 0.3 do 10 GHz za lokalne izpostavitve glave, še dodatna mejna vrednost, in sicer SA ne sme presegati 10 mJ kg^{-1} za zaposlene in 2mJ kg^{-1} za prebivalstvo, povprečeno na 10 g tkiva.
- Gostoto pretoka moči je potrebno povprečiti na 20 cm^2 ter na $68/f^{1.05}$ minutno periodo (kjer je *f* frekvenca v GHz).
- Lokalne maksimalne gostote pretoka moči, povprečene na 1 cm^2 ne smejo preseči 20 kratnika mejne vrednosti.

V praksi je ugotavljanje, ali so izpolnjene mejne vrednosti, zahtevno opravilo. Vse veličine, razen gostota pretoka moči, se namreč nanašajo na notranjost človeškega telesa in jih je neposredno nemogoče izmeriti. Zaradi lažje uporabe Smernic ICNIRP so mejnim vrednostim (*basic restrictions*) dodali še izvedene mejne vrednosti (*reference levels*). Izvedene mejne vrednosti se ne nanašajo na razmere v samem človeškem telesu, ampak na elektromagnetno polje v prostoru brez človeka. Zato so izvedene mejne vrednosti določene za veličine, ki so merljive v prostoru: električna poljska jakost, magnetna poljska jakost, gostota magnetnega pretoka in gostota pretoka moči. Podobno kakor za mejne vrednosti so tudi za izvedene mejne vrednosti uporabljena frekvenčna območja, ki pa se razlikujejo od frekvenčnih območji, uporabljenih za mejne vrednosti. Izvedene mejne vrednosti so podane v Tabeli 2.

Tabela 2: Izvedene mejne vrednosti (*reference levels*) po Smernicah ICNIRP. Izvedene mejne vrednosti so določene za posamezna frekvenčna območja, saj so glede na frekvenčno območje različne tako mejne vrednosti kakor tudi veličine, ki so omejene. Tabelo sestavljata dva dela, saj veljajo za prebivalstvo petkrat nižje mejne vrednosti kot za zaposlene, zato so tudi izvedene mejne vrednosti dva do petkrat nižje.

	Frekvenčno območje	Električna poljska jakost (Vm^{-1})	Magnetna poljska jakost (Am^{-1})	Gostota magnetnega pretoka (μT)	Gostota pretoka moči (Wm^{-2})
Izvedene mejne vrednosti za zaposlene	do 1 Hz	—	1.63×10^{5}	2×10^{5}	—
	1–8 Hz	20,000	$1.63\times10^{5}/f^{2}$	$2\times10^{5}/f^{2}$	—
	8–25 Hz	20,000	$2\times10^{4}/f$	$2.5\times10^{4}/f$	—
	0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	—
	0.82–65 kHz	610	24.4	30.7	—
	0.065–1 MHz	610	$1.6/f$	$2.0/f$	—
	1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	—
	10–400 MHz	61	0.16	0.2	10
	400–2,000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$0.01f^{1/2}$	$f/40$
	2–300 GHz	137	0.36	0.45	50
Izvedene mejne vrednosti za prebivalstvo	do 1 Hz	—	3.2×10^{4}	4×10^{4}	—
	1–8 Hz	10,000	$3.2\times10^{4}/f^{2}$	$4\times10^{4}/f^{2}$	—
	8–25 Hz	10,000	$4000/f$	$5000/f$	—
	0.025–0.8 kHz	$250/f$	$4/f$	$5/f$	—
	0.8 -3kHz	$250/f$	5	6.25	—
	3–150 kHz	87	5	6.25	—
	0.15–1 MHz	87	$0.73/f$	$0.92/f$	—
	1–10 MHz	$87/f^{1/2}$	$0.73/f$	$0.92/f$	—
	10–400 MHz	28	0.073	0.092	2
	400–2,000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	$0.0046f^{1/2}$	$f/200$
	2–300 GHz	61	0.16	0.2	10

Opombe:

- f je frekvenca.
- Če so izpolnjene mejne vrednosti, lahko izvedene mejne vrednosti prekoračimo.
- Za frekvence med 100 kHz in 10 GHz velja, da se vrednosti gostote pretoka moči ter vrednosti kvadrata električne ter magnetne poljske jakosti in gostote magnetnega pretoka povprečijo na 6 minutno periodo.
- Za maksimalne vrednosti pri frekvencah do 100 kHz glej Tabelo 1, opombo 3.
- Za maksimalne vrednosti električne in magnetne poljske jakosti pri frekvencah nad 100 kHz se uporablja interpolirani koeficient z vrednostjo 1.5 pri 100 kHz in 32 pri 10 MHz. Za višje frekvence se uporablja koeficient z vrednostjo 32, obenem pa naj maksimalna vrednost gostote pretoka moči povprečena preko ene periode ne preseže izvedene mejne vrednosti za več kot 1000 krat.
- Za frekvence višje od 10 GHz se gostote pretoka moči ter vrednosti kvadrata električne ter magnetne poljske jakosti in gostote magnetnega pretoka povpreči na $68/f^{1.05\ \mathrm{minutno}}$ period (f je v GHz).
- Za frekvence nižje od 1 Hz ni meje za električno poljsko jakost. Nevarnost električnega udara zaradi nizkoimpedančnih virov je zagotovljena s procedurami za za takšne naprave.

3.2 Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju

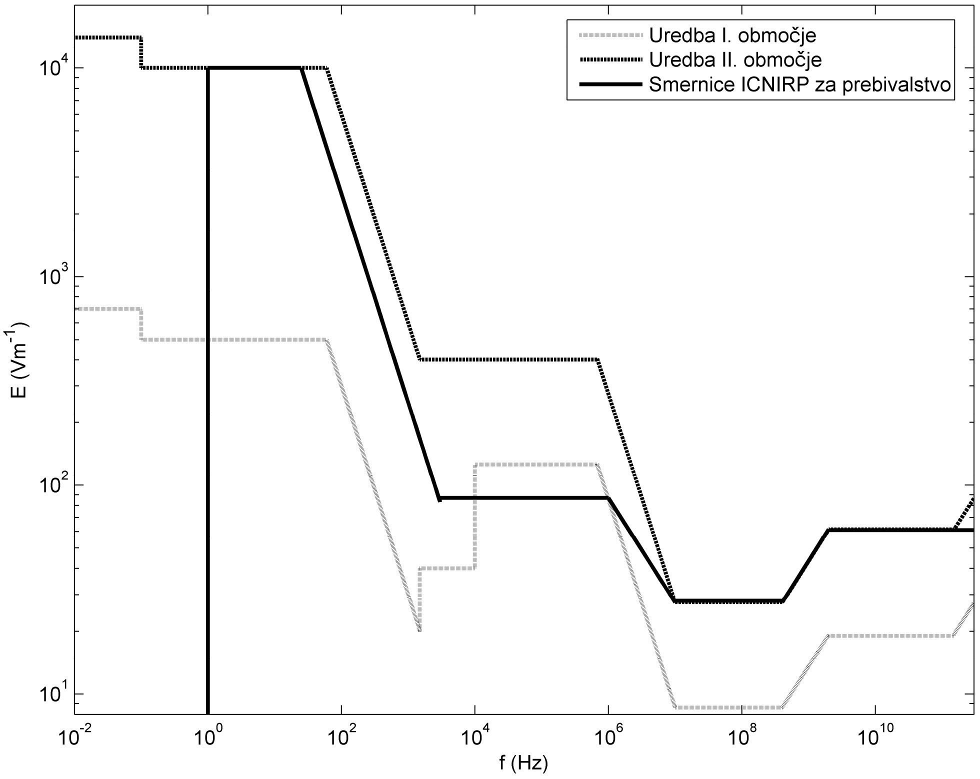
Tudi Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju

- Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju. 1996. Uradni list RS, št. 70/96.

sledi Smernicam ICNIRP, a ne tako dosledno kot Priporočila 1999/519/EC ali Direktiva 2004/40/EC. Uredba uporablja drugačna frekvenčna območja, ne ločuje na zaposlene in prebivalstvo, poleg tega pa glede na namen uporabe uvaja dve stopnji zaščite:

- I. stopnja: območja s potrebo po povečanem varstvu pred elektromagnetnimi sevanji (območja bolnišnic, zdravilišč, čisto stanovanjska območja, območja objektov vzgojnovarstvenega in izobraževalnega programa, igrišč…)
- II. stopnja: ostala območja.

Bistvena razlika je tudi v tem, da Uredba ne omejuje tistih veličin, ki jih omejujejo mejne vrednosti Smernic ICNIRP, ampak le izvedene mejne vrednosti Smernic ICNIRP. Bolj smiselno bi bilo torej mejne vrednosti Uredbe imenovati izvedene mejne vrednosti Uredbe, a ker sama Uredba uporablja izraz mejna vrednost, bo isti izraz uporabljen tudi v tem delu. Zaradi jasnosti bo vedno uporabljan kot »mejna vrednost Uredbe«.



Slika 2: Primerjava mejnih vrednosti električne poljske jakosti Uredbe in Smernic ICNIRP. Skoraj na celotnem frekvenčnem območju je Uredba za I. območje strožja od Smernic ICNIRP.

Uredba je še posebej v I. območju strožja od Smernic ICNIRP in Priporočil 1999/519/EC, kar je vidno iz Slike 2, kjer je predstavljena primerjava med izvedenimi mejnimi vrednostmi za električno poljsko jakost po Smernicah ICNIRP za prebivalstvo ter Uredbe. Uredba je pravni akt, ki velja v Republiki Sloveniji in je obvezujoča.

Tabela 3: Mejne efektivne vrednosti v Uredbi. Mejne vrednosti so določene za posamezna frekvenčna območja, saj so glede na frekvenčno območje različne tako mejne vrednosti kakor tudi veličine, ki so omejene. Tabelo sestavljata dva dela, zgornji del velja za I območje, to je območje s povečano stopnjo varovanja.

	Frekvenčno območje	Električna poljska jakost (Vm^{-1})	Magnetna poljska jakost (Am^{-1})	Gostota magnetnega pretoka (mT)	Gostota pretoka moči (Wm^{-2})
I. območje	0–0.1Hz	700	—	4	—
	0.1–1.15 Hz	500	—	2.8	—
	1.5–60 Hz	500	—	$0.5/f$	—
	60–1,500 Hz	$30000/f$	—	$0.5/f$	—
	1,500–10,000Hz	40	—	0.002	—
	0.01–0.042 MHz	126	5.3	—	—
	0.042–0.68 MHz	126	$0.22/f$	—	—
	0.68–10 MHz	$86/f$	$0.22/f$	—	—
	10–400 MHz	8.6	0,022	—	0,2
	400–2.000 MHz	$0.43f^{1/2}$	$1.15\times10^{-3} f^{1/2}$	—	$f/2000$
	2.000–150.000 MHz	19	0,05	—	1
	150.000–300.000 MHz	$0.05f^{1/2}$	$1.32\times10^{-3} f^{1/2}$	—	$0.67\times10^{-5}f$
II. območje	0–0.1Hz	14000	—	40	—
	0.1–1.15 Hz	10000	—	28	—
	1.5–60 Hz	10000	—	$5/f$	—
	60–1,500 Hz	$600000/f$	—	$5/f$	—
	1,500–10,000Hz	400	—	0.021	—
	0.01–0.042 MHz	400	16.8	—	—
	0.042–0.68 MHz	400	$0.7/f$	—	—
	0.68–10 MHz	$275/f$	$0.7/f$	—	—
	10–400 MHz	27.5	0,07	—	2
	400–2.000 MHz	$1.37f^{1/2}$	$3.64\times10^{-3} f^{1/2}$	—	$f/200$
	2.000–150.000 MHz	61.4	0,163	—	10
	150.000–300.000 MHz	$0.158f^{1/2}$	$4.21\times10^{-3} f^{1/2}$	—	$6.67\times10^{-5}f$

Opombe:

- Za frekvenčno območje od 0 do 0,1 Hz mejne vrednosti veljajo za temenske vrednosti.
- Za vrednost *f* se uporabi vrednost v istih enotah, kakor za frekvenčno območje tiste mejne vrednosti.

3.3 Priporočila 1999/519/EC

Priporočila 1999/519/EC Sveta Evrope:

- Council recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). 1999. Official Journal of the Europena Communities, L199.

zgolj povzemajo Smernice ICNIRP za prebivalstvo in na popolnoma enak način določajo mejne vrednosti in izvedene mejne vrednosti, edina razlika je, da pri mejnih vrednostih za frekvenco 0 (statično polje) dodatno omejujejo gostoto magnetnega pretoka, in sicer na vrednost 40 mT.

Priporočila 1999/519/EC so podobno kot Smernice ICNIRP zgolj predlog, kakšna je lahko nacionalna zakonodaja na področju zaščite pred elektromagnetnimi sevanji. Priporočila 1999/519/EC niso pravno zavezujoča.

3.4 Direktiva 2004/40/EC

Kakor je veljalo, da Priporočila 1999/519/EC povzemajo Smernice ICNIRP, velja popolnoma enako tudi za Direktivo o minimalnih zdravstvenih in varnostnih zahtevah v zvezi z izpostavljenostjo delavcev tveganjem, ki nastajajo zaradi fizikalnih dejavnikov (elektromagnetnih sevanj):

- Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields). 2004. Official Journal of the European Union L 184,

le da Direktiva 2004/40EC povzema Smernice ICNIRP za zaposlene in ne za prebivalstvo kakor Priporočila 1999/519/EC. Direktiva 2004/40EC se od Smernic ICNIRP za zaposlene razlikuje le v tem, da uporablja druga imena za mejo vrednost (*exposure limits*) in izvedeno mejno vrednost (*action values*). Direktivi 2004/40EC je dodana izvedena mejna vrednost za tok ob dotiku.

Z razliko od Priporočil 1999/519/EC je Direktiva 2004/40EC pravno zavezujoč dokument za članice Evropske Unije.

4 Materiali in metode

Numerični izračun v COMSOL Multiphysics-u temelji na naslednjih korakih:

- določitev oz. risanje geometrije;
- izgradnja mreže;
- določanje fizikalne narave problema (*application mode*), kajti parametri v naslednjih korakih so odvisni od fizikalne narave problema;
- določanje konstant, spremenljivk in sklapljanja;
- določanje robnih pogojev;
- določanje lastnosti snovi;
- izbor algoritmov in parametrov za reševanje ter reševanje samo in
- prikaz rezultatov.

Pri modeliranju človeškega telesa na podlagi medicinskih slik je potrebno pred prvim korakom, to je določitvijo geometrije, izvesti več korakov, ki nas pripeljejo do optimalne geometrije. Optimalna geometrija je geometrija, ki vsebuje kar največ podrobnosti, a je hkrati dovolj preprosta, da je mogoče v modelu zgraditi mrežo ter nato model izračunati. O tem, ali je model mogoče izračunati, odloča število prostostnih stopenj, ki opiše, koliko spremenljivk je potrebno izračunati. Število prostostnih stopenj je odvisno od števila vozlišč. Pri uporabi tetraedrov za gradnjo mreže ima tako vsak element štiri vozlišča, a vsi elementi znotraj mreže si delijo vozlišča, tako da je skupno število vozlišč manjše od štirikratnika števila vozlišč. Število prostostnih stopenj je tako odvisno od:

- števila elementov, večje kot je število elementov, večje je število prostostnih stopenj;
- oblike elementov;
- števila robnih elementov, v robnih elementih je vrednost spremenljivk določena in jih ni potrebno računati; vendar je več vozlišč, ki si jih delita zgolj dva elementa in ne tri ali več, kot velja znotraj mreže;
- stopnje elementov, kar pomeni stopnje polinoma, ki znotraj elementa opisuje potek spremenljivk, višja kot je stopnja, večje je število prostostnih stopenj;
- števila spremenljivk, ki jih je potrebno računati, v primeru stacionarnega tokovnega polja ali elektrostatičnega polja je to ena spremenljivka, in sicer električni potencial, v primeru kvazistatičnega elektromagnetnega polja pa so to štiri spremenljivke, in sicer električni potencial (ena spremenljivka) in vektorski magnetni potencial (tri spremenljivke, ker je magnetni potencial vektor).

Število prostostnih stopenj je torej odvisno od fizikalne narave ter geometrije modela. Po drugi strani pa je maksimalno število prostostnih stopenj, ki jih lahko z računalnikom izračunamo, odvisno od uporabljenega algoritma za reševanje in vgrajenega spomina računalnika. Pri spominu računalnika je zelo pomembna omejitev, ki velja v 32 bitni verziji, in sicer je maksimalni spomin, ki ga lahko COMSOL Multiphysics uporablja, največ do 1.5 Gb, četudi računalnik vsebuje več spomina. Zaradi te omejitve je mogoče z uporabo direktnih algoritmov izračunati modele do približno 60.000 prostostnih stopenj, za večje število prostostnih stopenj pa je potrebno uporabiti iterativne algoritme, s katerimi je mogoče izračunati do 130.000 prostostnih stopenj. Slabost iterativnih algoritmov je, da so manj robustni od direktnih, saj v primeru slabe mreže počasi konvergirajo. Zaradi vsega omenjenega je potrebno kompleksno geometrijo prilagajati posameznemu modelu in se med samim postopkom modeliranja včasih vrniti spet na izhodišče in geometrijo, ter seveda posledično tudi druge korake modeliranja, modificirati.

Če se zopet vrnemo k modeliranju človeškega telesa na podlagi medicinskih slik in potrebnih korakov pred določitvijo geometrije v programskem paketu za numerično modeliranje, je najprej potrebno medicinske slike obdelati in določiti robove tistih organov, ki jih želimo vključiti v model.

4.1 Obdelava slik

Obstaja več vrst medicinskih slik človeka, ki so primerne za gradnjo modelov. Med različnimi vrstami slik so številne pomembne razlike, kot na primer: ali so projekcijske ali prerezne, posnete na živem človeku ali kadavru, katere vrste tkiva prikazujejo… Najpomembnejša delitev je na slike, namenjene medicinski diagnostiki in slike prerezov človeškega kadavra.

4.1.1 Rentgenske slike

Najpreprostejše in najstarejše slike, ki prikazujejo notranjost človeškega telesa in so primarno namenjene medicinski diagnostiki, so rentgenske slike. Predstavljajo projekcijo dela človeškega telesa na dvodimenzionalen medij. V preteklosti je bil ta medij film, sodobnejše naprave pa imajo namesto filma elektronski senzor. Dobro prikazujejo kosti in kovinske implante, slabo pa mehko tkivo. Imajo veliko razločljivost, posnete so hitro, zato se uporabljajo v diagnostične namene predvsem pri poškodbah in sanaciji poškodb kosti. Slabo podajajo tridimenzionalno informacijo, saj je intenziteta osvetlitve posameznega dela slike odvisna od absorpcije rentgenskega sevanja na celotni poti sevanja skozi del telesa, zato slika predstavlja projekcijo tridimenzionalnega objekta na dvodimenzionalni medij. Poleg tega so v primeru uporabe filma kot medija, kar je običajna praksa, v analogni obliki in jih je potrebno pred uporabo kvalitetno digitalizirati.

4.1.2 CT slike

Nadgradnjo rentgenskega slikanja predstavlja CT slikanje, ki prav tako temelji na absorpciji rentgenskega sevanja v človeškem telesu, vendar CT naprava z razliko od običajnega rentgenskega aparata uporablja vir rentgenskih žarkov z močno usmerjenim snopom. Vir je usmerjen na elektronski senzor, med virom in senzorjem pa leži človek, ki ga je potrebno slikati. Med slikanjem se tako vir kakor tudi senzor vrtita okrog snemanega človeškega telesa. Ker leži senzor nasproti vira rentgenskih žarkov, zaznava prepuščen del rentgenskih žarkov. Po nadaljnji obdelavi zajetih podatkov dobimo dvodimenzionalno sliko enega prereza človeškega telesa v ravnini, po kateri sta se vir in senzor gibala. S spreminjanjem ravnine lahko dobimo tako več dvodimenzionalnih slik, ki nam lahko služijo za izdelavo tridimenzionalnih modelov.

4.1.3 MRI slike

Podobne slike prerezov dobimo tudi z MRI napravo, ki pa se po načinu delovanja zelo razlikuje od rentgenskega in CT slikanja. Atomi, katerih jedra so magnetni dipoli, so orientirani v poljubnih smereh in njihova vsota, imenovana magnetizacija, je enaka nič. Če takšne atome izpostavimo zunanjemu magnetnemu polju, magnetizacija kaže v smeri zunanjega magnetnega polja, vsak posamezen atom, katerega magnetni dipol ni v smeri zunanjega magnetnega polja, pa precesira okrog te smeri z njemu značilno frekvenco, odvisno od vrste atoma in zunanjega magnetnega polja. Za atom vodika, ki je pri uporabi MRI metode na človeku najpomembnejši, znaša 267.5 MHz/T. Vektor magnetizacije se pod vplivom dodatnega izmeničnega elektromagnetnega polja s frekvenco precesije odkloni in po koncu pulza precesira na enak način kot posamezen dipol. Odklon je odvisen od jakosti in dolžine pulza, po prenehanju dodatnega elektromagnetnega polja pa se precesija vrača v ravnovesno stanje. Zaradi precesije magnetizacije se v detekcijski tuljavi inducira napetost, ki je največja takoj po prenehanju dodatnega polja in s časom upada, vendar nekajkrat hitreje kot se magnetizacija vrača v ravnovesno stanje. Napetost upada hitreje, ker magnetni dipoli, ki so takoj ob koncu dodatnega elektromagnetnega polja sofazni, ne nihajo s popolnoma enako frekvenco in s časom nihajo vedno manj sofazno. Velikost inducirane napetosti v detekcijski tuljavici je odvisna od gostote jeder, ki smo jih z dodatnim poljem odklonili. Pri slikanju z magnetno resonanco položimo človeško telo v zunanje magnetno polje z gostoto magnetnega polja od 0,5 T do 1,5 T. V predelu, ki ga želimo slikati, dodamo še gradientno magnetno polje v eni smeri. Zato dobimo odvisnost frekvence precesije od lege v eni smeri in zajamemo cel frekvenčni spekter induciranih napetosti v detekcijiski tuljavi namesto ene same frekvence. S spreminjanjem orientacije gradientnega magnetnega polja ter kasnejšo računalniško obdelavo je mogoče dobiti gostoto želenega atoma, ponavadi vodika, v eni prerezni ravnini. S premikanjem tako vira dodatnega elektromagntnega polja kot tudi detekcijske tuljave in gradientnega magnetnega polja dobimo serijo slik, ki predstavljajo gostot želenega atoma. Ker je gostota atoma odvisna od vrste tkiva, dobimo sliko tkiva [povzeto po Božič *et al.*, 2005]. Slabost metode je njena dolgotrajnost v primerjavi s CT slikami, vendar ima metoda veliko razločljivost na področju mehkih tkiv, saj le ta vsebujejo različno količino vode, kjer je večina atomov vodika. Žal se metoda večinoma ne uporabna v primeru, ko ima človek kakšen kovinski implant. Razlog je, da bi nanj delovale v velikem magnetnem polju močne sile, poleg tega pa bi se zaradi dodatnega elektromagnetnega polja segreval, čeprav si literatura ni enotna o varnosti uporabe [Achenbach *et al.*, 1997, Chou, 2000, Shellock, 2001, Finelli *et al.*, 2002, Shellock, 2002, Martin *et al.*, 2004, Martin, 2005, Luechinger *et al.*, 2005].

4.1.4 VHDS slike

Posebna oblika slik so slike iz baze Visible Human Data Set (VHDS). Baza je po predhodnem dovoljenju in pod določenimi pogoji prosto dostopna na strani ameriške nacionalne medicinske knjižnice National Library of Medicine, National Institute of Health, Združene države Amerike. Baza vsebuje obsežno tridimenzionalno bazo slik moškega in ženskega kadavra, in sicer v CT in MRI tehniki ter v obliki barvnih bitnih slik prerezov zamrznjenih kadavrov.

Za nadaljnjo obdelavo so najbolj zanimive barvne bitne slike zamrznjenega kadavra. Posnete so aksialno z razločljivostjo 2048 krat 1216 točk (0.33 mm na točko) s 24 bitno barvno globino. Posamezne slike si sledijo z intervalom 1 mm pri moškem ter 0.33 mm pri ženski, tako da je ženski kadaver predstavljen s kockami z robom 0.33 mm.

Prednost slik iz baze VHDS je, da je baza prosto dostopna, natančna, slike so posnete z veliko razločljivostjo in z majhnimi presledki. Zaradi razširjene uporabe omogoča primerjavo rezultatov raziskave z že znanimi rezultati, objavljenimi v literaturi. Slabost te baze je, da kadavra, ki so ga uporabili za izdelavo slik, odstopa od povprečnih vrednosti glede na težo.

4.1.5 Izbor in obdelava slik

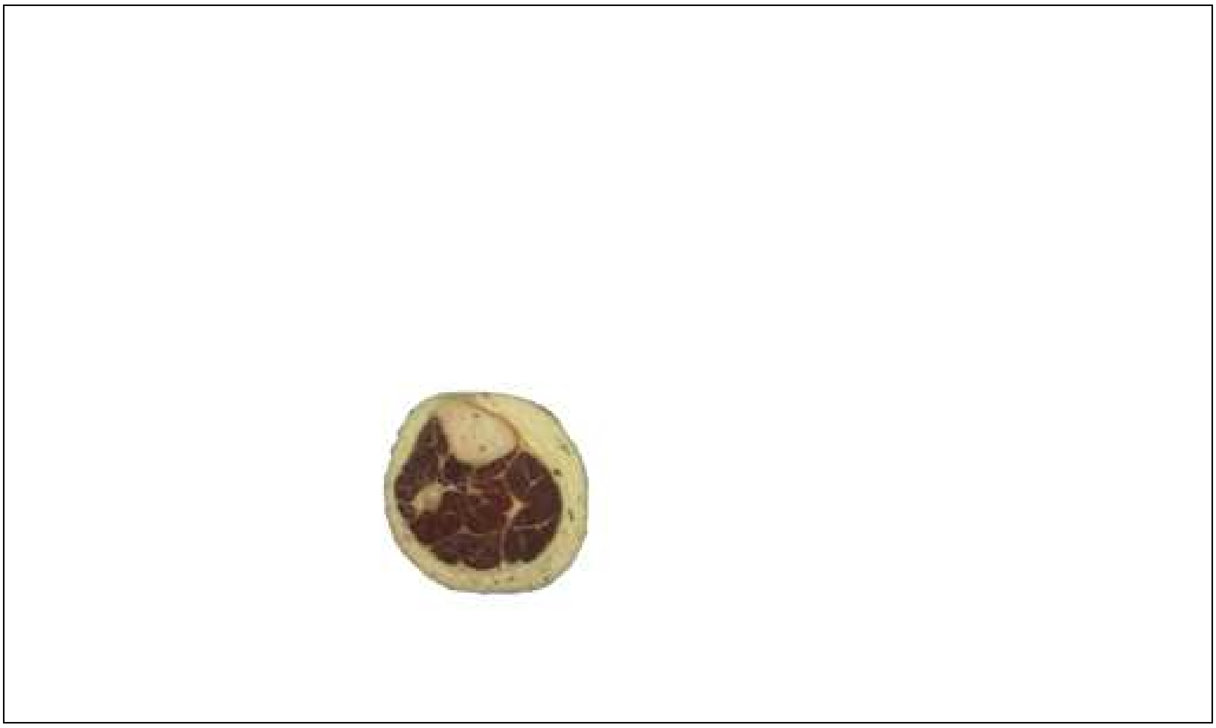
Model bi bilo najlažje zgraditi s pomočjo CT slik bolnika z vstavljenim implantom. Vendar se CT slikanje med običajnim zdravljenjem bolnikov z implanti izvaja le redko. Poleg tega se ponavadi izvede CT slikanje le tistega dela telesa, kje je implant. To nam onemogoča izdelavo modela celotnega človeškega telesa le z uporabo CT slik. Odločili smo se, da bodo osnovo za geometrijo predstavljale barvne slike prerezov zmrznjenega ženskega kadavra iz baze VHDS. Po potrebi smo v posamezno geometrijo vključili tudi druge slike, ki so nam omogočile vključitev implanta v model. Tudi druge slike so bile obdelane na enak način kot slike VHDS.

Pred obdelavo slik se je bilo potrebno odločiti, katera tkiva bomo v modelu razlikovali. Seveda bi bilo za kvaliteto izračuna bolje, če bi bilo teh tkiv kar največ, vendar to vodi v preveč kompleksen model. Za izračun elektromagnetnega polja v modelu je v večini primerov dovolj, če geometrija modela vsebuje tri objekte, in sicer mehko tkivo, kosti v tistem območju, ki nas zanima, ter implant. Kost ima namreč specifično prevodnost nekaj velikostnih razredov nižjo od specifične prevodnosti mehkih tkiv. Kovinski implant ima specifično prevodnost za nekaj velikostnih razredov večjo od najbolj prevodne snovi v telesu, ki je kri. Kri ima na celotnem frekvenčnem območju med 10 Hz in 10 GHz specifično prevodnost manjšo od 100 Sm^{-1}, medtem ko je značilna prevodnost kovin večja od 10^6 Sm^{-1}.

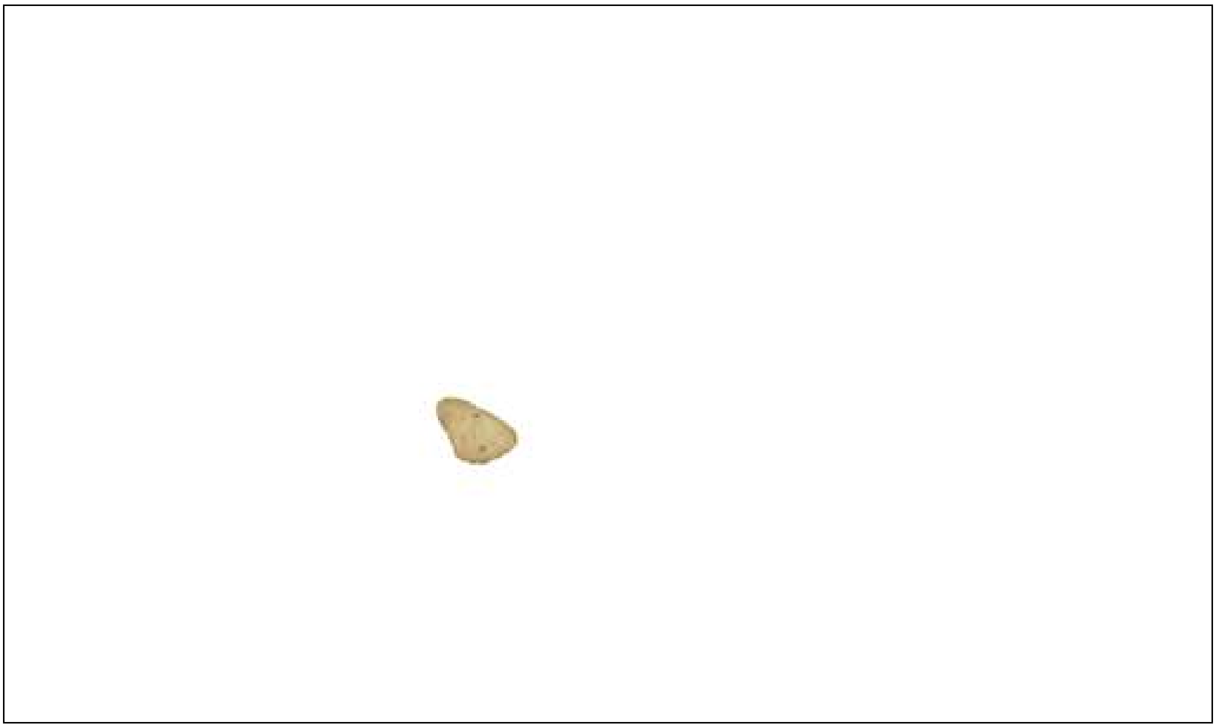
Slike smo najprej v Adobe Photoshopu (Adobe Systems Incorporated, ZDA) iz formata .raw pretvorili v format .jpg, ker je ta format manjši ter enostavnejši za obdelavo, hkrati pa je format .jpg dosti bolj razširjen kot format .raw. Nato smo za vsako vrsto tkiva izbrali določeno število slik, ki so služile za izdelavo geometrije. Namreč, pri metodi končnih elementov potrebujemo veliko manj prereznih ravnin, da lahko zgradimo verodostojno geometrijo, kakor jih je na voljo v bazi VHDS. Ko smo izbrali sliko, primer slike je prestavljen na Sliki 3, smo s pomočjo programa Corel Photopaint (Corel Corporation, Kanada) določili robove tistega tkiva, ki smo ga gradili. Prej omenjena slika nam je služila za gradnjo kar 4 različnih objektov: leve (Slika 4) in desne (Slika 5) noge ter kosti v desni nogi, in sicer golenice (Slika 6) in mečnico (Slika 7). Preden smo sliko posneli, smo vse območje izven meje nadomestili z belo barvo.

Slika 3: Slika iz baze VHDS, ki je služila za izdelavo geometrije modela. Slika nosi ime avf2300.raw.

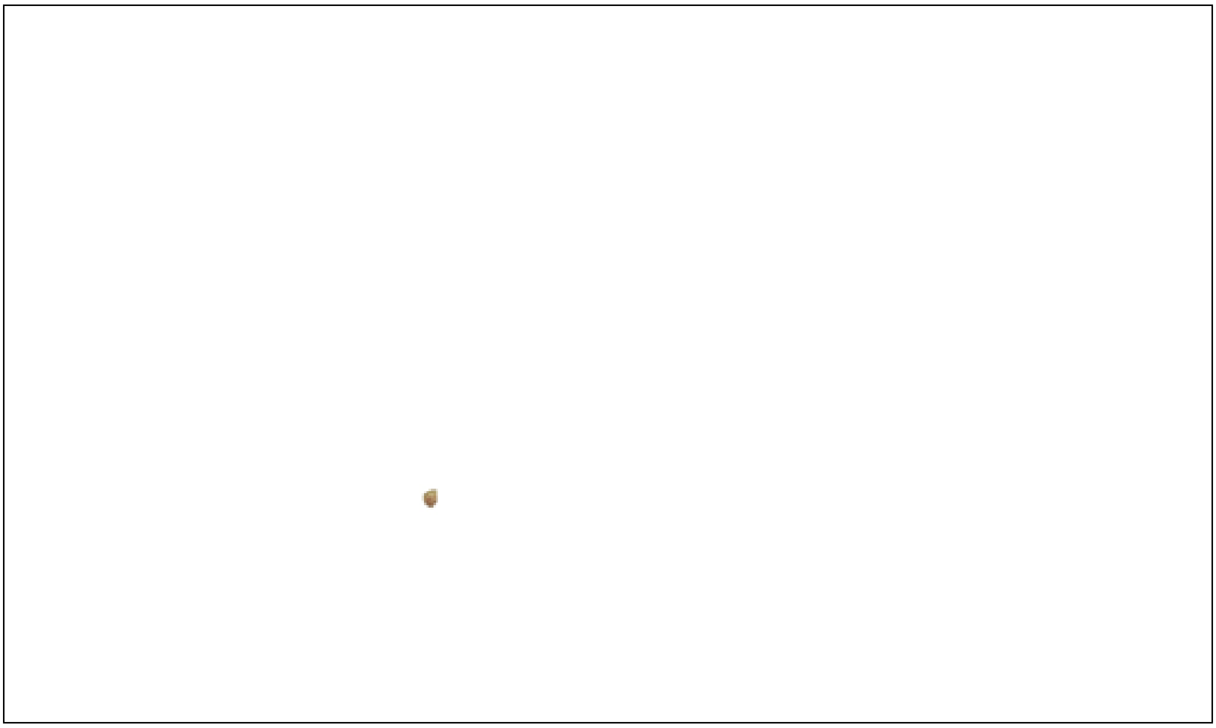
Slika 4: Obdelana Slika 3 za izdelavo geometrije leve noge.



Slika 5: Obdelana Slika 3 za izdelavo geometrije desne noge.



Slika 6: Obdelana Slika 3 za izdelavo geometrije tibie v desni nogi.

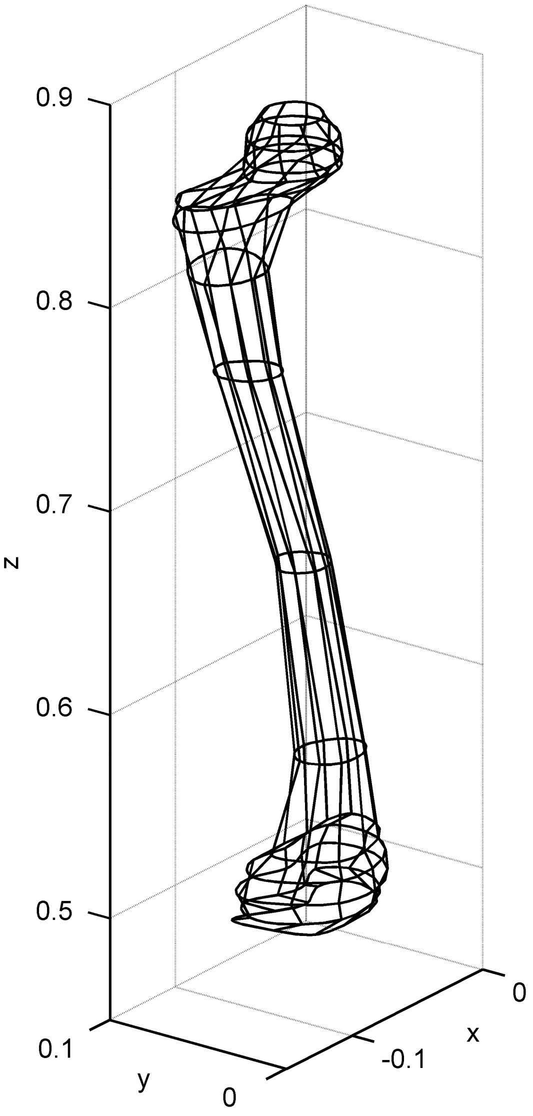


Slika 7: Obdelana Slika 3 za izdelavo geometrije fibule v desni nogi.

4.2 Gradnja geometrije

V COMSOL Multiphysics je za izdelavo geometrije na osnovi slik vgrajena funkcija z imenom *loft*. Ta v okolju MATLAB iz več krivulj zgradi tridimenzionalen objekt tako, da poveže vozlišča krivulj med seboj. Zato morajo krivulje vsebovati enako število vozlišč. Primer geometrije desne stegnenice je prestavljen na Sliki 8, kjer je bilo za izdelavo geometrije stegnenice uporabljenih 15 slik. Na vsaki sliki je bil rob kosti predstavljen s krivuljo z 10 točkami, tako je skupno v geometriji 150 točk. Točke so med seboj povezane z robovi, in sicer je vodoravnih robov 150, saj vsako krivuljo iz 10 točk (ki je sklenjena) povezuje med seboj 10 robov, takšnih krivulj pa je 15. Poleg tega je v geometriji še 140 nevodoravnih robov, ki povezujejo po dve soležni točki iz sosednjih krivulj. Ker je krivulj 15, dobimo tako 140 robov. Skupno tako model stegnenice vsebuje 290 robov. Robovi določajo ploskve, in sicer vsaki dve sosednji krivulji skupaj 10 ploskev, takšnih parov sosednih krivulj je 14, kar da skupno 140 ploskev, potrebno pa je dodati še po eno ploskev za skrajni krivulji (ploskvi objekt zapirata zgoraj in spodaj), skupno torej 142 ploskev.

Za gradnjo posameznih objektov smo v MATLABU napisali program, ki je v tisti mapi, kjer se je nahajal, prebral vse predhodno obdelane slike, v vsaki sliki določil mejo tkiva in zgradil tridimenzionalni objekt. Program je dodan v poglavju 11.1.



Slika 8: Geometrija stegnenice v desni nogi. Za izdelavo geometrije je bilo uporabljenih 15 slik. Na vsaki sliki je bil rob kosti predstavljen s krivuljo z 10 točkami.

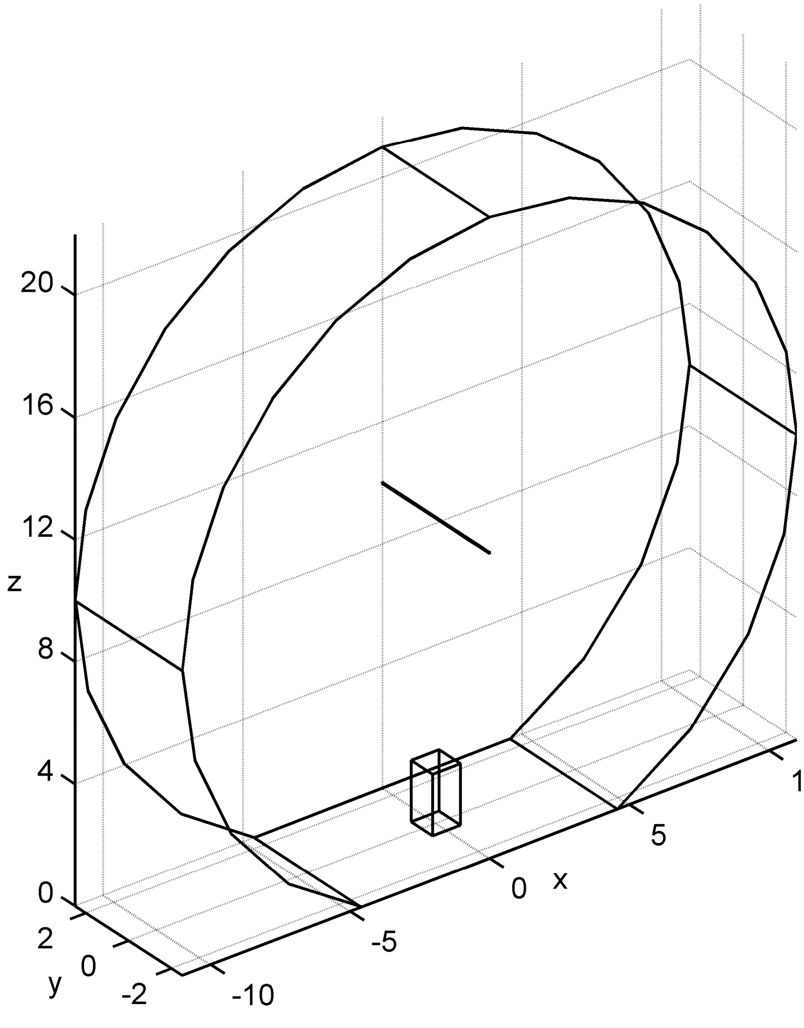
Program prebere eno po eno sliko iz trenutne mape. Glede na njeno ime določi njeno lego po z osi. Ime datoteke namreč v številkah na mestih 4 do 7 vsebuje lego prereza, merjeno od glave proti nogam. Na primer, v datoteki z imenom avf2300.raw (oz. .jpg ali .tif po pretvorbi) je shranjena slika prereza na razdalji 2300 mm merjeno od glave proti nogam. Če to vrednost odštejemo od 2730 mm, dobimo višino slike oziroma lego po *z* osi. Program nato sliko invertira (iz [0 0 0] v [255 255 255] ter obratno) in od slike odšteje neko manjšo vrednost, da odpravi napako zaradi stiskanja slike pri zapisu. Po seštevanju vse barvnih kanalov smo dobili sivinsko sliko, zmanjšali njeno razločljivost z 0.33 mm na 1 mm in z množenjem vsakega polja z ustrezno visoko vrednostjo naredili črno belo sliko z 1 bitno barvno globino. S COMSOL Multiphysics-ovo funkcijo *flim2curv* smo v sliki določili krivuljo meje objekta. Žal je funkcija *flim2curv* definirana tako, da njen vhodni parameter ni število vozlišč, iz katerih bo krivulja sestavljena, ampak nek parameter z vrednostjo med 0 in 1. Pri uporabi iste vrednosti tega parametra na različnih slikah pa ponavadi dobimo različno število vozlišč. Ker je za nadaljnjo gradnjo objekta nujno, da vse krivulje vsebujejo enako število vozlišč, smo v program dodali zanko, ki s pomočjo bisekcije poišče tisto vrednost parametra, da se število vozlišč ujema z želenim številom. Nato je potrebno krivuljo pretvoriti v *solid2* vrsto s pomočjo funkcije *solid2* ter jo skalirati s faktorjem 0.001, da so dolžine izražene v metrih. Ta postopek program ponovili za vse slike v posamezni mapi, nato pa s pomočjo COMSOL Multiphysics-ove funkcije *loft* program izdela tridimenzionalno geometrijo.

Za izdelavo programa za gradnjo tridimenzionalnih objektov iz že obdelanih slik smo se odločili, ker je bilo potrebno postopek gradnje posameznega objekta večkrat ponoviti. Potrebno je bilo namreč poiskati ustrezno število vozlišč v krivuljah, ki so služile za gradnjo objekta, poleg tega pa je bilo potrebno izbrati tiste slike, ki so kar najbolje opisale geometrijo. Za osnovo smo najprej izbrali enakomerno oddaljene slike z razmakom 5 cm. V tako dobljenem objektu smo ocenili, katere slike so odveč, hkrati pa izbrali področje, kjer je potrebno dodati še kakšno sliko. To je vidno tudi v geometriji stegnenice na Sliki 8. Za srednji del kosti, ki je razmeroma raven, je bilo uporabljeno le 4 od skupno 15 slik v razmaku 5 ali 10 cm, čeprav predstavlja večino dolžine prav ta del. Za oba skrajna dela pa smo uporabili precej več slik, še posebno za zgornji del. Ko smo na tak način zgradili vse objekte, ki smo jih želeli vključiti v en model, smo v grafičnem vmesniku COMSOL Multiphysics-a vnesli vse objekte v model, preverili, ali se med seboj ustrezno skladajo ter pričeli z gradnjo mreže. Bolj podrobno bo mreža v vsakem modelu predstavljena kasneje, odločitev za izdelavo programa za gradnjo tridimenzionalnih objektov pa upravičuje tudi dejstvo, da je zaradi nepotrebno majhnih površin in volumnov, ki so nastali, bilo potrebno nekatere objekte večkrat popraviti, da je bila gradnja mreže uspešna.

5 Vpliv intramedularnega žeblja v elektromagnetnem polju nizkih frekvenc

5.1 Geometrija modela

V modelu človeškega telesa z intramedularnim žebljem, izpostavljenega elektromagnetnemu polju nizkih frekvenc, smo želeli ugotoviti, kakšen je vpliv intramedularnega žeblja na porazdelitev gostote toka v človeku, izpostavljenem elektromagnetnemu polju nizkih frekvenc. Za opazovanje vpliva na gostoto toka smo se odločili, saj je v prav gostota toka v telesu tista veličina, ki jo Smernice ICNIRP, Priporočila 1999/519/EC in Direktiva 2004/40/EC omejujejo pri nizkih frekvencah.



Slika 9: Geometrija modela človeškega telesa v elektromagnetnem polju nizkih frekvenc. Na sliki je predstavljena okolica modela, viden pa je tudi manjši kvader, ki smo ga izrezali iz modela zaradi uporabe nelokalnega sklapljanja. Daljica v sredini valja predstavlja vodnik daljnovoda.

Geometrija modela je sestavljena iz valja s premerom 11 m in višino 5 m, postavljenega v prostor tako, da je njegova os vodoravna in v višini 10 m. Višina 0 m je višina tal. Valj je pod višino 0 m odrezan in predstavlja naše območje računanja. V osi valja je vodnik s polmerom 2 cm, ki predstavlja vodnik na daljnovodu in služi kot vir elektromagnetnega polja. Zaradi velikega geometrijskega razmerja v modelu je bilo potrebno uporabiti nelokalno sklapljanje, zato smo iz valja izrezali kvader višine 2 m ter širine in dolžine 1 m v katerem se nahaja človek. Geometrija je predstavljena na Sliki 9. Izrezan kvader tvori drugo geometrijo, v katero je vstavljen model človeka, ki temelji na slikah VHDS. V model so vključeni tridimenzionalni objekti, ki so predstavljeni v Tabeli 4, geometrija pa je prikazana na Sliki 10. Ob tem je pomembno poudariti, da se noge modela človeškega telesa ne dotikajo tal, kar je razvidno tudi iz Slike 10. Zato je model človeškega telesa električno izoliran od tal.

Tabela 4: Objekti, ki sestavljajo geometrijo človeškega telesa

ime	opis	število vozlišč	število slik	število robov	število ploskev
rfemur	desna stegnenica	10	15	290	142
rfibula	desna mečnica	6	7	78	38
rpatella	desna pogačica	6	4	42	20
rtibia	desna golenica	10	10	190	92
larm	leva roka	6	6	66	32
rarm	desna roka	6	6	66	32
head	glava	10	6	110	52
lleg	leva noga	10	11	210	102
rleg	desna noga	10	11	210	102
torzolow	spodnji del torza	11	6	121	57
torzoup	zgornji del torza	20	6	220	102
implant	kovinski intramedularni žebelj v desni stegnenici	na podlagi slik določena le njegova lega			

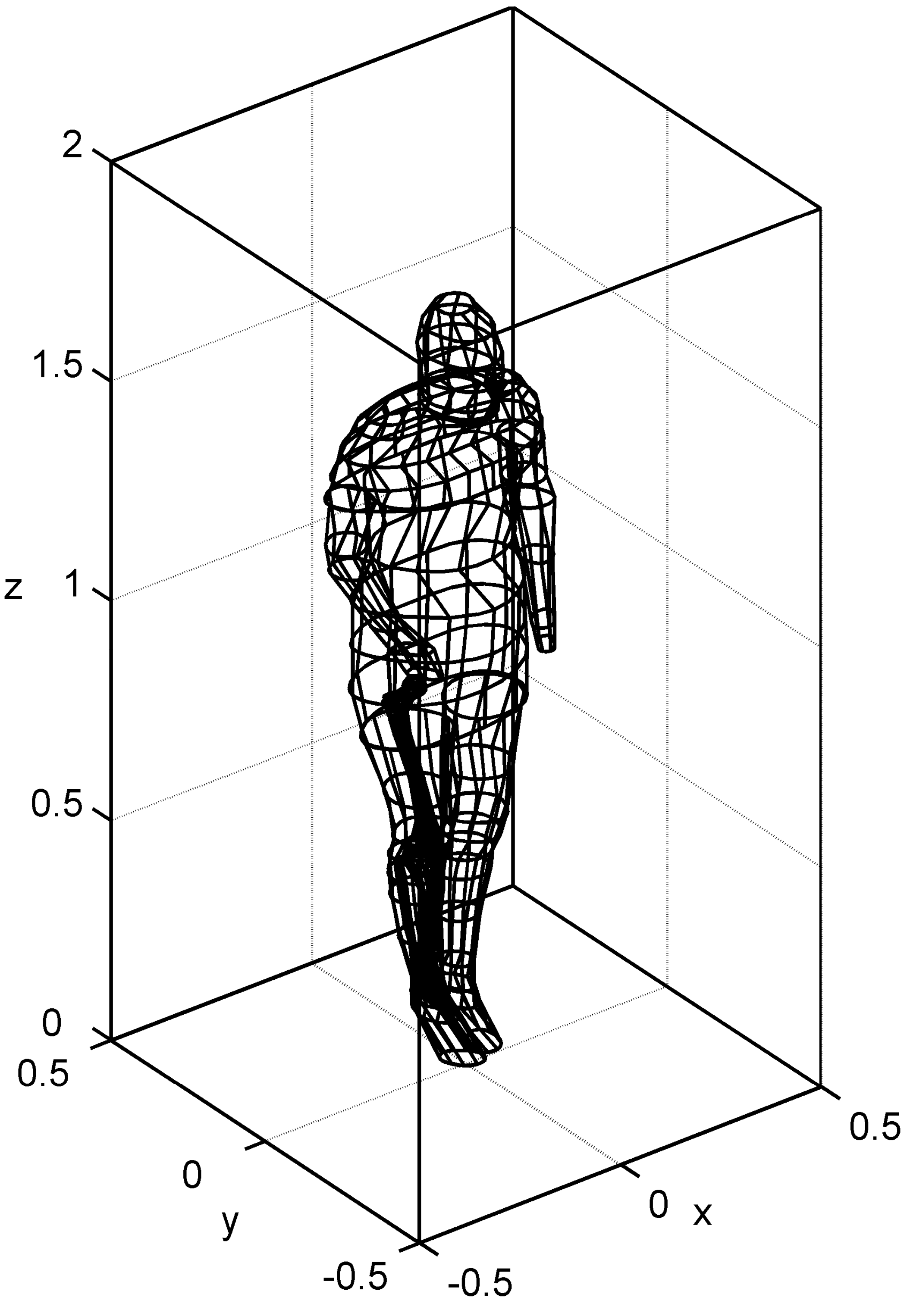
Glede na število vozlišč v vsaki krivulji ter glede na število teh krivulj (in slik) smo izračunali, koliko robov in koliko ploskev sestavlja geometrijo človeškega telesa. Velja:

$$\check{s}t.\, robov = \check{s}t.\, to\check{c}k\ v\ krivulji \times (2 \times \check{s}t.\, slik - 1)\,, \tag{5.1}$$

$$\check{s}t.\ ploskev = \check{s}t.\, to\check{c}k\ v\ krivulji \times (\check{s}t.\, slik - 1) + 2\,, \tag{5.2}$$

Skupaj sestavlja model človeškega telesa 1603 robovi ter 771 ploskev.

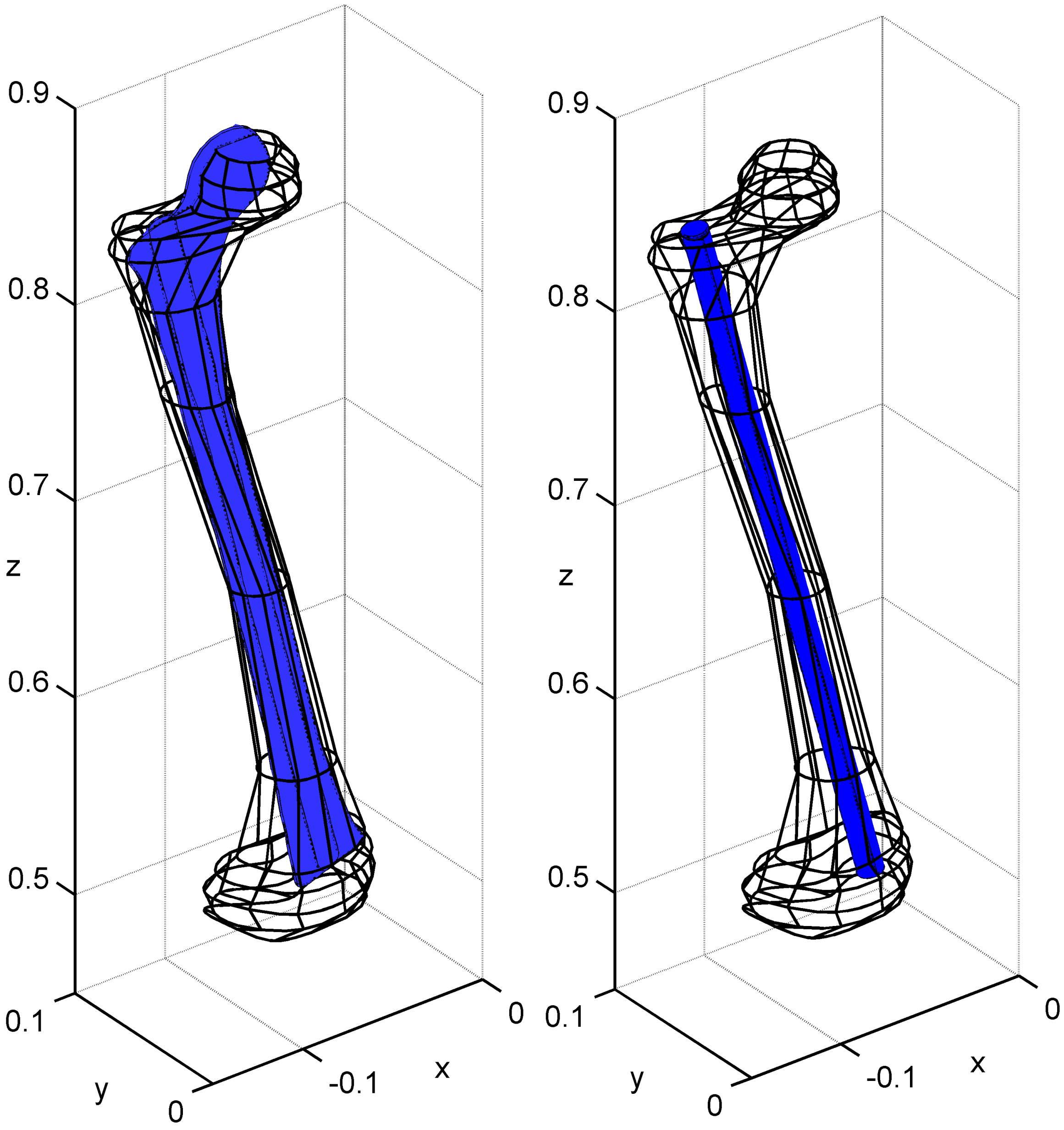
Vsi objekti so bili zgrajeni na podlagi slik iz baze VHDS, izjema je implant, ki ga seveda v slikah VHDS ni. Zato smo za izdelavo geometrije implanta uporabili rentgenske slike, posnete med običajnim postopkom zdravljenja bolnice, ki so ji po zlomu stegnenice le to fiksirali z uporabo intramedularnega žeblja. Poseg so izvedli v Kliničnem centru v Ljubljani, na Kirurški kliniki, Kliničnem oddelku za travmatologijo, od koder slike tudi izvirajo.



Slika 10: Geometrija modela človeškega telesa v elektromagnetnem polju nizkih frekvenc. Na sliki je predstavljena geometrija samega človeškega telesa.

Za določitev geometrije intramedularnega žeblja smo uporabili Sliko 11 levo, le da smo ji na spodnjem delu dodali še del iz Slike 11 desno. Kakor pri obdelavi VHDS slik smo tudi v tem primeru določili robove kosti in intramedularnega žeblja, robova nadomestili s krivuljama ter ti dve krivulji pretvorili v dvodimenzionalni COMSOL Multiphysics-ov objekt. Nato smo stegnenico, določeno na podlagi slik VHDS, ki je tridimenzionalni objekt, in stegnenico ter intramedularni žebelj, določena na podlagi rentgenskih slik, ki sta dvodimenzionalni objekt, vstavili v isto geometrijo ter poiskali ustrezno preslikavo, ki je dvodimenzionalna objekta postavila v enako pozicijo in orientacijo kot tridimenzionalni objekt. Razmere so prikazane na Sliki 12.

Slika 11: Rentgenska slika bolnice s stegnenico, fiksirano z intramedularnim žebljem. Predstavljen je pogled v dveh smereh.

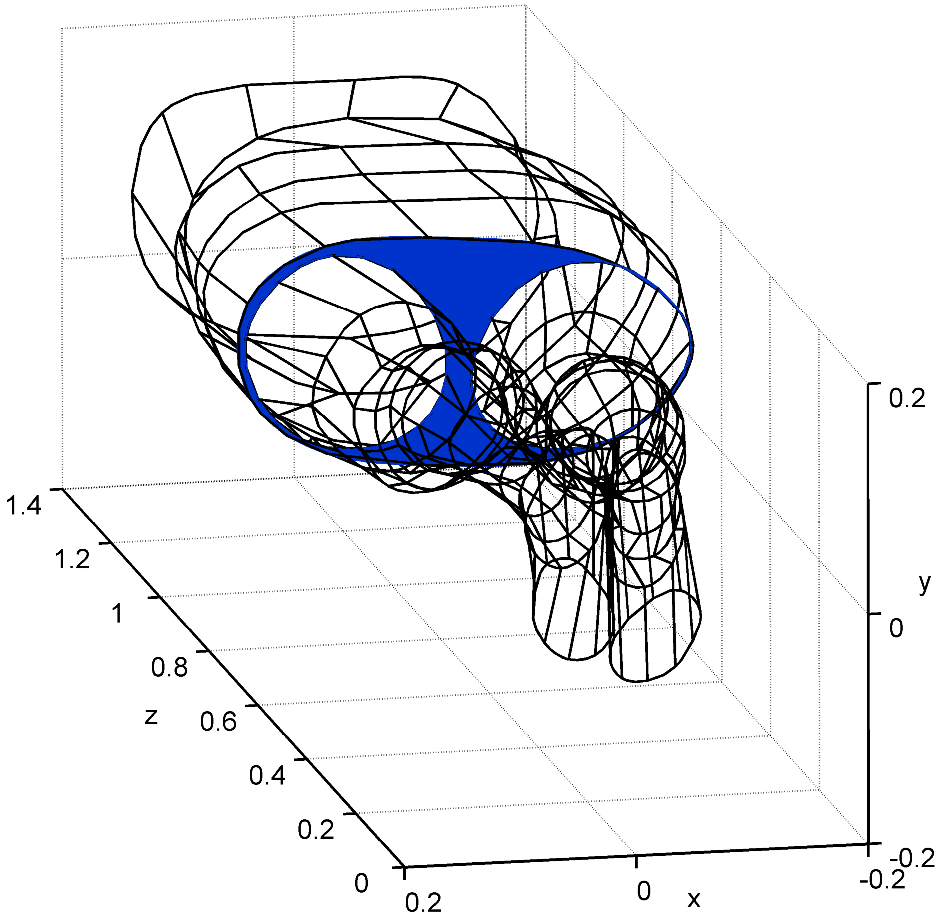


Slika 12: Na levi strani je predstavljena pridobljene s pomočjo VHDS slik (črno) ter geometrija stegnenice in intramedularnega žeblja, pridobljena s pomočjo rentgenskih slik (modro) po ustrezni preslikavi, tako da se sliki ujemata. Na desni je predstavljena geometrija stegnenice, pridobljene s pomočjo VHDS slik (črno) ter intramedularnega žeblja (modro), ki ga predstavlja ustrezno orientiran tridimenzionalni valj.

Če smo dvodimenzionalna objekta položili na ravnino z = 0 sta dvodimenzionalna objekta sovpadla s tridimenzionalnim po naslednjih preslikavah: zasuk okrog osi x za -92°; zasuk okrog osi y za -8°; premik za vektor (-0.215, 0.035, 0.895). V zadnjem koraku smo dvodimenzionalni žebelj nadomestili z valjem dolžine 0.365 m in polmera 0.006 m z izhodiščno točko (-0.068, 0.02, 0.52) ter z orientacijo (sferične koordinate) $\theta = 14^{\circ}$ in $\varphi = 170^{\circ}$. Tako orientiran valj sovpada z dvodimenzionalnim intramedularnim žebljem, kakor je pokazano na Sliki12.

5.2 Mreža

O zahtevnosti gradnje mreže v modelih z nepravilnimi geometrijskimi oblikami in velikim geometrijskim razmerjem je bilo več napisano že v 2. poglavju, kjer je predstavljeno nelokalno sklapljanje. Med gradnjo mreže smo morali nekajkrat v nekaterih podrobnostih spremeniti geometrijo posameznih objektov, da smo uspeli zgraditi mrežo. Težave so prestavljale površine, kjer sta se stikala dva ali več objektov, kot denimo na mestu stika obeh nog in spodnjega dela torza. Ker so na mestu spoja nastale dolge zelo ozke ploskve, na teh ploskvah algoritem ni uspel zgraditi mreže, še posebej v tistih primerih, ko sta se krivulji sekali. Če je bila denimo na enem delu noga tanjša od torza, na drugem pa obratno, je nastalo presečišče pod zelo majhnim kotom. Zato je bilo potrebno prilagoditi geometrijo nog tako, da je bila stična (najvišja) ploskev nog manjša od stične (najnižje) ploskve spodnjega dela torza.



Slika 13: Slika obeh nog ter spodnjega dela trupa. Na stičišču teh objektov je na levi in desni strani vidna ploskev, ki je dolga in ozka, saj sega okrog cele noge.

Ker smo uporabili direkten algoritem za reševanje modela, je bilo potrebno zgraditi mrežo z največ 60.000 prostostnimi stopnjami. V veliki geometriji smo uporabili parametre za normalno gosto mrežo (/ 1 1.5 0.6 0.03 0.5), ki ima 16827 elementov, v majhni pa mrežo s parametri za redko mrežo (/ 2.3 2.8 0.6 0.039 0.5), ki ima 32.790 elementov.

5.3 Lastnosti snovi

V modelu smo predstavili vsa mehka tkiva kot eno tkivo z električnimi lastnostmi mišice, tako da so bile v model vključene le snovi, predstavljene v Tabeli 5.

Tabela 5: Lastnosti snovi, vključenih v model človeka izpostavljenega elektromagnetnemu polju nizkih frekvenc (50 Hz)

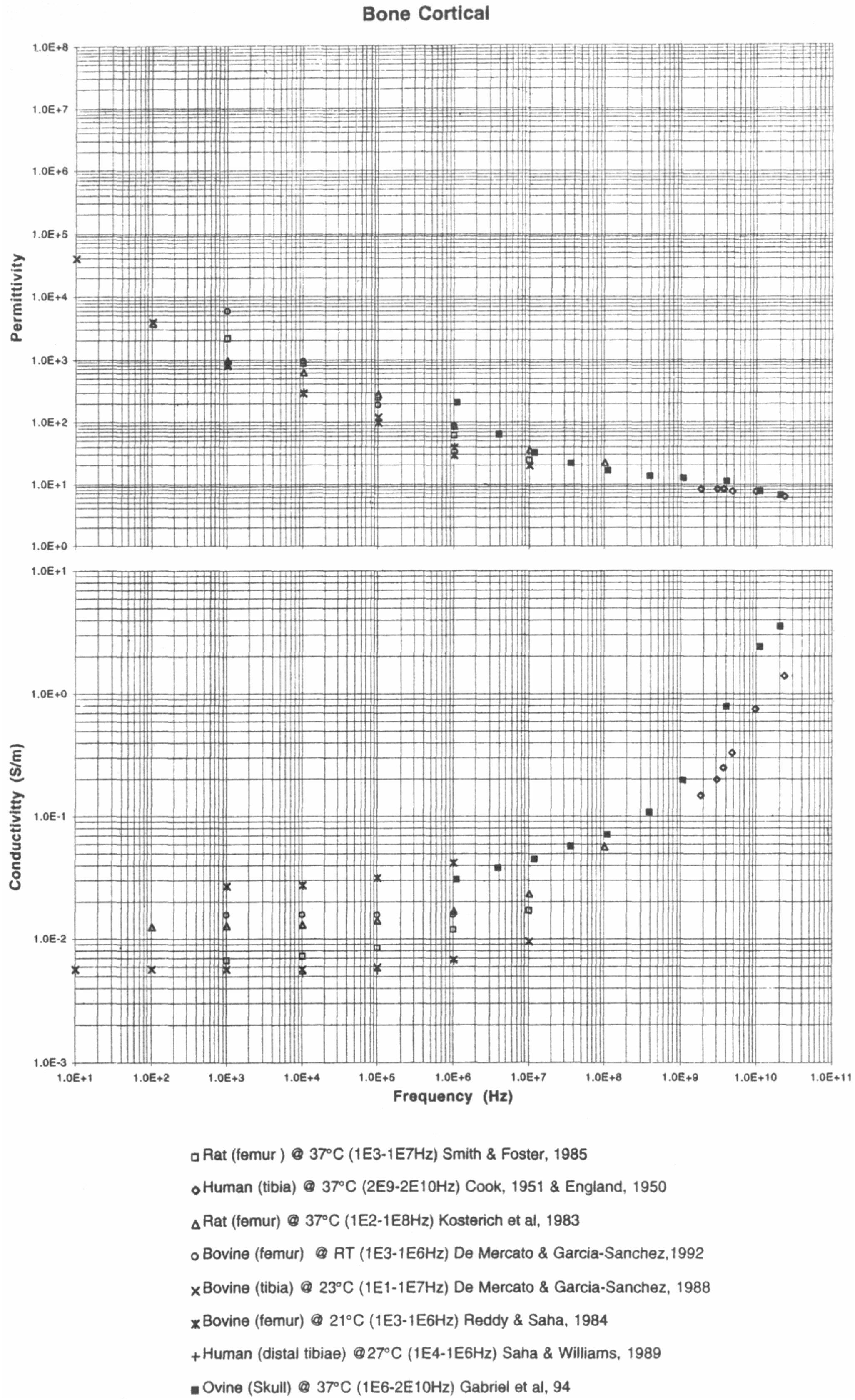
Material	σ (Sm^{-1})	ε_r	μ_r	vir
mehko tkivo	0.2 - 0.4	10^6 - 10^7	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
kost	0.005 -0.009	10^3 - 10^4	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996
zrak	0	1	1	COMSOL Multiphysics, vakuum
intramedularni žebelj	4.032×10^6	1	1	COMSOL Multiphysics, jeklo

Za potrebe modela smo dielektrične lastnosti bioloških tkiv povzeli po literaturi. Ker pa so podatki v literaturi, kakor je razvidno iz Slike 14, razpršeni, ter je frekvenčno območje 50 Hz na meji meritev, smo namesto točnih vrednosti določili območje vrednosti. S parametrizacijo izračuna glede na vrednost prevodnosti in dielektričnosti [Gajšek, 2001] smo izračune opravili za kombinacije različnih vrednosti električne prevodnosti in dielektričnosti, predstavljenih v Tabeli 6.

Tabela 6: vrednosti dielektričnih lastnosti snovi, pri katerih so bili opravljeni izračuni.

mehko tkivo		kost	
σ (Sm^{-1})	ε_r	σ (Sm^{-1})	ε_r
0.2	10^6	0.005	10^3
0.2	10^6	0.005	10^4
0.2	10^6	0.009	10^3
0.2	10^6	0.009	10^4
0.2	10^7	0.005	10^3
0.2	10^7	0.005	10^4
0.2	10^7	0.009	10^3
0.2	10^7	0.009	10^4
0.4	10^6	0.005	10^3
0.4	10^6	0.005	10^4
0.4	10^6	0.009	10^3
0.4	10^6	0.009	10^4
0.4	10^7	0.005	10^3
0.4	10^7	0.005	10^4
0.4	10^7	0.009	10^3
0.4	10^7	0.009	10^4

Skupaj smo izračunali 16 modelov z implantom ter 16 modelov brez implanta. Da bi namreč lahko ocenili vpliv implanta, smo v enakem modelu z isto geometrijo ter mrežo dielektrične lastnosti implanta nadomestili z lastnostmi tistega tkiva, ki bi bilo na mestu implanta (večinoma kosti, le majhen del na vrhu mehko tkivo).



Slika 14: Primer grafov dielektričnih lastnosti kosti v odvisnosti od frekvence [Gabriel *et al,*. 1996a].

5.4 Fizikalna narava modela in robni pogoji

Za izračun elektromagnetnega polja nizkih frekvenc je mogoče uporabiti kvazistatično elektromagnetno polje, kjer sta neznani veličini električni potencial V in vektorski magnetni potencial $\vec{A}$. Uporaba kvazistatičnega polja je upravičena, če je velikost modela nekajkrat manjša od valovne dolžine, kar je v primeru 50 Hz vsekakor izpolnjeno. Izhodišče za zapis kvazistatičnih enačb so Maxwellove enačbe. Amperov zakon

$$\nabla\times\vec{H}-\frac{\partial\vec{D}}{\partial t}=\vec{J}_{prosti}, \tag{5.3}$$

bomo preoblikovali. Če upoštevamo, da je $\vec{B}=\mu_r\mu_0\vec{H}$ ter $\vec{D}=\varepsilon_r\varepsilon_0\vec{E}$, se enačba (5.3) glasi

$$\nabla\times\left(\mu_r^{-1}\mu_0^{-1}\vec{B}\right)-\frac{\partial\varepsilon_r\varepsilon_0\vec{E}}{\partial t}=\vec{J}_{prosti}, \tag{5.4}$$

Za gostoto toka prostih nabojev velja, da je

$$\vec{J}_{prosti}=\vec{J}_{kond}+\vec{J}_{konv}. \tag{5.5}$$

Če je gostota konvektivnega toka $\vec{J}_{konv}$ enaka nič, lahko gostoto toka prostih nabojev $\vec{J}_{prosti}$ poenostavljeno [Sinigoj, 1996] zapišemo:

$$\vec{J}_{prosti}=\sigma\vec{E}+\vec{J}_g, \tag{5.6}$$

kjer smo z $\vec{J}_g$ označili gostoto toka zaradi virov. Enačbo (5.4) lahko zapišemo kot

$$\nabla\times\left(\mu_r^{-1}\mu_0^{-1}\vec{B}\right)-\varepsilon_r\varepsilon_0\frac{\partial\vec{E}}{\partial t}-\sigma\vec{E}=\vec{J}_g, \tag{5.7}$$

Za magnetni vektorski potencial velja:

$$\vec{B}=\nabla\times\vec{A}. \tag{5.8}$$

Če to vstavimo Faradayev zakon indukcije

$$\nabla\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0 \tag{5.9}$$

dobimo:

$$\nabla\times\left(\vec{E}+\frac{\partial\vec{A}}{\partial t}\right)=0\,. \tag{5.10}$$

Polje $\vec{E}+\frac{\partial\vec{A}}{\partial t}$ je gradientno, kajti le gradientno polje je takšno, da je njegov rotor enak nič.

$$-\nabla V=\vec{E}+\frac{\partial\vec{A}}{\partial t}=0\,, \tag{5.11}$$

ali drugače zapisano

$$\vec{E}=-\nabla V-\frac{\partial\vec{A}}{\partial t}\,, \tag{5.12}$$

Če enačbo (5.12) vstavimo v enačbi (5.7) in (5.8), dobimo

$$\nabla\times\left(\mu_r^{-1}\mu_0^{-1}\left(\nabla\times\vec{A}\right)\right)+\varepsilon_r\varepsilon_0\frac{\partial}{\partial t}\left(\nabla V+\frac{\partial\vec{A}}{\partial t}\right)+\sigma\left(\nabla V+\frac{\partial\vec{A}}{\partial t}\right)=\vec{J}_g\,, \tag{5.13}$$

in po ureditvi

$$\nabla\times\left(\mu_r^{-1}\mu_0^{-1}\left(\nabla\times\vec{A}\right)\right)+\left(\sigma\nabla V+\varepsilon_r\varepsilon_0\frac{\partial}{\partial t}\nabla V\right)+\left(\varepsilon_r\varepsilon_0\frac{\partial}{\partial t}\frac{\partial\vec{A}}{\partial t}+\sigma\frac{\partial\vec{A}}{\partial t}\right)=\vec{J}_g\,. \tag{5.13}$$

Enčaba (5.13) je ena izmed enačb, ki jo uporablja COMSOL Multiphysics pri računanju kvazistatičnega elektromagnetnega polja. Druga enačba, ki jo upoablja, izhaja iz kontinuitetnega enačbe za proste naboje:

$$\nabla\times\vec{J}_{prosti}+\frac{\partial\rho_{prosti}}{\partial t}=0\,, \tag{5.14}$$

kjer z ρ_{prosti} označujemo prostorsko gostoto električnih nabojev. Če v enačbo (5.14) vstavimo enačbi (5.5) ter (5.6) ter upoštevamo Gaussov stavek za električno polje

$$\nabla \cdot \vec{D} = \rho_{prosti}, \tag{5.15}$$

enačbo (5.14) zapišemo kot

$$\nabla \times \left(\sigma \vec{E} + \vec{J}_g \right) + \frac{\partial \nabla \cdot \vec{D}}{\partial t} = 0. \tag{5.16}$$

Ker je $\vec{D} = \varepsilon_r \varepsilon_0 \vec{E}$, enačbo (5.16) pretvorimo v:

$$\nabla \times \left(\sigma \vec{E} + \varepsilon_r \varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{J}_g \right) = 0. \tag{5.17}$$

Vstavimo še enačbo (5.12) ter zapis poenostavimo:

$$-\nabla \times \left(\left(\sigma \nabla V + \varepsilon_r \varepsilon_0 \frac{\partial}{\partial t} \nabla V \right) + \left(\sigma \frac{\partial \vec{A}}{\partial t} + \varepsilon_r \varepsilon_0 \frac{\partial}{\partial t} \frac{\partial \vec{A}}{\partial t} \right) - \vec{J}_g \right) = 0. \tag{5.18}$$

Enačba (5.18) je druga enačba, ki jo uporablja COMSOL Multiphysics pri računanju kvazistatičnega elektromagnetnega polja, tretja enačba pa je [Comsol AB., 2005]

$$\nabla \cdot \vec{A} = 0, \tag{5.19}$$

ki tudi zagovavlja izpolnjevanja Gausovega stavek za magnetno polje $\nabla \cdot \vec{B} = 0$.

Za harmonično elektromagnetno polje velja, da je $V(x, y, z, t) = \mathrm{Re}(\underline{V} \cdot e^{j\omega t})$ ter $\vec{A}(x, y, z, t) = \mathrm{Re}(\underline{\vec{A}} \cdot e^{j\omega t})$. Z upoštevanjem tega se enačbe (5.13), (5.18) in (5.19) glasijo:

$$\nabla \times \left(\mu_r^{-1} \mu_0^{-1} \nabla \times \underline{\vec{A}} \right) + \left(j\omega\sigma - \varepsilon_r \varepsilon_0 \omega^2 \right) \underline{\vec{A}} + \left(\sigma + j\omega\varepsilon_r\varepsilon_0 \right) \nabla \underline{V} = \underline{\vec{J}}_g, \tag{5.20}$$

$$-\nabla \times \left(\left(j\omega\sigma - \varepsilon_r \varepsilon_0 \omega^2 \right) \underline{\vec{A}} + \left(\sigma + j\omega\varepsilon_r\varepsilon_0 \right) \nabla \underline{V} - \underline{\vec{J}}_g \right) = 0 \tag{5.21}$$

$$\nabla \cdot \underline{\vec{A}} = 0. \tag{5.22}$$

V modelu smo želeli izračunati porazdelitev elektromagnetnega polja nizkih frekvenc v človeku. Kot vir elektromagnetnega polja smo uporabili preprost daljnovod z enim samim vodnikom, zaradi česar smo naredili napako, saj:

- je napetost med posameznim vodnikom in tlemi res enaka v primeru enega vodnika ali običajnega trofaznega sistema, vendar je razporeditev električne poljske jakosti drugačna, ker ima napetost v posameznih vodnikih fazni zamik ene tretjine periode. Ko doseže napetost v eni fazi maksimum, je v drugih dveh fazah napetost negativna in ima amplitudo polovico maksimalne vrednosti. Ker je električno polje vsota prispevkov polj vseh treh vodnikov, je rezultirajoče električno polje trofaznega sistema manjše kot pri enofaznem, v daljavi pa celo enako 0, saj je vsota vseh treh napetosti vedno enaka 0;
- se magnetno polje prav tako sešteva, zaradi faznega zamika je pri približno simetričnem vodniku tudi magnetno polje manjše;

vendar v modelu ni bil cilj računati elektromagnetnega polja daljnovoda, ampak z dovolj enostavnim virom elektromagnetnega polja doseči v območju, kjer se lahko nahaja človek takšno polje, da bodo ravno še izpolnjene izvedene mejne vrednosti Uredbe za II. območje. Zato smo za izhodišče vzeli 110 kV daljnovod z enim samim vodnikom, po katerem teče tok vrednosti 300 A efektivno. Izhodiščni tok smo določili glede na podate o maksimalnih obremenitvah 110 kV daljnovodov [ELES, 2003], ki znašajo do 100 MW (za trofazni sistem). Vrednost napetosti je ustrezna, saj električna poljska jakost v območju, kjer se lahko nahaja človek, ne preseže vrednosti 7000 Vm^{-1}, kar je malo manj od izvedene mejne vrednosti Uredbe za električno poljsko jakost, ki znaša 10000 Vm^{-1}. Vrednost toka je bila premajhna, saj je bila gostota magnetnega pretoka v območju, kjer se lahko nahaja človek, manjša od 10 µT, medtem ko je mejna vrednost Uredbe za II. območje za gostoto magnetnega pretoka 100 µT. Tok smo zato povečali za 10 krat na vrednost 3000 A in dobili gostoto magnetnega pretoka približno 60 µT. S tem smo določili takšne robne pogoje, da je bil model človeka izpostavljen elektromagnetnemu sevanju z vrednostmi, podobnimi mejnim vrednostim Uredbe za II. območje.

V COMSOL Multiphysics-u je potrebno v primeru kvazistaičnega elektromagnetnega polja določiti električne in magnetne robne pogoje. Kot vir elektromagnetnega polja smo za električne robne pogoje na robovih, kjer bi se nahajal vodnik (glej Sliko 9), nastavili potencial 110 kV. Na zunanjih robovih modela v veliki geometriji smo določili robne pogoje, ki kar najbolje predstavljajo neskončen prostor. Za električno polje smo določili električno izolirane robne pogoje, ki določajo, da je normalna komponenta toka na tej meji enaka 0:

$$J_n = 0\,. \tag{5.23}$$

Pri tem bi lahko nastala napaka zaradi polarizacijskega toka v dielektriku, vendar velja, da je polarizacijski tok enak

$$\vec{J}_{pol} = \frac{\partial \vec{P}}{\partial t}, \tag{5.24}$$

ker pa je

$$\vec{P} = (\varepsilon_r - 1)\varepsilon_0 \vec{E} \tag{5.25}$$

velja, da je $\vec{P}$ v zraku enaki 0, zato je tudi polarizacijski tok enak 0. Različen robni pogoj je bil le na ploskvi v ravnini $z = 0$, kjer je določen potencial 0 V, ker ta ploskev predstavlja površino tal.

Za magnetno polje smo na zunanjih robovih določili magnetno izolirane robne pogoje, ki določajo, da sta tangencialni komponenti vektorskega magnetnega potenciala enaki 0:

$$n \times \vec{A} = 0\,. \tag{5.26}$$

Zaradi tega nastane napaka. Magnetni vektorski potencial premega vodnika upada z logaritmom oddaljenosti:

$$\vec{A} = -\frac{\mu_0 \vec{I}}{2\pi} \ln R\,. \tag{5.27}$$

Za gostoto magnetnega pretoka velja:

$$B_\varphi = \frac{\mu_0 I}{2\pi R}\,. \tag{5.28}$$

V razdalji 10 m od vodnika je vrednost $B\varphi$ po enačbi (5.28) enaka 60 µT, v modelu s takšnim robnim pogojem pa je približno 50 µT. Sicer je napaka relativno velika, približno 15 %, a na sam izračun porazdelitve elektromagnetnega polja ne vpliva. Za določitev magnetnega polja, ki je posledica toka po vodniku, smo iz premega toka izračunali komponente magnetne poljske jakosti. Ker je tok vzporeden z osjo y, velja:

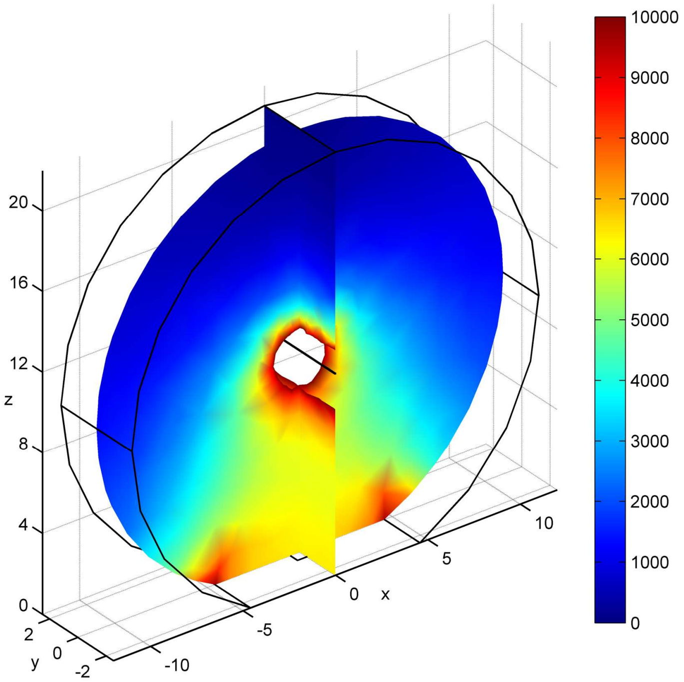
$$H_\varphi = \frac{I}{2\pi R}, \tag{5.29}$$

kjer je $H\varphi$ tangencialna komponenta magnetne poljske jakosti, R pa je polmer valja, v našem primeru 2 cm. Če to zapišemo v kartezičnih koordinatah, velja:

$$H_x = \frac{I}{2\pi R}\frac{z-10}{R}, \tag{5.30}$$

ker je vodnik dvignjen 10 m nad koordinatno izhodišče, in

$$H_z = -\frac{I}{2\pi R}\cos\ \varphi\ =\ -\frac{I}{2\pi R}\frac{x}{R}. \tag{5.31}$$



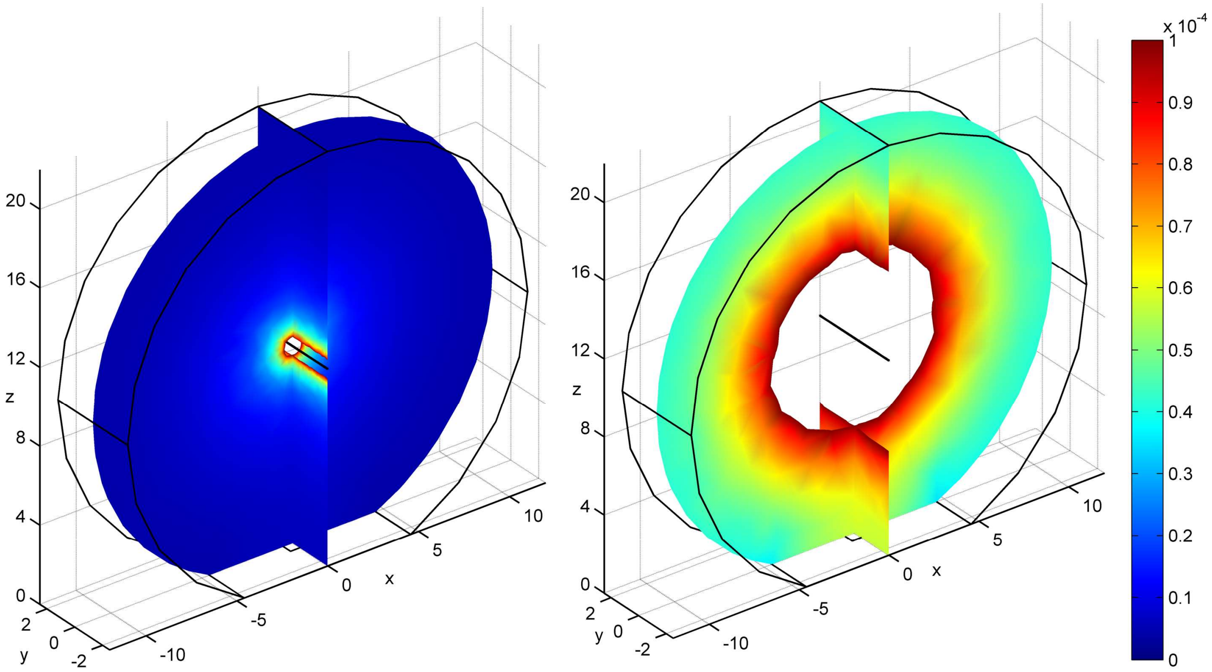
Slika 15: Porazdelitev elektromagnetnega polja v okolici vodnika. Predstavljena je električna poljska jakost v ravnini *xz* pri $y = 0$ ter ravnini *yz* pri $x = 0$. Barvna skala zavzema vrednosti od 0 do 10000 Vm^{-1}, kar je pri 50 Hz izvedena mejna vrednost za električno poljsko jakost po Smernicah ICNIRP za zaposlene ter za II območje po Uredbi. Na območju prereza, ki je v bližini vodnika in je prozorno, je presežena izvedena mejna vrednost.

Takšni robnimi pogoji so bili uporabljeni na Slikah 15 in 16. Vendar v celotnem modelu ni potrebno računati kvazistatičnega elektromagnetnega polja. Namreč, relativna permeabilnost vseh snovi v modelu je enaka, zato je porazdelitev magnetnega polja odvisna le od geometrije modela in ne od lastnosti snovi. Če lahko analitično določimo robne pogoje za magnetno polje v mali geometriji, bi lahko v veliki geometriji računali le eletrostatično polje, kar pa zahteva štirikrat manj prostostnih stopenj kot kvazistatično elektromagnetno polje (računa se le električni potencial V), saj je potrebno rešiti le enačbo:

$$-\nabla\left(\left(\sigma + j\omega\varepsilon_r\varepsilon_0\right)\nabla \underline{V} - \underline{\vec{J}}_g\right) = 0 . \tag{5.32}$$

Iz enačbe (5.29) lahko določimo, kakšno je magnetno polje pod vodnikom. Najenostavneje je določiti komponento polja v osi *y*, ki je povsod enako nič, saj je to smer, vzporedna s smerjo toka *I*. Točno pod vodnikom je magnetno polje v smeri *x* enako:

$$H_x = -\frac{I}{2\pi(10-z)} . \tag{5.33}$$



Slika 16: Porazdelitev elektromagnetnega polja v okolici vodnika. Predstavljena je gostota magnetnega pretoka v ravnini *xz* pri *y* = 0 ter ravnini *yz* pri *x* = 0 pri obremenitvi 300 A (levo) in 3000 A (desno). Barvna skala zavzema vrednosti od 0 do 100 µT, kar je pri 50 Hz izvedena mejna vrednost za gostoto magnetnega pretoka po Smernicah ICNIRP za prebivalstvo ter za II območje po Uredbi. Na območju prereza, ki je v bližini vodnika in je prozoren, je presežena izvedena mejna vrednost.

Izven lege pod vodnikom se prične *x* komponenta magnetnega polja manjšati, in sicer se manjša s kosinusom kota med trenutno točko, vodnikom in točko točno pod vodnikom. Kosinus tega kota je na področju celotne male geometrije večji od:

$$\cos\varphi_{\min} = \frac{8}{\sqrt{8^2 + 0.5^2}} = 0.9981 , \tag{5.34}$$

kar pomeni, da se *x* komponenta magnetnega polja tako malo spreminja z oddaljevanjem od točke pod vodnikom, da lahko to zanemarimo in za celotno malo geometrijo upoštevamo enačbo (5.30).

Za *z* komponento magnetnega polja zaradi enačbe (5.29) velja, da je točno pod vodnikom enaka 0 ter prične naraščati s sinusom kota med trenutno točko, vodnikom in točko točno pod vodnikom. Sinus tega kota je na področju celotne male geometrije manjši od

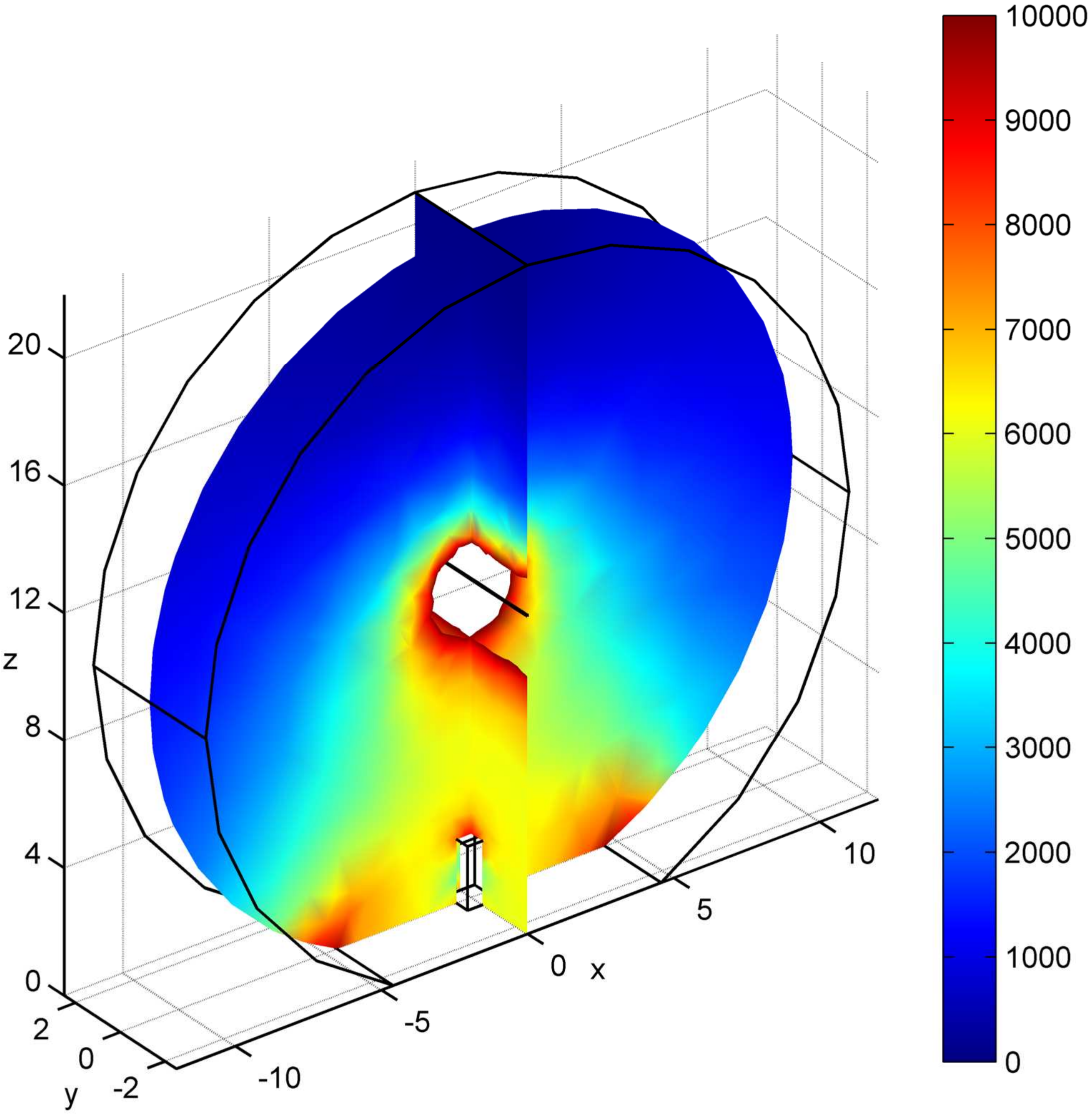
$$\sin\varphi_{\max} = \frac{0.5}{8} = 0.0625\,, \tag{5.35}$$

zaradi česar lahko brez večje napake za celotno malo geometrijo predpostavimo, da je *z* komponenta magnetnega polja enaka 0. Zato smo na vseh robovih male geometrije določili robne pogoje za magnetno polje tako, da smo za *x* komponento določili vrednost po enačbi (5.30), za komponenti *y* in *z* pa določili vrednost 0. S takšnim načinom določitve robnega pogoja za magnetno polje smo obenem odpravili napako zaradi robnega pogoja po enačbi (5.26).

Ob uporabi elektrostatičnega polja v veliki geometriji ter kvazistatičnega elektromagnetnega polja v mali geometriji ima model 53555 prostostnih stopenj.

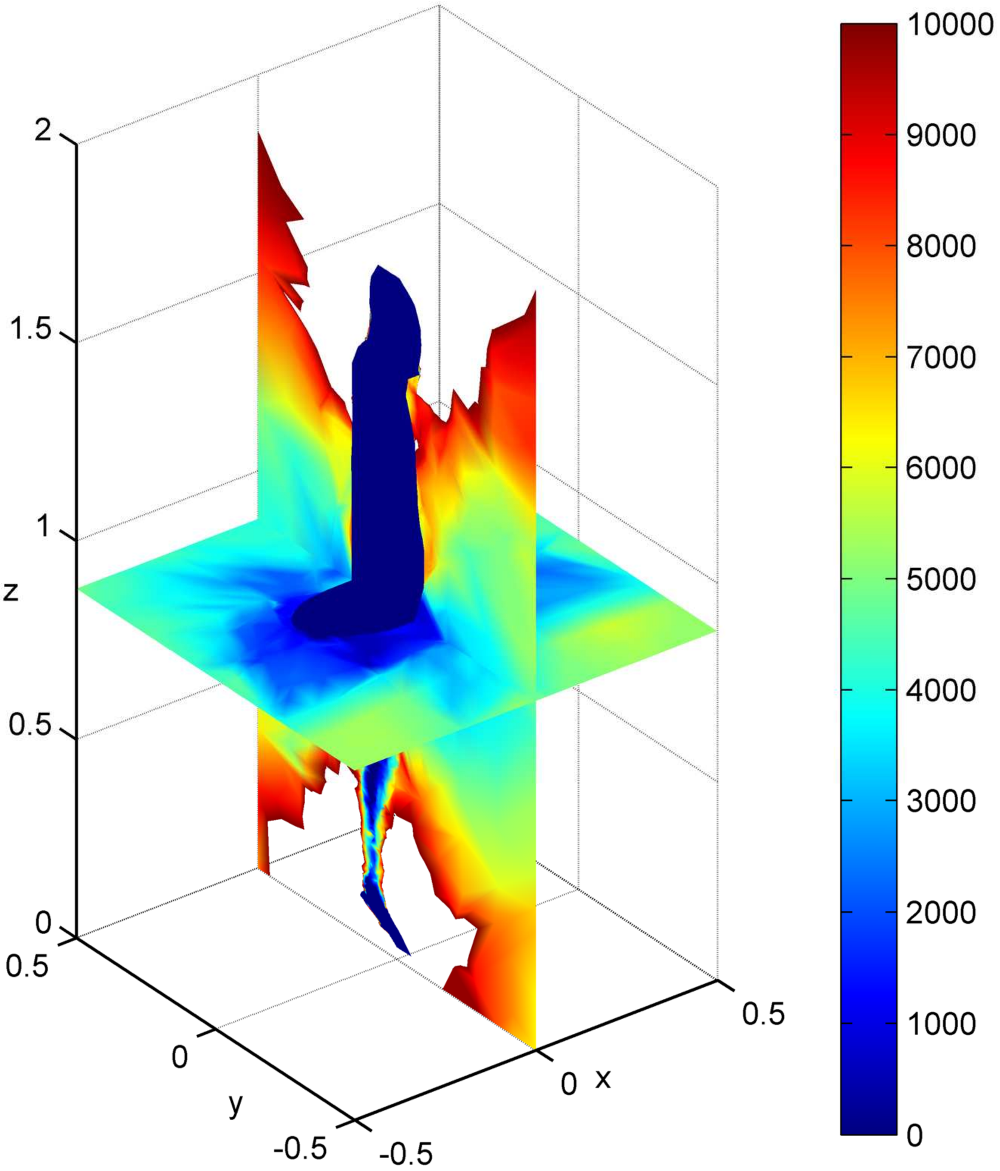
5.5 Rezultati in razprava

V modelu človeškega telesa, izpostavljenega elektromagnetnemu polju nizkih frekvenc smo izračunali porazdelitev elektromagnetnega polja. Vir elektromagnetnega polja v modelu je bil izbran tako, da so bile v območju, kjer se lahko nahaja človek, dosežene maksimalne izvedene mejne vrednosti po Uredbi. Kot vir elektromagnetnega polja smo uporabili en vodnih 110 kV visokonapetostnega daljnovoda, po katerem teče tok z efektivno vrednostjo 3000 A. Vodnik daljnovoda je 10 m nad tlemi. Porazdelitev električnega polja v okolici vodnika je prikazana na Sliki 17.



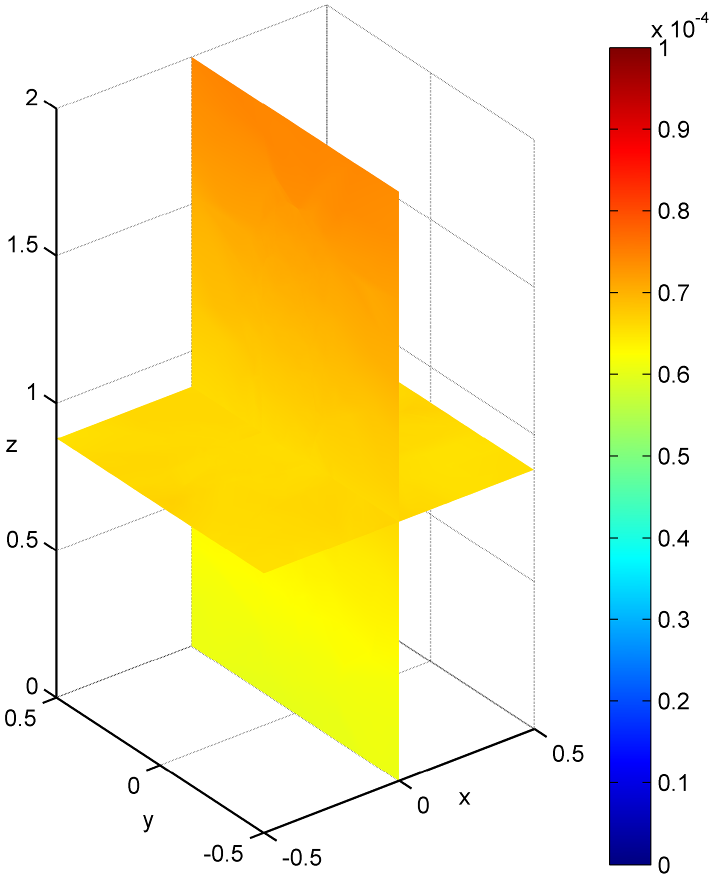
Slika 17: Porazdelitev električnega polja v okolici vodnika. Predstavljena je električna poljska jakost v ravnini *xz* pri $y = 0$ ter ravnini *yz* pri $x = 0$. Barvna skala zavzema vrednosti od 0 do 10000 Vm^{-1}. 10000 Vm^{-1} je namreč pri 50 Hz izvedena mejna vrednost za električno poljsko jakost po Smernicah ICNIRP za zaposlene ter za II območje po Uredbi. Na območju prereza, ki je v bližini vodnika in je prozorno, je presežena izvedena mejna vrednost.

Iz Slike 17 je razvidno, da izvedena mejna vrednost za električno poljsko jakost za zaposlene po Smernicah ICNIRP na območju, ki je v dosegu človeka, ni presežena, prav tako ne po Uredbi za II. območje, saj znaša v obeh primerih 10000 Vm^{-1} (preseženi pa sta izvedena mejna vrednost po Smernicah ICNIRP za prebivalstvo (5000 Vm^{-1}) in mejna vrednost Uredbe za I. območje, ki je 10 krat manjša od izvedene mejne vrednosti Smernic ICNIRP za prebivalstvo in znaša 500 Vm^{-1}). Pod vodnikom tik nad tlemi je na Sliki 17 prozoren kvader. Ta predstavlja malo geometrijo, v katero smo namestili model človeškega telesa, sestavljen iz 12 objektov. Porazdelitev elektromagnetnega polja v mali geometriji v bližini modela človeškega telesa je prikazan na Slikah 18 in 19.



Slika 18: Porazdelitev elektromagnetnega polja v bližini človeškega telesa. Predstavljena je električna poljska jakost v ravnini *yz* pri *x* = 0 ter ravnini *xy* pri *z* = 0.88. Barvna skala zavzema vrednosti od 0 do 10000 Vm^{-1}. 10000 Vm^{-1} je namreč pri 50 Hz izvedena mejna vrednost za električno poljsko jakost po Smernicah ICNIRP za zaposlene ter za II območje po Uredbi. Na območju prereza, ki je prozoren, je presežena izvedena mejna vrednost.

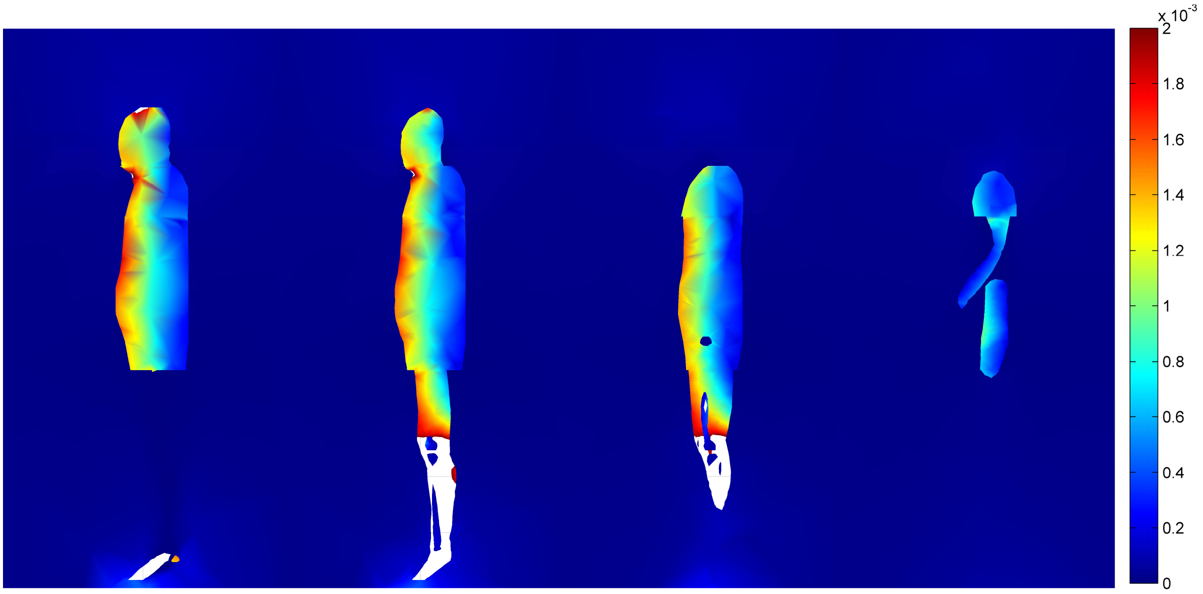
Iz Slike 18 je razvidno, da se polje v bližini modela človeškega telesa deformira in preseže izvedene mejne vrednosti za električno poljsko jakost po Smernicah ICNIRP za zaposlene ter po Uredbi za II območje v predelu glave in nog. Za gostoto magnetnega pretoka je iz Slike 19 razvidno, da je le ta na celotnem območju odvisna le od položaja po osi *z* in je nižja od izvedene mejne vrednosti po Smernicah ICNIRP ter po Uredbi za II. območje, kjer v obeh primerih znaša 100 µT.



Slika 19: Porazdelitev elektromagnetnega polja v bližini človeškega telesa. Predstavljena je gostota magnetnega pretoka v ravnini *yz* pri $x = 0$ ter ravnini *xy* pri $z = 0.88$. Barvna skala zavzema vrednosti od 0 do 100 µT. 100 µT je namreč pri 50 Hz izvedena mejna vrednost za gostoto magnetnega pretoka po Smernicah ICNIRP za prebivalstvo ter za II območje po Uredbi.

Za takšen vir elektromagnetnega polja smo se odločili, saj je zaradi električnega polja v smeri *z* pričakovati, da bo vpliv implanta, ki je orientiran v isti smeri, največji, prav tako povzroči orientacija magnetnega polja pravokotno na os *z* največjo inducirano napetost v telesu.

Za ugotavljanje učinkov elektromagnetnega polja nizkih frekvenc na človeško telo je pomembna gostota toka, zaradi česar je to veličina, ki jo Smernice ICNIRP, Priporočila 1999/519/EC in Direktiva 2004/40/EC omejujejo pri nizkih frekvencah. Smernice ICNIRP za 50 Hz predlagajo mejno vrednost za prebivalstvo 2 mAm^{-2} ter za zaposlene 10 mAm^{-2}. Velja za glavo in trup, kajti namenjena je varovanju pred učinki na centralni živčni sistem.

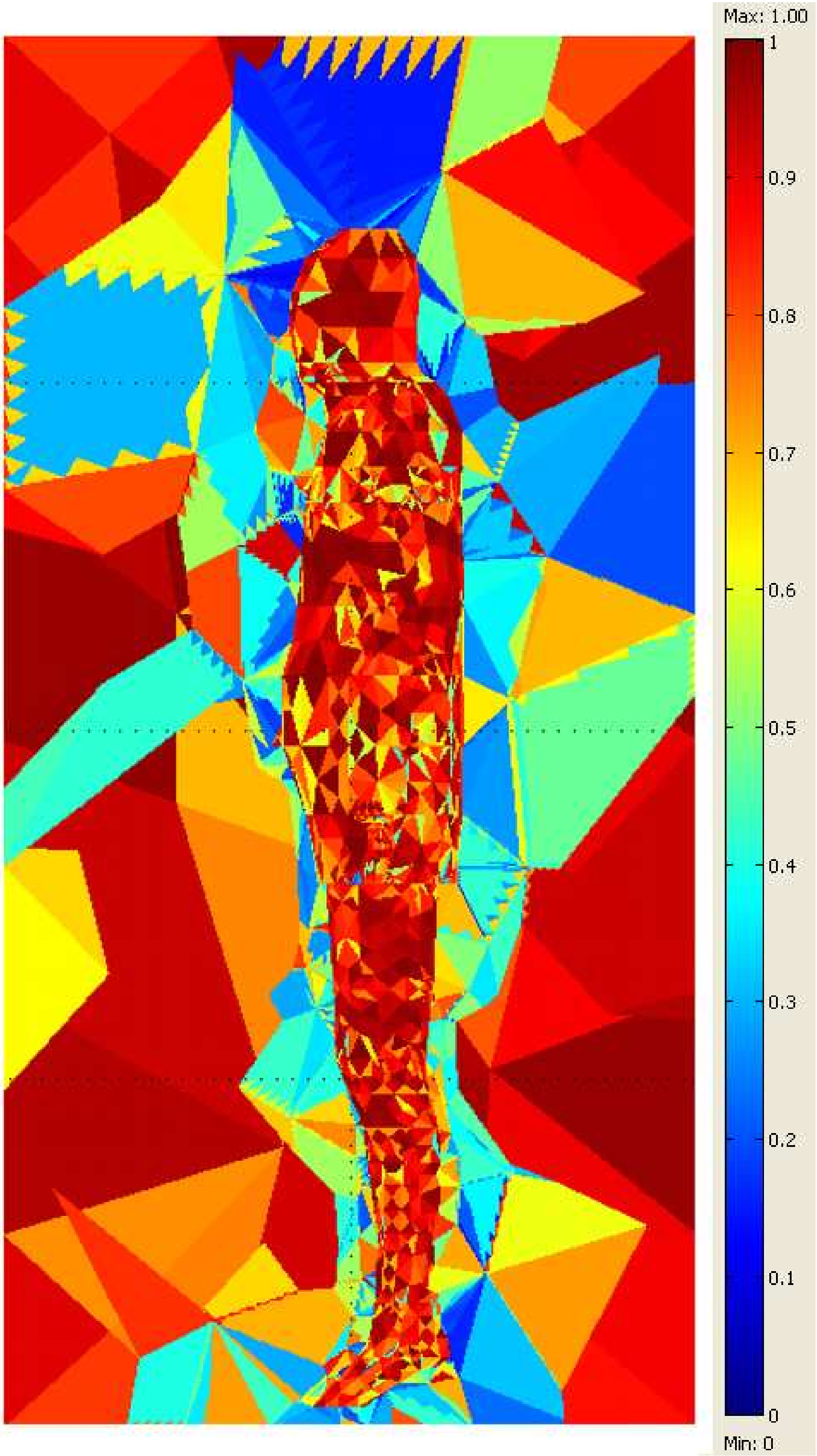


Slika 20: Gostota električnega toka v modelu človeškega telesa. Barvna skala zavzema vrednosti od 0 do 2 mAm^{-2}. 2 mAm^{-2} je namreč pri 50 Hz mejna vrednost za gostoto električnega toka po Smernicah ICNIRP za prebivalstvo. Na levi je predstavljen presek skozi središče modela v ravnini *yz* pri $x = 0$, proti desni pa si vrstijo slike pri $x = -0.05$ m, -0.1 m in -0.2 m. Na območju prereza, ki je prozoren, je presežena mejna vrednost.

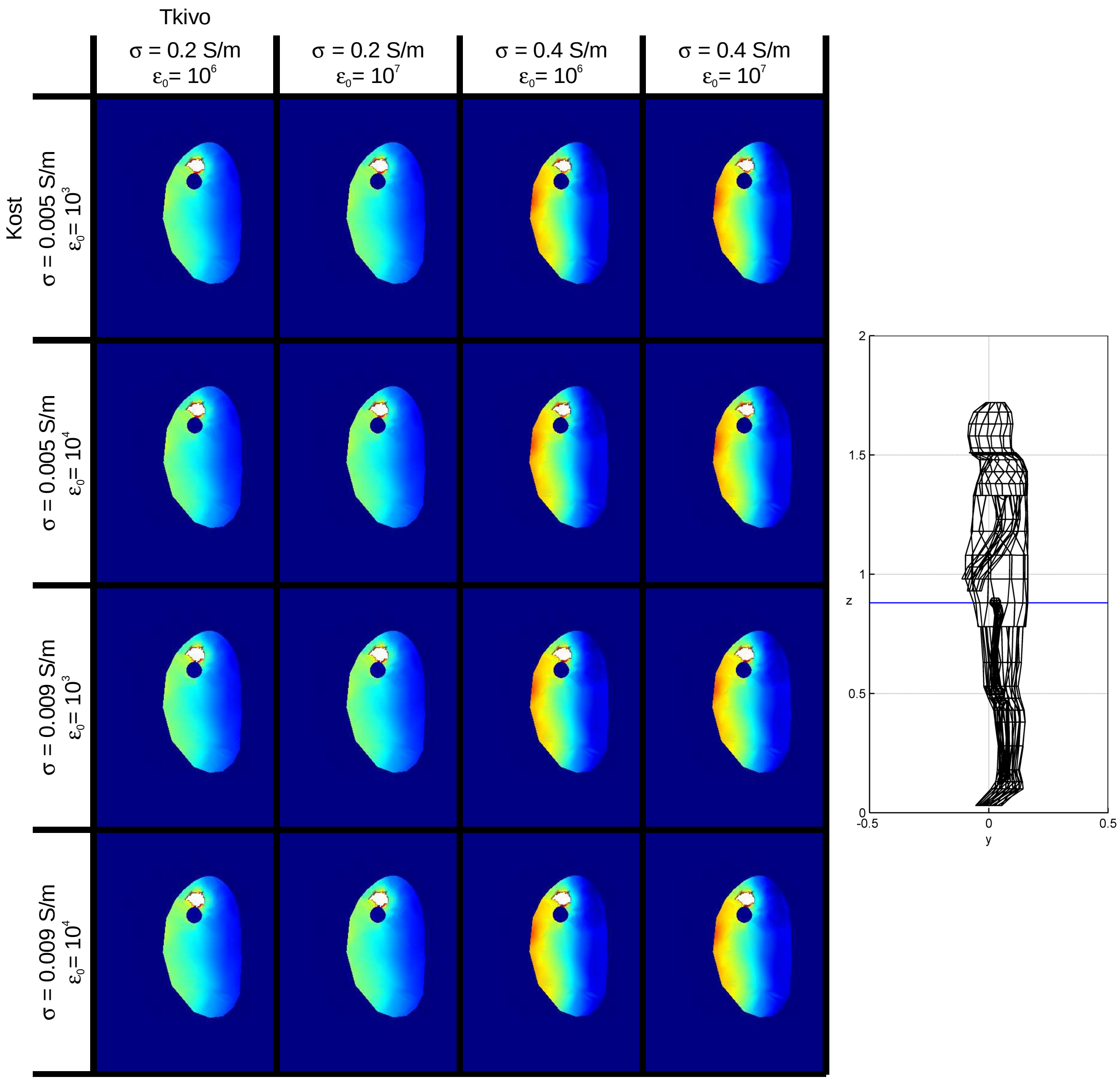
Iz Slike 20, kjer je predstavljena gostota električnega toka v nekaj prereznih ravninah za model brez implanta, je razvidno, da v glavi in trupu mejna vrednost po smernicah ICNIRP za prebivalstvo ni presežena, prav tako ni presežena v rokah. Presežena pa je v nogah, še posebej v spodnjem delu pod koleni. Na skrajno levi strani Slike 20 pa je vendarle opazno, da je na vrhu glave na manjšem delu presežena mejna vrednost. Poleg dejstva, da je tam res velika električna poljska jakost in posledično gostota električnega toka, je za to kriva tudi mreža, ki je prav nad glavo slabe kvalitete, kar je razvidno iz Slike 21. Kvaliteto posameznega elementa v primeru elementov v obliki tetraedrov COMSOL Multiphysics izračuna iz formule:

$$q = \frac{72\sqrt{3}V}{\left(h_1^2 + h_2^2 + h_3^2 + h_4^2 + h_5^2 + h_6^2\right)^{3/2}}, \tag{5.18}$$

kjer je q kvaliteta elementa, V volumen in h_1 do h_6 dolžine stranic tetraedra. $q = 1$ za enakostranični tetraeder. Navodila za uporabo [COMSOL AB., 2005] navajajo, da kvaliteta mreže ne vplivala na rezultat, če je $q > 0.1$. Iz Slike 21 je razvidno, da je kvaliteta elementov nad glavno ravno na sprejemljivi meji kvalitete.



Slika 21: Kvaliteta mreže v mali geometriji (presek na sredini modela, ravnina *yz*, *x* = 0). Bliže kot je vrednosti 1 (rdeča barva), kvalitetnejši je element (bolj je podoben enakostraničnemu tetraedru). V predelu tik nad glavo, kjer je mejna vrednost za gostoto toka presežena, je tudi kvaliteta mreže najslabša, kar je možen vzrok za takšen rezultat. Kvalitetnejše mreže v modelu ni bilo mogoče zgraditi, ker bi sicer vsebovala preveč elementov in bi izračun ne bil mogoč.



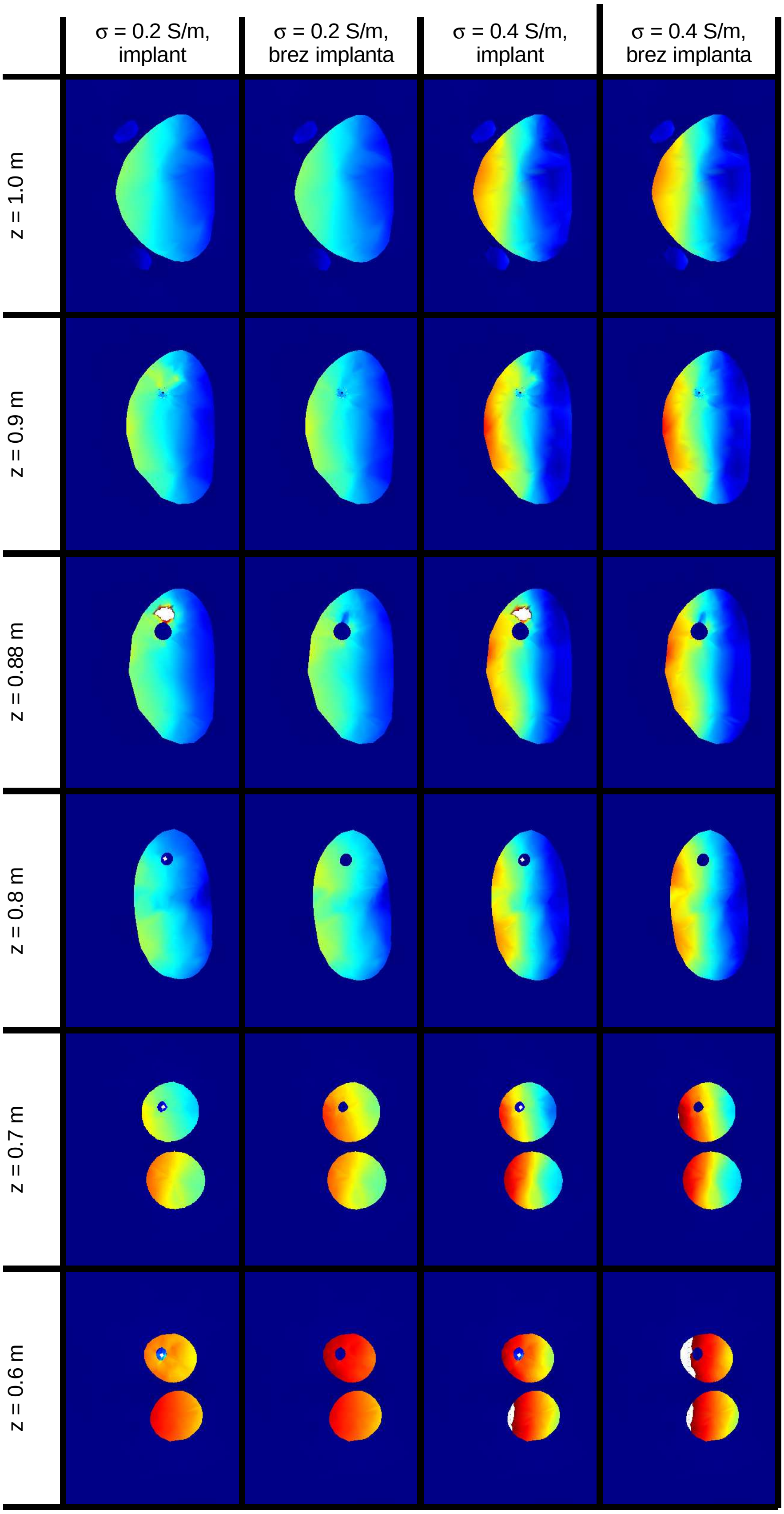
Slika 22: Primerjava gostote električnega toka v odvisnosti od prevodnosti in dielektričnosti snovi. Porazdelitev je predstavljena v ravnini *xy* pri *z* = 0.88 m. Ravnina je predstavljena na desni sliki z modro črto. Za to ravnino smo se odločili, kajti tukaj intramedularni žebelj ravno izstopa iz kosti, zato je v tem območju pričakovati povečano gostoto toka, kar je razvidno tudi iz slik, saj je poleg modrega kroga, ki predstavlja glavo stegnenice (v kosteh je zaradi nižje prevodnosti gostota toka majhna) še prozorno območje, kjer je presežena mejna vrednost za gostoto električnega toka po Smernicah ICNIRP za prebivalstvo. Barvna skala je enaka kot na Sliki 20.

V modelu človeškega telesa izpostavljenega elektromagnetnemu polju nizkih frekvenc smo opravili izračune za različne vrednosti prevodnosti in dielektričnosti. Primerjava gostot toka za model z implantom v odvisnosti od prevodnosti in dielektričnosti snovi je prikazana na Sliki 22. Porazdelitev je predstavljena v ravnini *xy* pri *z* = 0.88 m, saj ravno v tej ravnini intramedularni žebelj izstopa iz kosti in je v tem območju pričakovati povečano gostoto toka. To je razvidno tudi iz slik, saj je poleg modrega kroga, ki predstavlja glavo stegnenice (v kosteh je zaradi nižje prevodnosti in dielektričnosti gostota toka majhna) prozorno območje, kjer je mejna vrednost gostote toka po Smernicah ICNIRP za prebivalstvo presežena. Opaziti je, da vrednosti dielektričnosti opazno ne vplivajo tako na porazdelitev gostote toka v mehkem tkivu kakor tudi na območje v mehkem tkivu, kjer je presežena mejna vrednost gostote električnega toka po Smernicah ICNIRP za prebivalstvo, opazno pa je povečanje gostote toka v primeru večje prevodnosti mehkega tkiva. Zaradi tega smo se odločili, da bomo za nadaljnje predstavljanje rezultatov uporabili dva modela z implantom in dva modela brez implanta z naslednjimi vrednostmi prevodnosti in dielektričnosti:

- mehko tkivo: $\sigma = 0.2$ in 0.4 Sm^{-1}; $\varepsilon_r = 10^6$;
- kost: $\sigma = 0.005$ Sm^{-1}; $\varepsilon_r = 10^3$.

Primerjava porazdelitve gostote toka v modelu z implantom in brez je predstavljena na Sliki 23, kjer so prikazane porazdelitve gostote električnega toka pri različnih višinah v modelu. Višine so označene na levem robu slike. Kakor je razvidno iz Slike 22 desno, so vse višine na Sliki 23 izbrane v območju med kolenom in pasom, torej v območju, v katerem se nahaja implant. V prvem in tretjem stolpcu so predstavljeni rezultati za modela z implantom, v drugem in četrtem pa za modela brez implanta. Iz primerjave prvega in drugega stolpca, kjer je uporabljena specifična prevodnost mehkega tkiva $\sigma = 0.2$ Sm^{-1}, je razvidno, da je gostota toka povečana v zelo majhnem predelu tik ob izstopu implanta iz kosti (višina $z = 0.88$ m). Če se le malo odmaknemo od tega mesta ($z = 0.9$ m), je povečanje gostote toka mnogo manjše in pri višini $z = 1$ m razlika ni več opazna. Zanimivo je tudi opazovanje gostote toka v sami nogi, ki je precej večja od gostote toka v trupu. Porazdelitev gostote toka v tisti nogi, v kateri ni kosti, je enaka ne glede na to, ali je v drugi nogi implant ali ne, kar je normalno. V drugi nogi pa je opazno, da je gostota toka manjša v tistem modelu, kjer je implant. Tudi za tretji in četrti stolpec, kjer so prestavljeni rezultati za modele s specifično prevodnostjo mehkega tkiva $\sigma = 0.4$ Sm^{-1}, veljajo vse pravkar opisane lastnosti, opazno je le, da je gostota toka na slikah v tretjem in četrtem stolpcu višja od gostote toka v prvem in drugem stolpcu, kar se sklada tudi z rezultati na Sliki 22.

Na osnovi rezultatov modela smo določili povprečno vrednost gostote tkiva v območju tik nad mestom, kjer intramedularni žebelj izstopa iz kosti. To je tudi mesto, kjer je v celotnem modelu dosežena največja gostota toka, večja kot v nogah. Povprečna vrednost v 10 gramih tkiva znaša približno 7 mAm^{-2}, kar pomeni, da je mejna vrednost (*basic restrictions*) Smernic ICNIRP za prebivalstvo presežena za več kot trikrat. V modelu brez implanta znaša povprečna vrednost v 10 gramih tkiva 0.7 mAm^{-2}, kar pomeni, da je implant povzročil približno 10 kratno povečanje gostote toka v tkivu v bližini implanta. Razlika v povprečni vrednosti gostote toka v 10 gramih tkiva med modelom, v katerem je specifična prevodnost mehkega tkiva $\sigma = 0.2$ Sm^{-1} in modelom, kjer je 0.4 Sm^{-1}, je majhna.



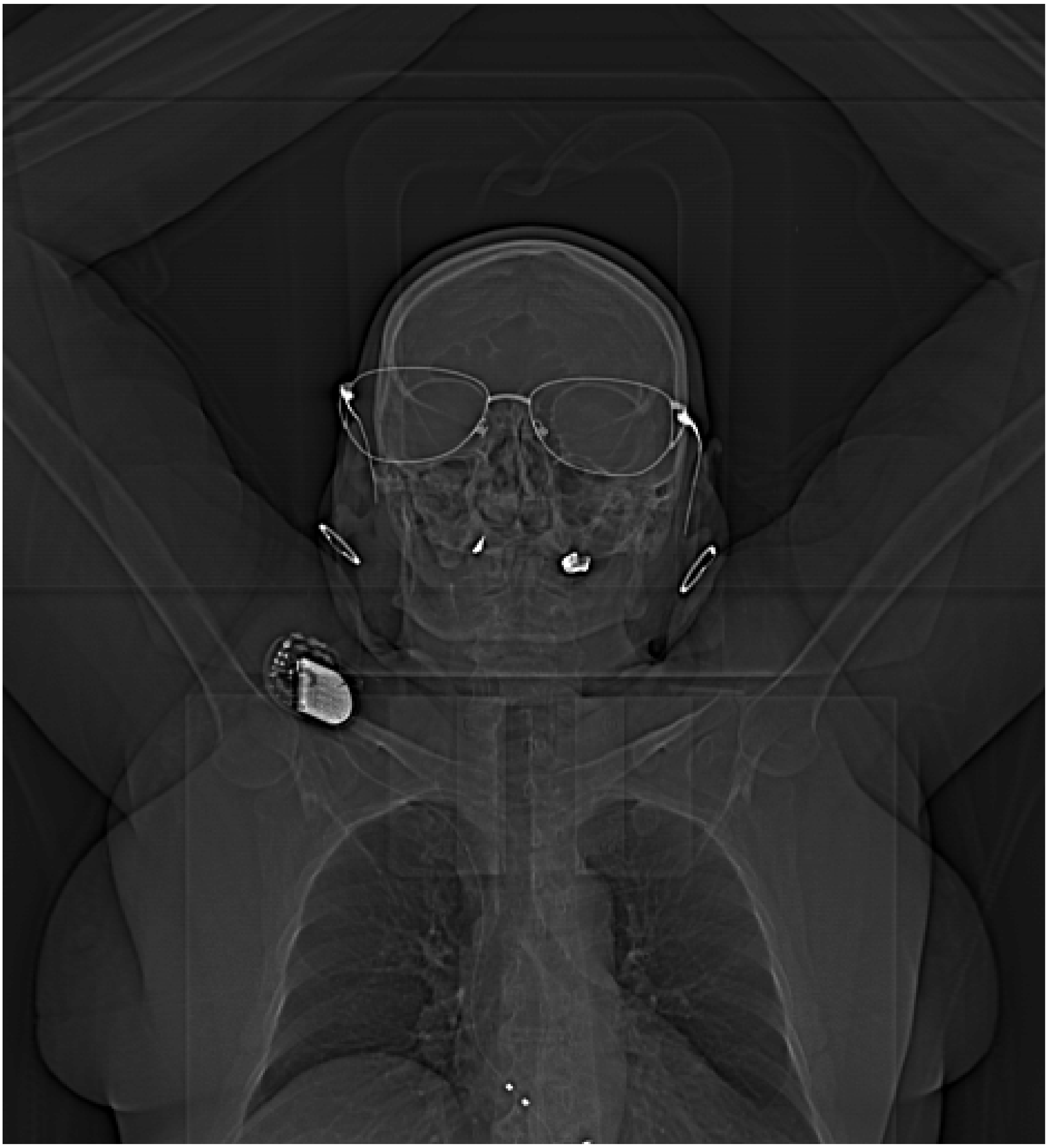
Slika 23: Primerjava gostote električnega toka v odvisnosti od prevodnosti snovi ter višine v modelu. Porazdelitev je predstavljena v ravnini *xy* pri različnih višinah *z*. Barvna skala je enaka kot na Sliki 20.

6 Vpliv srčnega spodbujevalnika v elektromagnetnem polju srednjih frekvenc

6.1 Geometrija modela

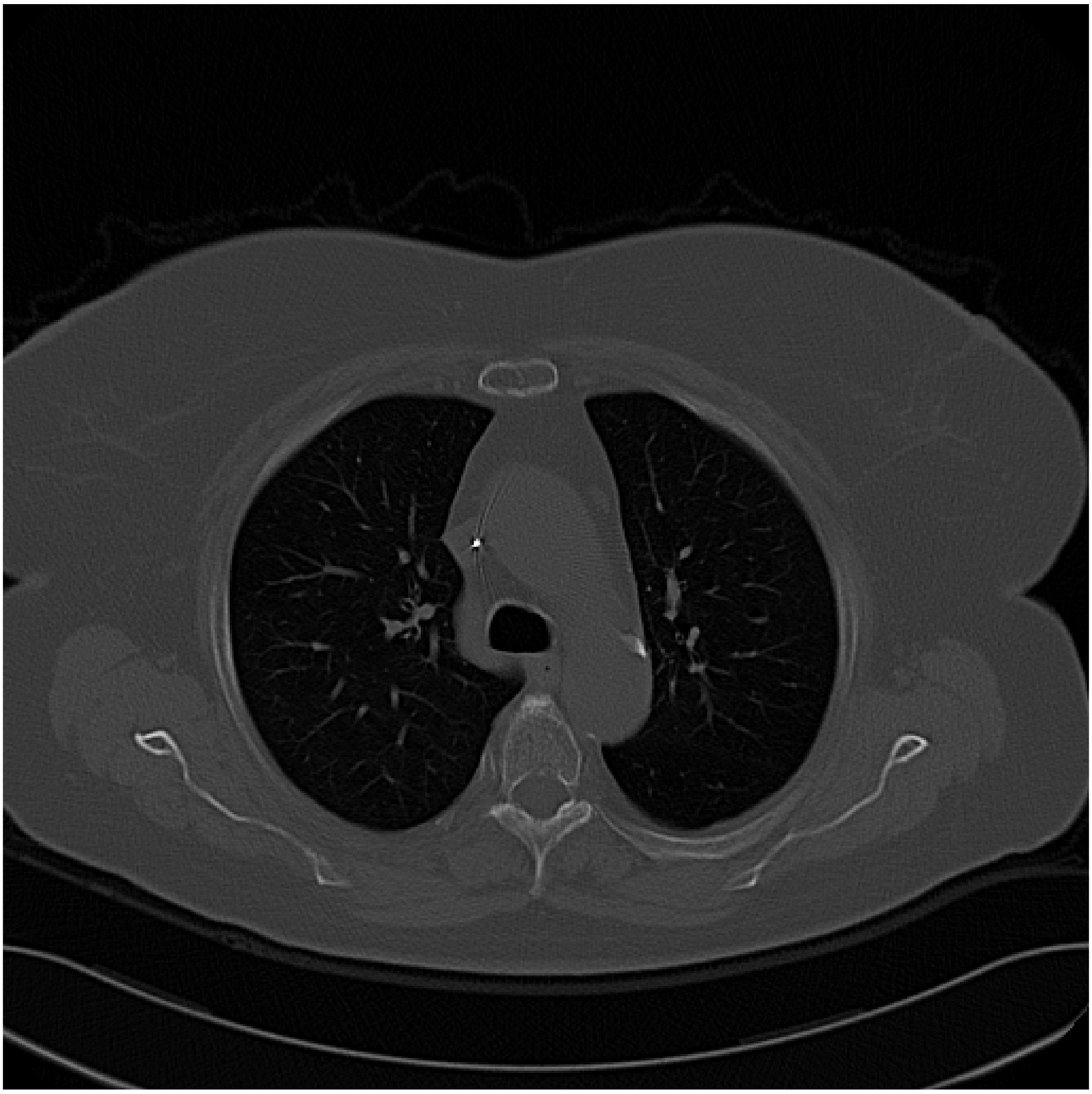
V modelu človeškega telesa s srčnim spodbujevalnikom, izpostavljenega elektromagnetnemu polju srednjih frekvenc, smo želeli določiti vpliv srčnega spodbujevalnika s pripadajočimi elektrodami na porazdelitev SAR v človeku. V modelu, opisanem v prejšnjem poglavju, smo opazovali porazdelitev gostote toka, saj je bil model nizkofrekvenčen. V primeru modela na področju višjih frekvenc pa je SAR tista veličina, ki jo omejujejo tako Smernice ICNIRP kot tudi Priporočila 1999/519/EC, Uredba in Direktiva 2004/40/EC.

Želeli smo zgraditi model celotnega človeškega telesa z vstavljenim srčnim spodbujevalnikom. Za ta namen smo uporabili predhodno zgrajen model človeškega telesa, uporabljenega za ugotavljanje vpliva intramedularnega žeblja na porazdelitev gostote toka v elektromagnetnem polju nizkih frekvenc. Model človeškega telesa smo poenostavili, saj vanj nismo vključili kosti v nogi. Njihov vpliv na porazdelitev elektromagnetnega polja v okolici srčnega spodbujevalnika je zanemarljiv, smo pa dodali pljuča, ki imajo manjšo prevodnost od mehkega tkiva, kakor je razvidno iz Tabele 9, nahajajo pa se v neposredni bližini srčnega spodbujevalnika in elektrode. Glede na prevodnosti srca ter krvi, ki je podobna kot je prevodnost mehkega tkiva, smo se odločili, da srca v model ne bomo vključili. V model je bilo potrebno vključiti tudi srčni spodbujevalnik. Le ta je sestavljen iz dveh večjih sklopov, in sicer samega spodbujevalnika in elektrode. Za določanje geometrije spodbujevalnika in elektrod smo uporabili CT slike bolnice, ki so bile posnete v Kliničnem centru, Ljubljana. Na sliki 24 je predstavljena bolnica z vstavljenim srčnim spodbujevalnikom. Razločno je viden srčni spodbujevalnik, malo slabše pa elektroda. Na elektrodi sta v srcu opazna dva svetlejša predela, kjer sta dve konici elektrode. Slika 24 ni bila uporabljena za gradnjo geometrije, pač pa so bile za to uporabljene slike, posnete pravokotno na to sliko. Ena izmed teh pravokotnih slik je predstavljena na Sliki 25 in prikazuje prerez bolnice v predelu pljuč in srca. Bela točka v levem predelu srca je elektroda.



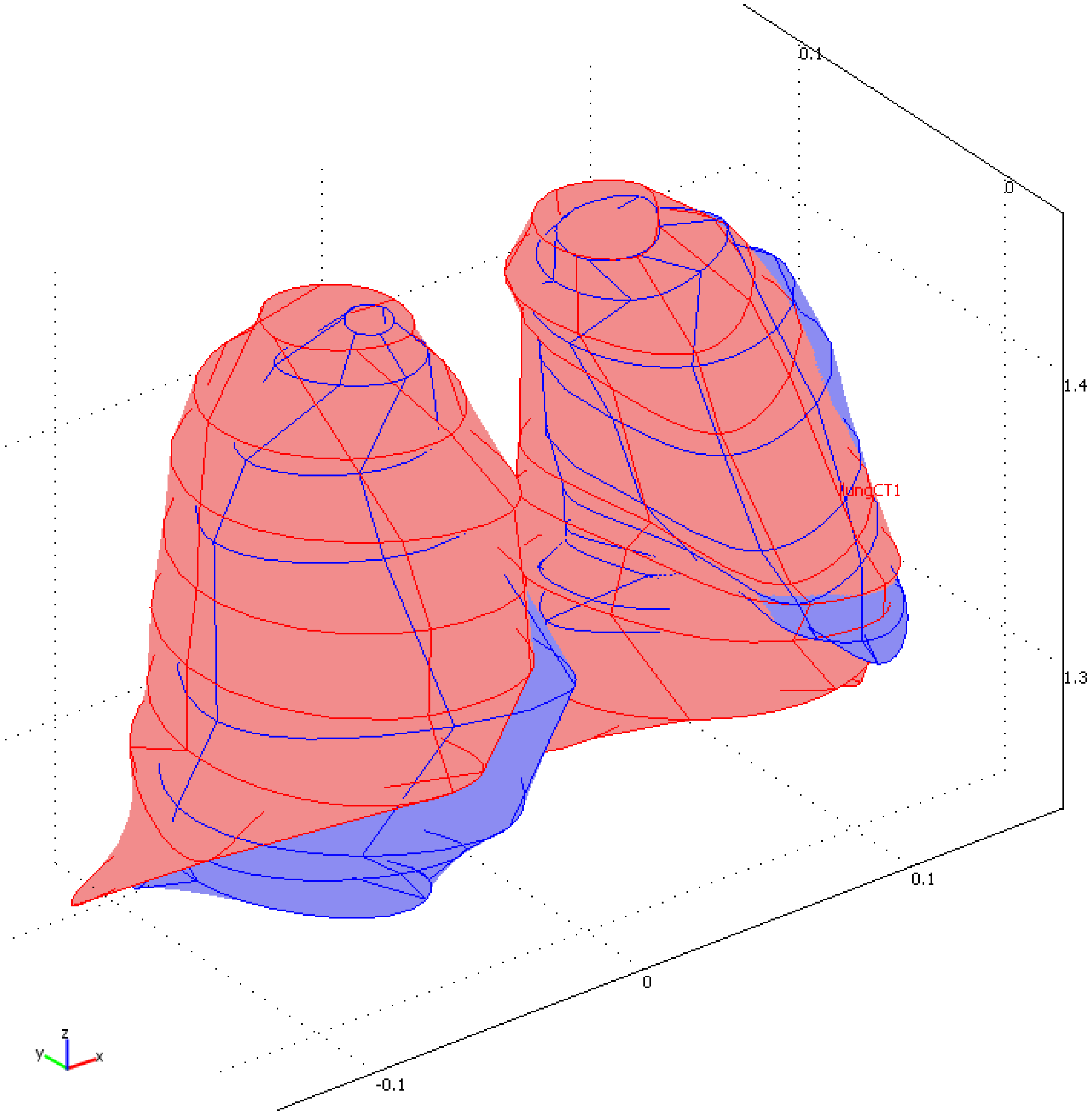
Slika 24: CT slika bolnice z vstavljenim srčnim spodbujevalnikom. Razločno je viden srčni spodbujevalnik, malo slabše pa elektroda, razen dveh svetlejših točk na elektodi v srcu, ki sta konici elektrod. Ta slika ni bila uporabljena za gradnjo geometrije, pač pa so bile za to uporabljene slike, ki so bile posnete pravokotno na to sliko.

Da bi lahko CT slike v predelu srca poravnali z modelom na osnovi slik VHDS, smo na podlagi CT slik zgradili model pljuč. Nato smo model pljuč, zgrajen s pomočjo CT slik, poravnali z modelom pljuč, zgrajenim s pomočjo slik VHDS. Edini podatek, s katerim smo razpolagali, je bil korak, s katerim so bile CT slike posnete: 5 mm vzdolž telesa (smer *z*), nismo pa imeli podatka o razločljivosti posamezne slike (smer *x* in *y*). Torej smo morali določiti izhodiščno višino po osi *z*, izhodišče osi *x* in *y* ter razločljivost po osi *x* in *y*.



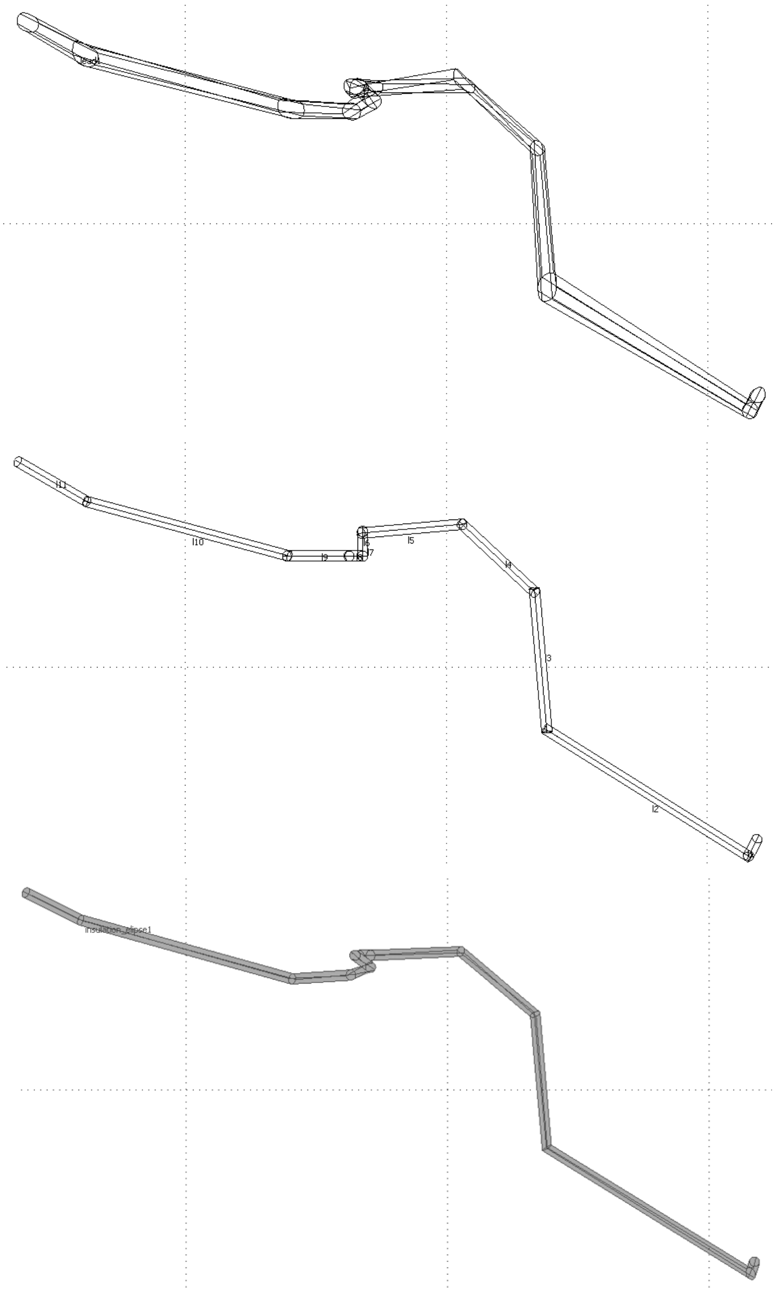
Slika 25: CT slika bolnice z vstavljenim srčnim spodbujevalnikom. Svetla točka v levem predelu srca je elektroda.

S poizkušanjem smo ugotovili, da je velikost točke 0.75 mm tako po osi *x* kot *y*. Po osi *x* smo morali slike premaknit za 1 cm, po osi *y* za 2.5 cm in po osi *z* za 167 cm. Na Sliki 26 sta prikazana poravnana modela pljuč, narejena na osnovi CT slik in VHDS slik. Po poravnavi, ko so nam bili znani tako razločljivost kot tudi premiki CT slik, smo pričeli z gradnjo elektrod. V ta namen nam je služilo 13 CT slik. V njih smo določili robove elektrod ter zgradili model elektrod na enak način kot smo to naredili za vse druge objekte v modelu. Ta postopek pa se ni izkazal za ustreznega. Kakor je razvidno iz Slike 27 levo, elektrode niso bile enako debele po celotni dolžini. Poskušali smo jih nadomestiti z 11 valji s polmerom 1 mm, kolikor znaša polmer elektrod [Medtronik, 2001]. Tudi ta rešitev ni bila ustrezna, saj zaradi velikega števila presekov med valji mreže ni bilo mogoče zgraditi.



Slika 26: Model pljuč, narejen na podlagi CT slik (rdeče) in na podlagi VHDS slik (modro) po poravnavi.

Zaradi tega smo se odločili, da elektrode zgradimo na naslednji način: eno za drugo smo v MATLAB prebrali vsako od trinajstih CT slik; iz vsake slike smo določili le središčno lego elektrode, tako smo skupaj s predhodno določeno razločljivostjo slik ter potrebnim premikom za ujemanje CT in VHDS slik dobili točke, ki določajo lego sredine elektrode v modelu. Če bi te točke med seboj povezali, bi dobili odsekoma linearno večkrat lomljeno krivuljo v središču elektrode. Okrog te premice smo želeli napeti valj. Zato smo na podlagi točk, ki določajo lego sredine elektrode, določili smerne vektorje posameznih odsekov elektrod ter nato lego ravnine v vsaki točki, ki tvori z obema odsekoma elektrode iz tiste točke enak kot. Na to ravnino smo položili krog s polmerom 1 mm (ali v primeru majhnega kota med ravnino in odsekom elektrode elipso z manjšo polosjo 1 mm in večjo enako projekciji 1 mm na ravnino) in na koncu tako dobljene kroge in elipse pomočjo funkcije *loft* povezali v objekt, ki je predstavljal izolacijo elektrode. Enako smo storili tudi s krogi ter elipsami z manjšim premerom 0.5 mm in tako zgradili objekt, ki je predstavljal notranji kovinski del elektrode. Program, ki je te operacije izvajal, je dodan v Dodatku. Tako dobljena elektroda ima presek, ki se ne spreminja. Ker CT slike niso vsebovale območja, v katerem je vstavljen sam srčni spodbujevalnik, smo ga v model vključili kot valj s polmerom 2 cm in višino 1 cm. Model smo na koncu vstavili v kvader z višino 2 m ter širino in globino 1 m, ki je predstavljal okolico modela.



Slika 27: Model elektrod, zgrajenih neposredno na podlagi CT slik (zgoraj), sestavljen iz 11 valjev (v sredini) in zgrajenih s pomočjo krogov in elips, orientiranih na podlagi CT slik (spodaj). Prve elektrode niso bile primerne za uporabo v modelu, ker se je nihov premer spreminjal, druge niso niso bile uporabne zaradi velikega števila presekov ni bilo mogoče zgraditi mreže. Z zadnjmi smo kljub zahtevni geometriji (majhen premer 2mm) model uspeli izračunati.

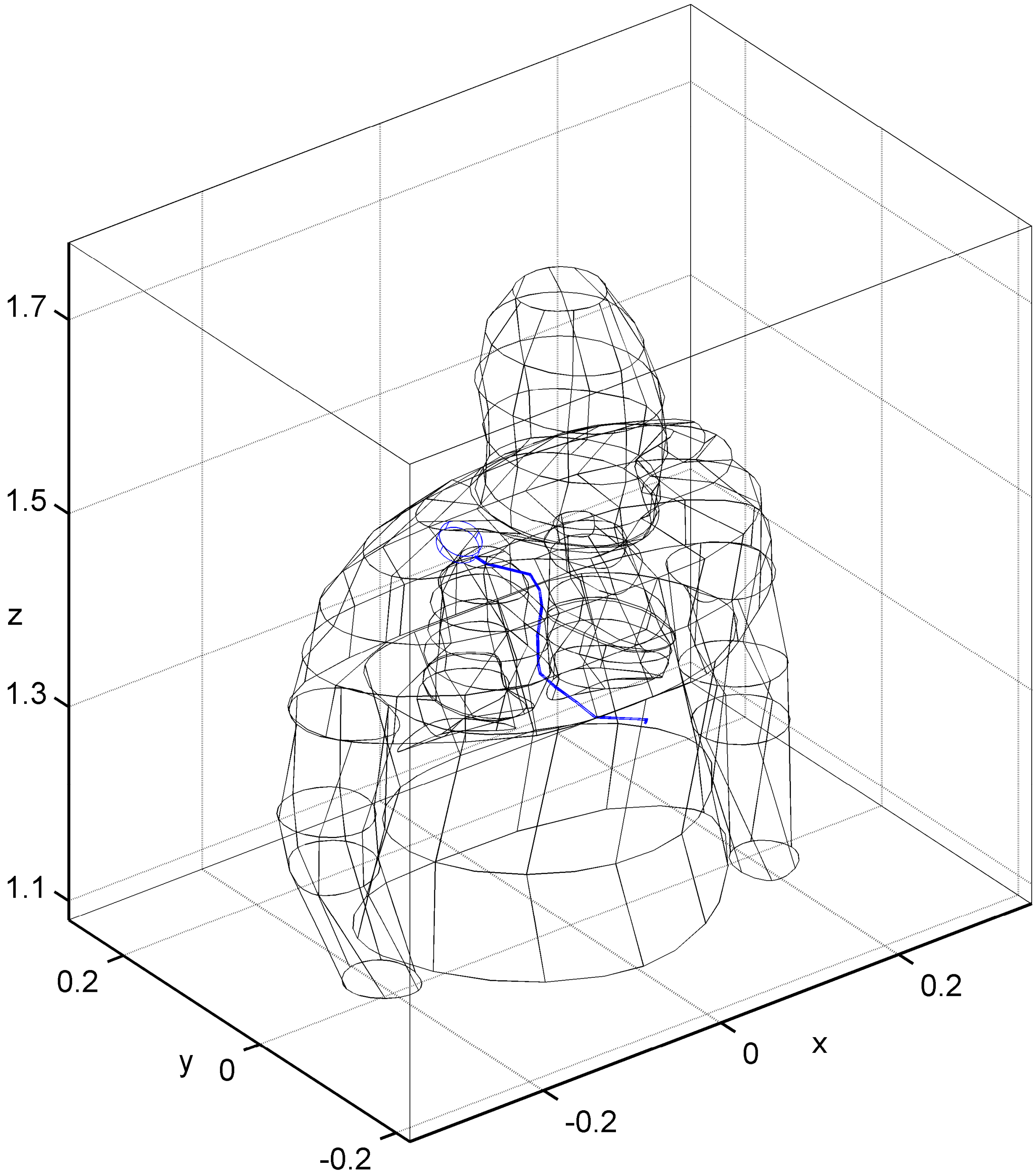
Tabela 7: Objekti, ki sestavljajo geometrijo človeškega telesa ali smo jih pri izdelavi geometrije zgradili, a ne uporabili.

ime	opis	število vozlišč	število slik	število robov	število ploskev
larm	leva roka	6	6	66	32
rarm	desna roka	6	6	66	32
head	glava	10	6	110	52
lleg	leva noga	10	11	210	102
rleg	desna noga	10	11	210	102
torzolow	spodnji del torza	11	6	121	57
torzoup	zgornji del torza	20	6	220	102
llung	levo pljučno krilo	6	11	126	62
rlung	desno pljučno krilo	6	9	102	54
llungCT	levo pljučno krilo (CT)	6	8	90	44
rlungCT	desno pljučno krilo (CT)	6	8	90	44
lead	elektroda	6	13	150	74
lead_cyl	elektroda	z 11 valji nadomeščena elektroda, zgrajena s pomočjo slik			
lead_elipse	elektroda	na podlagi slik določena središča krogov s polmerom 0.5 mm ali elips z manjšim polmerom 0.5 mm ter njihova orientacija v prostoru, s povezovanjem zaporednih krogov ali elips nastala elektroda			
insulation_elipse	izolacija elektrode	na podlagi slik določena središča krogov s polmerom 1 mm ali elips z manjšim polmerom 1 mm ter njihova orientacija v prostoru, s povezovanjem zaporednih krogov ali elips nastala izolacija elektrode			
pacemaker	srčni spodbujevalnik	cilinder s polmerom 2 cm in višino 1 cm			

6.2 Mreža

V tako zgrajenem modelu mreže ni bilo mogoče zgraditi. Zato je bilo potrebno zmanjšati tako velikost kocke kakor tudi število objektov. Najprej smo se odpovedali nogam, kajti njihov vpliv na porazdelitev elektromagnetnega polja v okolici srčnega spodbujevalnika in elektrod je zelo majhen. Ker to še vedno ni bilo dovolj, smo odrezali še del spodnjega dela torza in spodnji del obeh rok na višini 108 cm. Model smo vstavili v kvader višine 0.7 m, širine 0.7 m in globine 0.5 m. Geometrija modela je prikazana na Sliki 28, podatki o novih objektih, ki so bili vključeni v model, pa so v Tabeli 8. V tako poenostavljenem modelu je bilo mogoče zgraditi mrežo. Vendar izračun z iterativnim algoritmov ni konvergiral, zato je bilo potrebno uporabiti direktni algoritem za izračun. Pri tem pa so se pojavili problemi z zasedenostjo spomina. Običajno se da z direktnim algoritmom izračunati modele z do 60.000 prostostnih stopenj, vendar se ta meja od modela do modela razlikuje. Pri uporabi direktnega algoritma je potrebno izračunati inverzno matriko velikosti (število prostostnih stopenj × število prostostnih stopenj), algoritem pa pri tem izkorišča praznost matrike, ki pa se od modela do modela razlikuje. Ker je bila matrika v tem modelu očitno zelo polna, je bil izračun mogoč le za manj kot 27.000 prostostnih stopenj (26.377), kar je v primeru uporabe kvazistatičnega elektromagnetnega polja doseženo pri 17.088 elementih in parametrih algoritma (/ 5 3.5 0.734

0.089 0.299). Takšna mreža je zelo redka. Kakor je razvidno iz parametrov algoritma, so nekateri določeni tudi na tri mesta natančno. Njihovo vrednost je bilo potrebno določiti s poskušanjem, zaradi česar je bila gradnja mreže zelo dolgotrajen postopek.



Slika 28: Geometrija modela človeškega telesa s srčnim spodbujevalnikom in elektrodami (modro) v elektromagnetnem polju srednjih frekvenc. V primerjavi z modelom človeškega telesa z intramedularnim žebljem v elektromagnetnem polju nizkih frekvenc je opazno, da je bilo potrebno zaradi težavne gradnje mreže iz modela izključiti noge ter skrajšati trup in roke.

Tabela 8: Objekti, ki sestavljajo geometrijo človeškega telesa

ime	opis	število vozlišč	število slik	število robov	število ploskev
larmsmall	leva roka (skrajšana)	6	4	42	20
rarmsmall	desna roka (skrajšana)	6	4	42	20
head	glava	10	6	110	52
torzolowsmall	spodnji del torza (skrajšan)	11	3	55	24
torzoup	zgornji del torza	20	6	220	102
llungCT	levo pljučno krilo (CT)	6	8	90	44
rlungCT	desno pljučno krilo (CT)	6	8	90	44
lead_elipse	elektroda	na podlagi slik določena središča krogov s polmerom 0.5 mm ali elips z manjšim polmerom 0.5 mm ter njihova orientacija v prostoru, s povezovanjem zaporednih krogov ali elips nastala elektroda			
insulation_elipse	izolacija elektrode	na podlagi slik določena središča krogov s polmerom 1 mm ali elips z manjšim polmerom 1 mm ter njihova orientacija v prostoru, s povezovanjem zaporednih krogov ali elips nastala izolacija elektrode			
pacemaker	srčni spodbujevalnik	cilinder s polmerom 2 cm in višino 1 cm			

6.3 Lastnosti snovi

V Tabeli 9 so predstavljene lastnosti tkiv pri 27 MHz, ki so pomembne za model človeškega telesa s srčnim spodbujevalnikom.

Tabela 9: Lastnosti snovi, pomembnih za model človeka izpostavljenega elektromagnetnemu polju srednjih frekvenc (27 MHz)

Material	σ (Sm^{-1})	ε_r	μ_r	vir
mehko tkivo	0.6 – 0.8	80 – 110	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
srce	0.7 - 0.8	60 – 80	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
kri	0.8 – 1.5	70 – 100	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
pljuča	0.2 – 0.4	90 – 110	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
zrak	0	1	1	COMSOL Multiphysics, vakuum
elektrode	18000	1	1	Medtronic, 2001
izolacija elektrod	10^{-12}	12.1	1	COMSOL Multiphysics, silikon
spodbujevalnik	4032000	1	1	COMSOL Multiphysics, jeklo

Kakor je označeno v Tabeli 9, smo specifično prevodnost določili s pomočjo tehničnih specifikacij Medtronic-ovih elektrod CAPSURE Z NOVUS 5554, običajnih bipolarnih elektrod [Medtronic, 2001]. V tehničnih specifikacijah je navedeno, da je normalna upornost teh elektrod, uporabljenih na unipolarni način, 37 Ω pri dolžini elektrod 53 cm. Če za elektrodo s polmerom 0.5 mm izračunamo specifično prevodnost, dobimo iz enačbe

$$R = \frac{1}{\sigma}\frac{l}{S}, \tag{6.1}$$

kjer je R upornost, σ specifična prevodnost, l dolžina in S presek elektrod, naslednjo vrednost za specifično prevodnost:

$$\sigma = \frac{l}{RS} = \frac{0.53}{37 \cdot \pi \cdot 0.0005^2} = 18238 \approx 18000\, Sm^{-1} \tag{6.1}$$

Kakor je navedeno že v podpoglavju o gradnji geometrije, v model nismo vključili srca in krvi, kajti razlika v specifični prevodnosti v primerjavi z okoliškim tkivom ni velika. Prav tako v tem modelu nismo naredili parametrizacije izračuna glede na specifične prevodnosti in dielektričnosti posameznih tkiv, kajti v tem frekvenčnem območju so dielektrične lastnosti tkiv v literaturi manj razpršene kot pri frekvenci 50 Hz. V modelu smo za mehko tkivo uporabili vrednosti $\sigma = 0.8$ Sm^{-1} in $\varepsilon = 100$, za pljuča pa vrednosti $\sigma = 0.3$ Sm^{-1} in $\varepsilon = 100$.

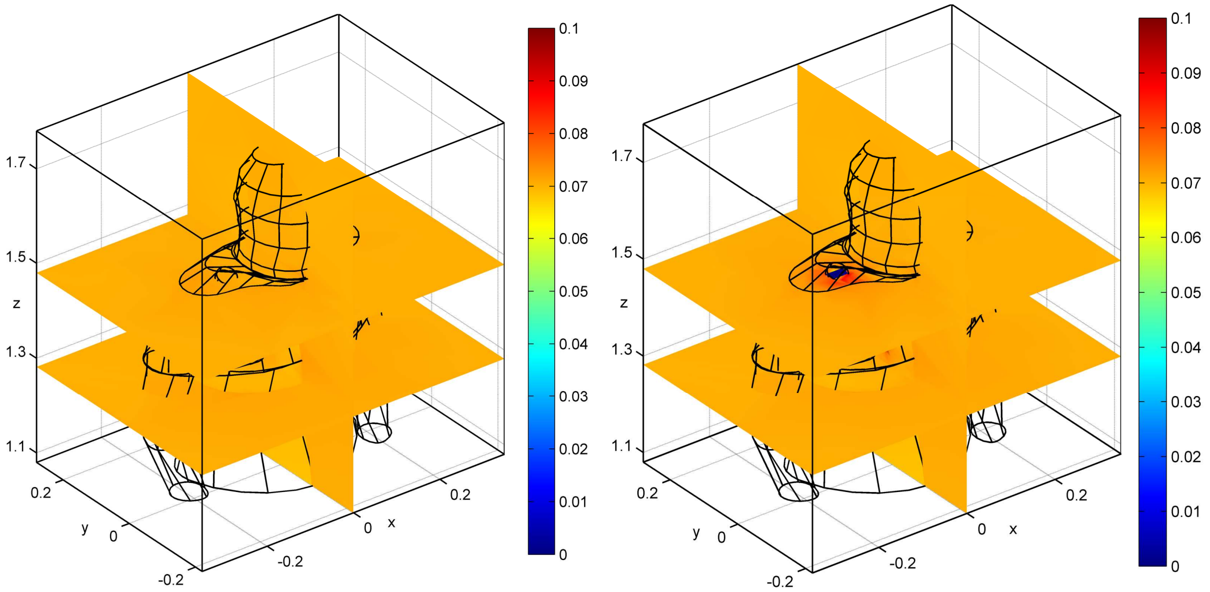
6.4 Fizikalna narava modela in robni pogoji

Kakor v modelu človeškega telesa z intramedularnim žebljem v elektromagnetnem polju nizkih frekvenc smo lahko tudi v tem modelu uporabili kvazistatično elektromagnetno polje, kjer sta neznani veličini električni potencial V in vektorski magnetni potencial $\vec{A}$. Uporaba kvazistatičnega polja je upravičena, saj je velikost modela manj kot 1 m, valovna dolžina pri 27 MHz pa več kot 10 m. Enačbe, ki se pri kvazistatičnem elektromagnetnem polju računajo, so opisane v prejšnjem poglavju.

V COMSOL Multiphysics-u je potrebno v primeru kvazistatičnega elektromagnetnega polja določiti električne in magnetne robne pogoje. V modelu smo z robnimi pogoji določili električno polje 28 Vm^{-1} v smeri y tako, da smo eni stranici kvadra v ravnini xz določili potencial 14 V, drugi pa potencial 0 V, kar bi v primeru homogenega modela ustrezalo točno 28 Vm^{-1}, saj je dimenzija kvadra v tej smeri 0.5 m. Za takšno vrednost električnega polja smo se določili, saj Uredba za II območje predvideva mejno vrednost 27.5 Vm^{-1}, Smernice ICNIRP za prebivalstvo pa 28 Vm^{-1}. Na ostalih stranicah kvadra smo določili električno izolirane robne pogoje. Za magnetno polje smo na vseh stranicah kvadra določili vrednost magnetne poljske jakosti v smeri z na 0.07 Am^{-1}, kar ustreza tako Uredbi za II območje kot tudi Smernicam ICNIRP za prebivalstvo. Z mejnimi pogoji smo tako modelirali elektromagnetno polje z električno poljsko jakostjo v smeri y ter magnetno poljsko jakostjo v smeri z. Rezultati ne odražajo razmer v odprtem prostoru, saj je velikost kvadra, v katerega je umeščen model, premajhna v primerjavi z velikostjo modela človeškega telesa.

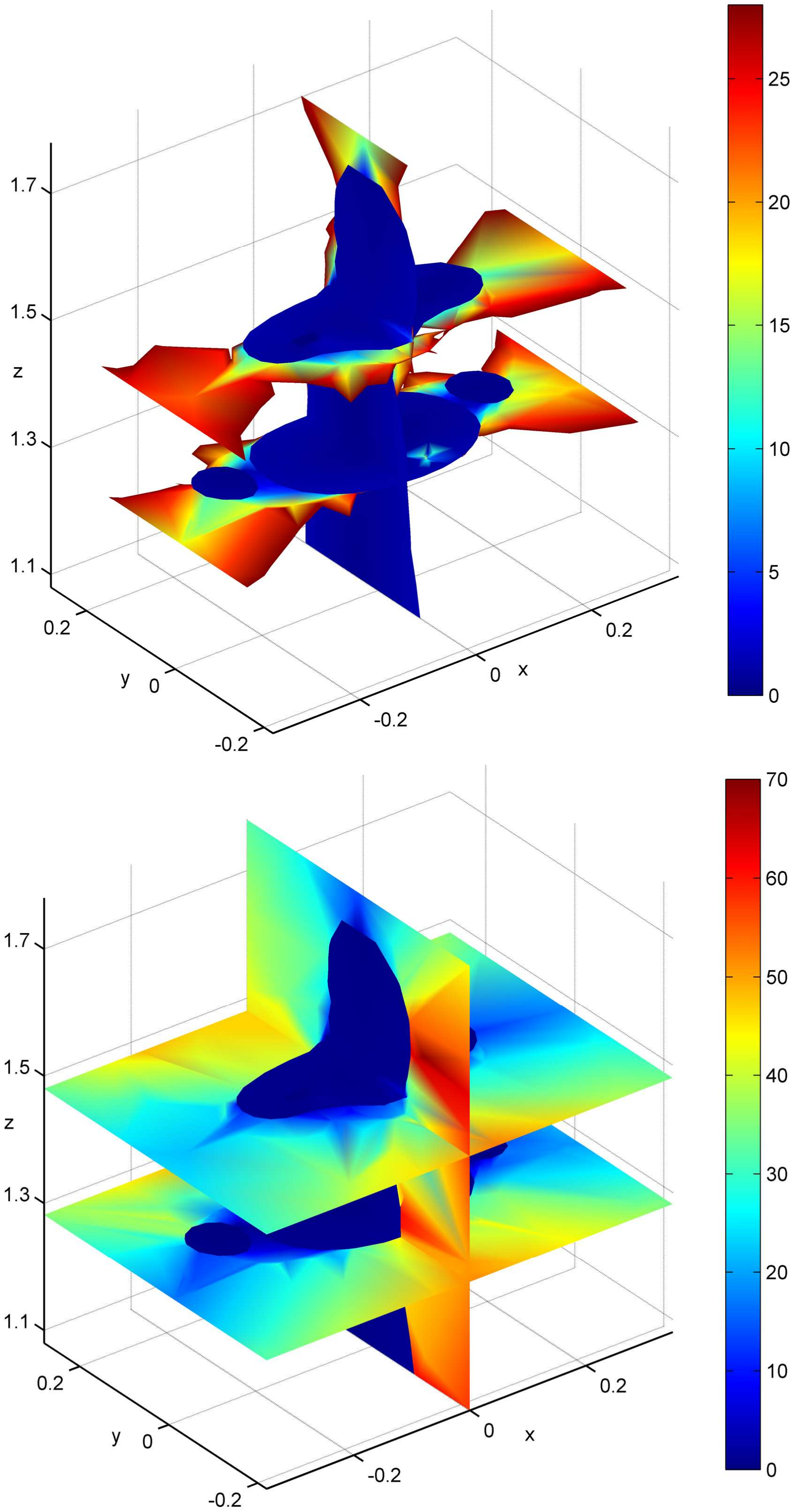
6.5 Rezultati in razprava

V modelu človeškega telesa, izpostavljenega elektromagnetnemu polju srednjih frekvenc, smo izračunali porazdelitev elektromagnetnega polja. Vir elektromagnetnega polja v modelu je bil izbran tako, da so bile dosežene maksimalne mejne vrednosti po Uredbi za II območje. Iz Slike 29, kjer je predstavljena magnetna poljska jakost v modelu v ravninah *xy* pri $z = 1.282$ ter 1.48 ter ravnini yz pri $x = 0$ pa je razvidno, da se magnetna poljska jakost v modelu brez srčnega spodbujevalnika (levo) ne spreminja, četudi model ni homogen. Vzrok temu je homogenost modela za magnetno polje, kajti vse snovi v njem imajo relativno permeabilnost 1. Vendar je na Sliki 29 desno, kjer je predstavljena magnetna poljska jakost v modelu s srčnim spodbujevalnikom opazno, da je magnetna poljska jakost v samem implantu zelo nizka, v okolici implanta pa je opazno njeno povečanje.



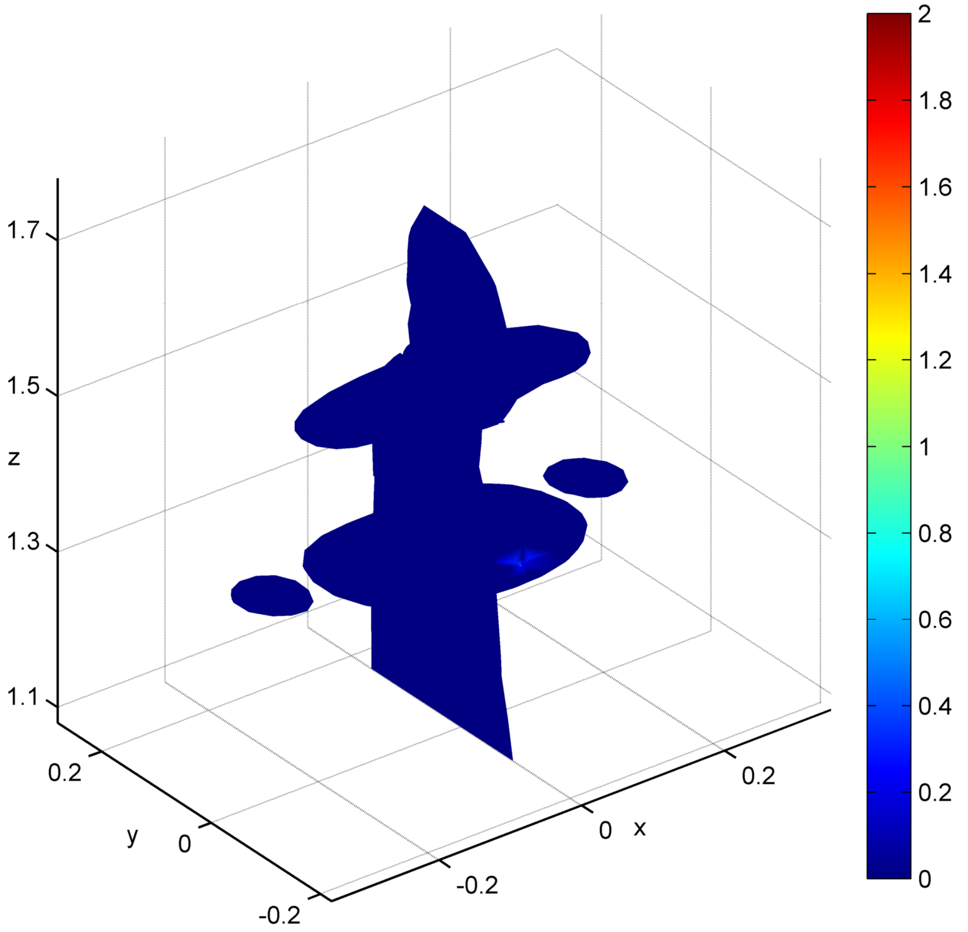
Slika 29: Magnetna poljska jakost v modelu človeškega telesa brez srčnega spodbujevalnika (levo) in s srčnim spodbujevalnikom (desno) v elektromagnetnem polju srednjih frekvenc v ravninah *xy* pri $z = 1.282$ ter 1.48 ter ravnini yz pri $x = 0$. Barvna skala v Am^{-1} sega do 0.1, kar je malo nad mejno vrednostjo Uredbe za II. območje (0.07 Am^{-1}).

Na vseh slikah, ki predstavljajo modelčloveškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju srednjih frekvenc smo rezultate predstavili v ravninah *xy* pri $z = 1.282$ ter 1.48 ter ravnini yz pri $x = 0$. Za obe ravnini *xy* smo se odločili, saj zgornja ($z = 1.48$) poteka skozi sam srčni spodbujevalnik, spodnja ($z = 1.282$) pa poteka tik pod koncem elektrod srčnega spodbujevalnika v predelu, kjer se nahaja srce.



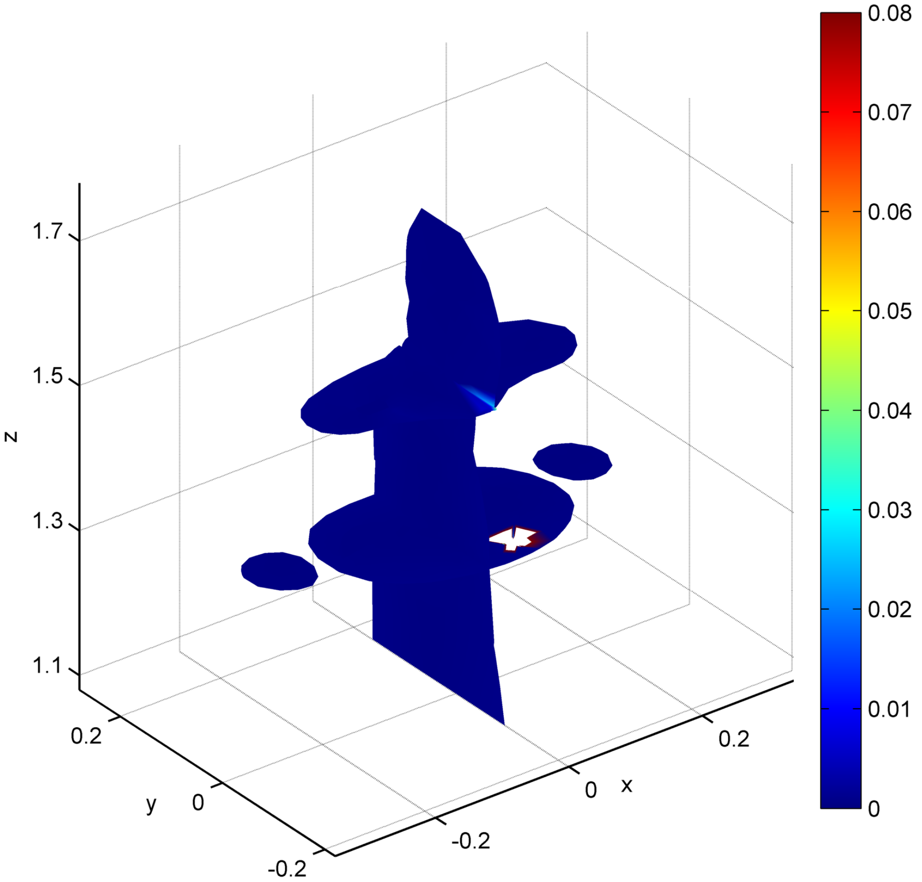
Slika 30: Električna poljska jakost v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju srednjih frekvenc v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini yz pri *x* = 0. Na zgornji sliki sega barvna skala v Vm^{-1} do mejne vrednosti po Uredbi za II območje, pri spodnji pa zavzema celotno območje vrednosti. Na zgornji sliki lahko opazimo povečanje električnega polja v levem predelu nižje prerezne ravnine *xy*, kjer se končuje elektroda srčnega spodbujevalnika.

Električna poljska jakost v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini yz pri *x* = 0 je predstavljena na Sliki 30, in sicer za dve barvni skali. Na zgornji sliki sega barvna skala do mejne vrednosti po Uredbi za II območje, pri spodnji pa zavzema celotno območje vrednosti. Iz slike je razvidno, da človeško telo v veliki meri spremeni porazdelitev električne poljske jakosti v prostoru. Če bi bil prostor homogen, bi bilo v njem električno polje 28 Vm^{-1}, zaradi nehomogenosti pa doseže na nekaterih delih skoraj 70 Vm^{-1}. Prav tako je na zgornji sliki opazen vpliv elektrod na porazdelitev elektromagnetnega polja, saj je v levem predelu opazno povečanje električne poljske jakosti na spodnjem prerezu pri višini pri *z* = 1.282 m. Elektroda se namreč končuje tik nad tem prerezom, tako da je v tem prerezu opazno povečanje električne poljske jakosti tik pod elektrodino konico. Povečanja električne poljske jakosti na drugem koncu elektrod, kjer je nanje priključen srčni spodbujevalnik, ni zaznati. Vzrok za to je v veliki stični površini med srčnim spodbujevalnikom in okoliškim tkivom, ki je nekaj razrednih stopenj večja od stične površine med koncem elektrode in okoliškim tkivom.

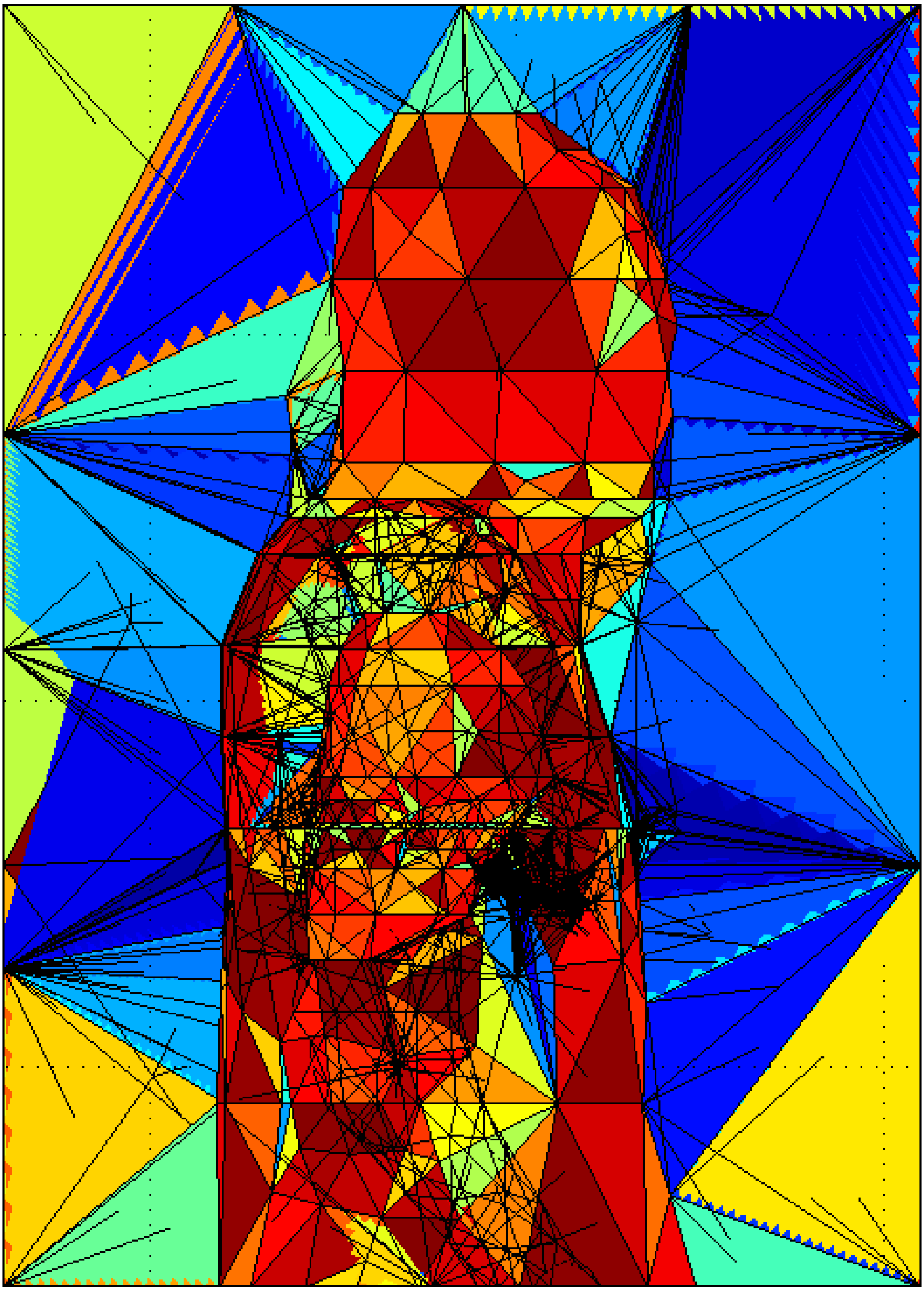


Slika 31: SAR v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju srednjih frekvenc v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini yz pri *x* = 0. Opazno je povečanje SAR tik pod elektrodo. Barvna skala v Wkg^{-1} obsega vrednosti do mejne vrednosti za lokalni SAR glede na Smernice ICNIRP za prebivalstvo.

Smernice ICNIRP kot mejno vrednost na tem frekvenčnem območju določajo vrednosti SAR. Mejna vrednost SAR za prebivalstvo za celotno telo je 0.08 Wkg^{-1}, za lokalno vrednost (povprečje katerihkoli 10 g tkiva) pa znaša 2 Wkg^{-1} za glavo in trup ter 4 Wkg^{-1} za okončine. Kakor je razvidno iz Slike 31, je SAR v modelu povsod nižji od mejne vrednosti za lokalni SAR za glavo in trup. Vendar je v levem predelu spodnje prerezne ravnine, ki je tik pod koncem elektrode, opazno povečanje vrednosti SAR v okolici tik pod elektrodo. Na Sliki 32 je prav tako predstavljen rezultat za SAR, vendar je barvna skala spremenjena, tako da zavzema vrednosti do mejne vrednosti SAR za celotno telo, zato je mnogo bolj vidno območje, kjer pride do povečanja SAR zaradi implanta. V tem območju je mejna vrednost SAR za celo telo sicer presežena, vendar bi morala biti mejna vrednost SAR presežena v celotnem telesu, da bi to bilo pomembno. Opazimo lahko povečano vrednost SAR v spodnjem predelu vratu, kr je prej napaka zaradi slabe mreže kot dejstvo, da je porazdelitev elektromagnetnega polja res takšna. Kakor je razvidno iz Slike 33, je mreža med modelom in zunanjim robom večinoma precej nekvalitetna, poleg tega pa posamezni elementi segajo neposredno od zunanjega roba modela (površine kvadra) do površine modela človeškega telesa (kože), kar lahko vodi do dodatnih napak.

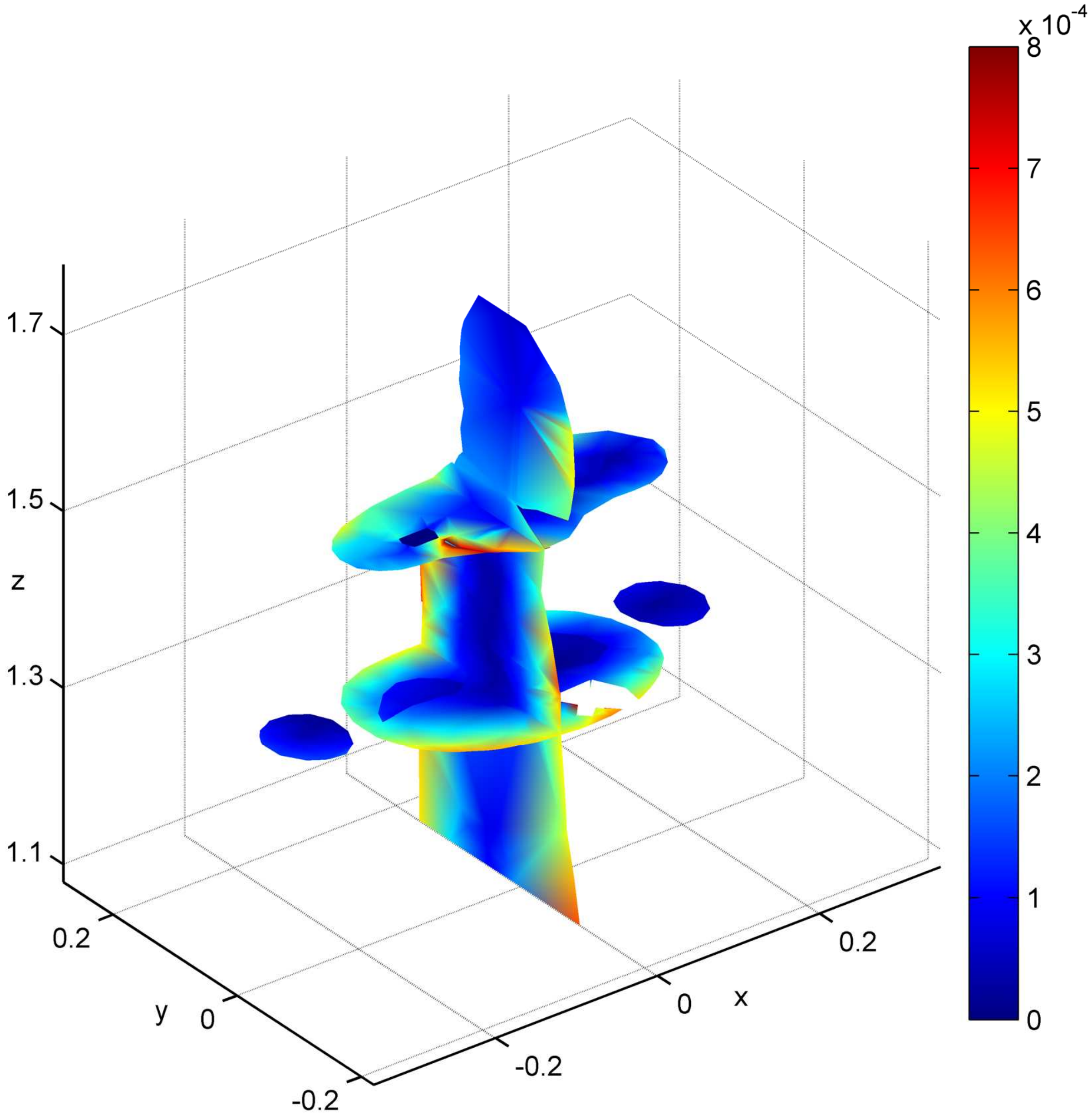


Slika 32: SAR v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju srednjih frekvenc v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini yz pri *x* = 0. V primerjavi s prejšnjo sliko je na tej povečanje SAR tik pod elektrodo bolj opazno. Barvna skala v Wkg^{-1} obsega vrednosti do mejne vrednosti za SAR za celotno telo glede na Smernice ICNIRP.

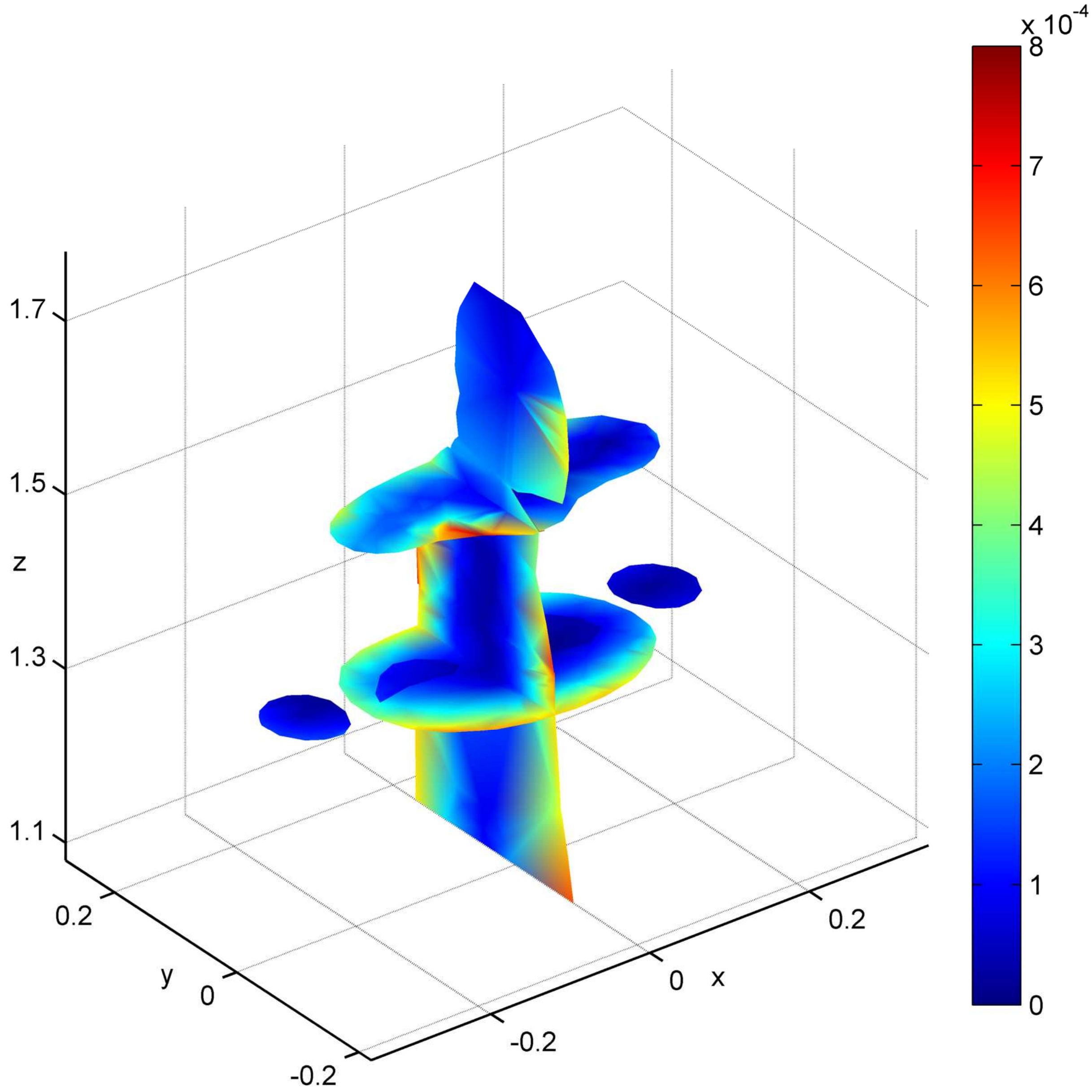


Slika 33: Kvaliteta mreže v modelu (presek na sredini modela, ravnina *yz*, *x* = 0). Bliže kot je vrednosti 1 (rdeča barva), kvalitetnejši je element (bolj je podoben enakostraničnemu tetraedru). Mreža je občutno slabše kvalitete v primerjavi z modelom v nizkofrekvenčnem elektromagnetnem polju (Slika 21). V predelu pred glavo so elementi ob glavi slabe kvalitete, poleg tega pa segajo od zunanjega roba (površine kvadra) do površine modela človeškega telesa (kože). Kvalitetnejše mreže v modelu ni bilo mogoče zgraditi, ker bi sicer vsebovala preveč elementov in bi izračun ne bil mogoč.

Kljub precej nižjim vrednostim barvne skale na Sliki 32 v primerjavi s Sliko31, je večina modela tudi na Sliki 32 še vedno modra, kar pomeni, da je SAR majhen. Na Sliki 34 in Sliki 35, kjer primerjamo porazdelitev SAR v modelu z implantom (Slika 34) in v modelu brez implanta (Slika 35) smo nastavili takšno skalo, da se razločno vidi, kakšna je vrednost SAR v modelu. Na obeh slikah lahko opazimo, da je vrednost SAR manjša od 0.0008 Wkg^{-1}, izjema je le Slika 34, kjer je v bližini konice elektrod SAR precej večji od 0.0008 Wkg^{-1}. Iz primerjave Slik 31 in 34 vidimo, da je vpliv implanta zelo omejen, saj je kljub 100 krat nižjm vrednostim barvne skale na Sliki 34 v primerjavi s Sliko 32 območje, kjer je presežena najvišja vrednost, na obeh slikah približno enako veliko.



Slika 34: SAR v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju srednjih frekvenc v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini yz pri *x* = 0. Barvna skala je v Wkg^{-1}.



Slika 35: Enako kot Slika 34, le da je na tej sliki predstavljena SAR v modelu brez implanta. Porazdelitev SAR se v območjih, ki niso v neposredni bližini implanta, vidno ne razlikuje.

Na osnovi rezultatov modela smo določili največjo povprečno vrednost SAR v 10 gramih tkiva v območju kjer se končuje elektroda. To je tudi mesto, kjer je v celotnem modelu dosežena največja vrednost SAR. Povprečna vrednost v 10 gramih tkiva znaša 0.27 Wkg^{-1}, kar pomeni, da je 7 krat nižja od mejna vrednost (*basic restrictions*) Smernic ICNIRP za prebivalstvo, ki znaša 2 Wkg^{-1}. V modelu brez implanta znaša povprečna vrednost SAR v 10 gramih tkiva na istem mestu 0.00035 Wkg^{-1}, kar pomeni, da je implant povzročil približno 1000 kratno povečanje gostote toka v tkivu v bližini implanta. V bližini srčenga spodbujevalnika ni opaznega povečanja povprečne vrednosti SAR v 10 gramih tkiva, saj znaša v modelu z in brez srčnega spodbujevalnika enako, in sicer 0.00025 Wkg^{-1}.

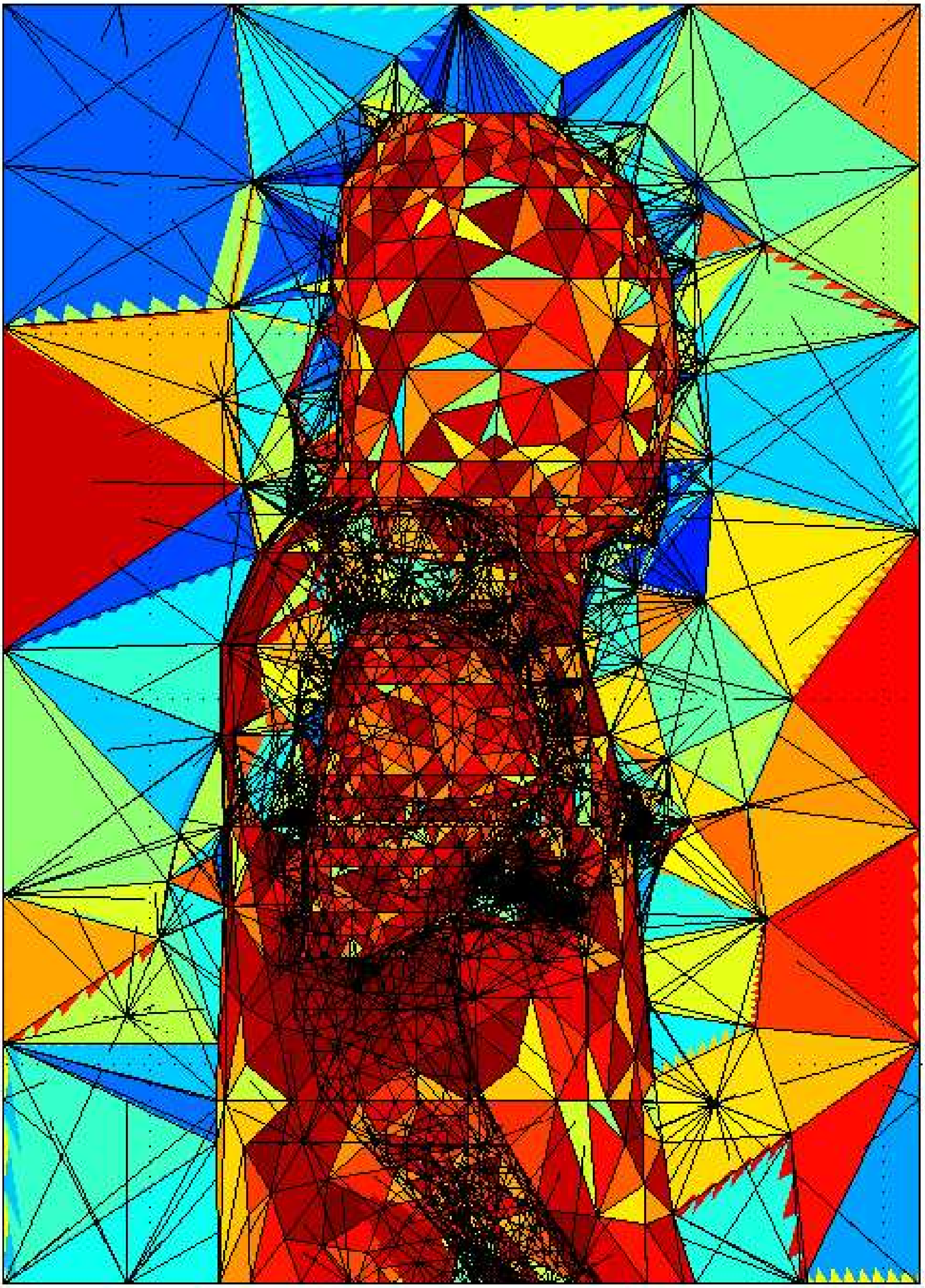
7 Vpliv srčnega spodbujevalnika v elektromagnetnem polju visokih frekvenc

7.1 Geometrija modela

V prejšnjem poglavju je bil predstavljen model človeškega telesa s srčnim spodbujevalnikom, izpostavljen elektromagnetnemu polju srednjih frekvenc, in sicer 27 MHz. V tem poglavju je predstavljen model, ki je osnovan na isti geometriji, z njegovo pomočjo pa smo določili vpliv srčnega spodbujevalnika in elektrod na porazdelitev SAR v človeku, izpostavljenem elektromagnetnemu polju visokih frekvenc, in sicer 900 MHz. Za določanje vpliva srčnega spodbujevalnika in elektrod na porazdelitev SAR smo se podobno kot v modelu srednjih frekvenc odločili zato, ker je SAR tista večina, ki jo Smernice ICNIRP na tem frekvenčnem območju omejujejo. Ker je geometrija modela popolnoma enaka kakor v modelu srednjih frekvenc, je tu ne bomo podrobneje predstavili.

7.2 Mreža

Podobno kakor v modelu, opisnem v prejšnjem poglavju, smo tudi v tem modelu uporabili direktni algoritem, le da je bil izračun opravljen za elektromagnetno polje in ne kvazistatično elektromagnetno polje. Ker se pri izračunu kvazistatičnega elektromagnetnega polja izračunavajo štiri spremenljivke: skalarni električni potenical (ena spremenljivka) ter vektrorski magnetni potencial (tri spremenljivke), pri elektromagnetnem polju pa v enem koraku le tri spremenljivke (električna poljska jakost), smo v tem modelu lahko zgradili mrežo z več vozlišči kot v modelu pri 27. MHz. Mreža je imela 59299 vozlišči, tako da je model imel 70116 prostostnih stopenj. Za takšno mrežo so bili uporabljeni naslednji parametri algoritma za generiranje mreže: (/ 2.3 2.6 0.6 0.039). Mreža je v tem modelu bolj kvalitetna, kar je razvidno tudi iz primerjave Slik 36 in 33, kjer je na prvi predstavljena kvaliteta mreže v modelu pri 900 MHz, v drugi pa v modelu pri 27 MHz.



Slika 36: Kvaliteta mreže v modelu (presek na sredini modela, ravnina *yz*, *x* = 0). Bliže kot je vrednosti 1 (rdeča barva), kvalitetnejši je element (bolj je podoben enakostraničnemu tetraedru). Mreža je občutno boljše kvalitete v primerjavi z modelom pri 27 MHz (Slika 33).

7.3 Lastnosti snovi

V Tabeli 10 so predstavljene dielektrične lastnosti snovi, pomembnih za model človeškega telesa s srčnim spodbujevalnikom. Od vrednosti pri 27 MHz se razlikejejo le dielektrične lastnosti tkiv, saj je specifična prevodnost vseh tkiv, še posebej pljuč, pri 900 MHz večja kot pri 27 MHz, dielektričnost pa je pri 900 MHz manjša. V modelu smo za mehko tkivo uporabili vrednosti $\sigma = 1\ \mathrm{Sm}^{-1}$ in $\varepsilon = 50$, za pljuča pa vrednosti $\sigma = 0.9\ \mathrm{Sm}^{-1}$ in $\varepsilon = 80$. Srca in krvi v model nismo vključili.

Tabela 10: Lastnosti snovi, pomembnih za model človeka izpostavljenega elektromagnetnemu polju visokih frekvenc (900 MHz)

Material	σ (Sm^{-1})	ε_r	μ_r	vir
mehko tkivo	0.6 – 1.2	30 - 70	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
srce	0.9 - 1.2	40 – 70	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
kri	1 – 1.2	50 – 80	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
pljuča	0.9 – 1	70 – 90	1	Gabriel *et al*,. 1996a, Gabriel *et al.*, 1996b
zrak	0	1	1	COMSOL Multiphysics, vakuum
elektrode	18000	1	1	Medtronic, 2001
izolacija elektrod	10^{-12}	12.1	1	COMSOL Multiphysics, silikon
spodbujevalnik	4032000	1	1	COMSOL Multiphysics, jeklo

7.4 Fizikalna narava modela in robni pogoji

Kakor smo že omenili, smo v tem modelu namesto kvazistatičnega elektromagnetnega polja izračunali elektromagnetno polje. To je potrebno, saj valovna dolžina ni več nekajkrat večja od dimenzij modela, ampak je celo manjša od dimenzij modela. Pri izračunu harmoničnega elektromagnetnega polja je potrebno izračunati električno poljsko jakost $\vec{E}$ in magnetno poljsko jakost $\vec{H}$. Elektromagnetno polje v snovi opisujejo Maxwellove enačbe:

$$\nabla \times \vec{H} = \vec{J}_{prosti} + \frac{\partial \vec{D}}{\partial t}, \tag{7.1}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \tag{7.2}$$

$$\nabla \cdot \vec{B} = 0, \tag{7.3}$$

$$\nabla \cdot \vec{E} = \rho_{prosti}, \tag{7.4}$$

V odsotnosti virov električnega polja velja približek gostote električnega toka v obliki Ohmovega zakona [Sinigoj, 1996]:

$$\vec{J}_{kond} = \sigma \vec{E} \, , \tag{7.5}$$

Če se nahajamo v snovi, kjer ni konvektivnega toka $\vec{J}_{konv}$, velja, da je $\vec{J}_{prosti} = \vec{J}_{kond}$, saj velja:

$$\vec{J}_{prosti} = \vec{J}_{kond} + \vec{J}_{konv} \, , \tag{7.6}$$

zato lahko Amperov zakon (7.1) zapišemo kot

$$\nabla \times \vec{H} = \sigma \vec{E} + \frac{\partial \varepsilon \vec{E}}{\partial t} \, . \tag{7.7}$$

Za harmonično elektromagnetno polje velja, da je

$$\vec{E}(x,y,z,t) = \mathrm{Re}(\underline{\vec{E}} \cdot e^{j\omega t}) \, , \tag{7.8}$$

$$\vec{H}(x,y,z,t) = \mathrm{Re}(\underline{\vec{H}} \cdot e^{j\omega t}) \, . \tag{7.9}$$

Enačbi (7.8) in (7.9) vnesemo v enačbi (7.7) in Faradayev zakon (7.2):

$$\nabla \times \underline{\vec{H}} = \sigma \underline{\vec{E}} + j\omega\varepsilon \underline{\vec{E}} \, , \tag{7.10}$$

$$\nabla \times \underline{\vec{E}} = -j\omega\mu \underline{\vec{H}} \, . \tag{7.11}$$

Če iz ene izmed enačb (7.10) ali (7.11) izrazimo eno izmed spremeljivk in jo vstavimo v drugo, lahko zapišemo enačbo za električno poljsko jakost ali magnetno poljsko jakost. Želeli smo dobiti enačbo za elektročno poljsko jakost, zato smo iz enačbe (7.11) izrazili magnetno poljsko jakost in jo vstavili v enačbo (7.10). Dobimo

$$\underline{\vec{H}} = \frac{\nabla \times \underline{\vec{E}}}{-j\omega\mu} \tag{7.12}$$

in to vstavimo v enačbo (7.10):

$$\nabla \times \mu^{-1} \left(\nabla \times \underline{\vec{E}} \right) + (j\omega\sigma - \omega^2 \varepsilon) \underline{\vec{E}} = 0 \, , \tag{7.13}$$

Enačba (7.13) skupaj s preostalima dvema Maxwellovima enačbama (7.3) in (7.4), ob pogoju da ni presežka prostih elektronov v snovi, predstavlja sistem enačb, ki ga COMSOL Multiphysics v primeru harmoničnega elektromagnetnega polja računa [COMSOL AB., 2005]:

$$\nabla\times\mu^{-1}\left(\nabla\times\underline{\vec{E}}\right)+(j\omega\sigma-\omega^{2}\varepsilon)\underline{\vec{E}}=0\,, \tag{7.13}$$

$$\nabla\cdot\underline{\vec{H}}=0\,, \tag{7.3}$$

$$\nabla\cdot\underline{\vec{E}}=0\,, \tag{7.4}$$

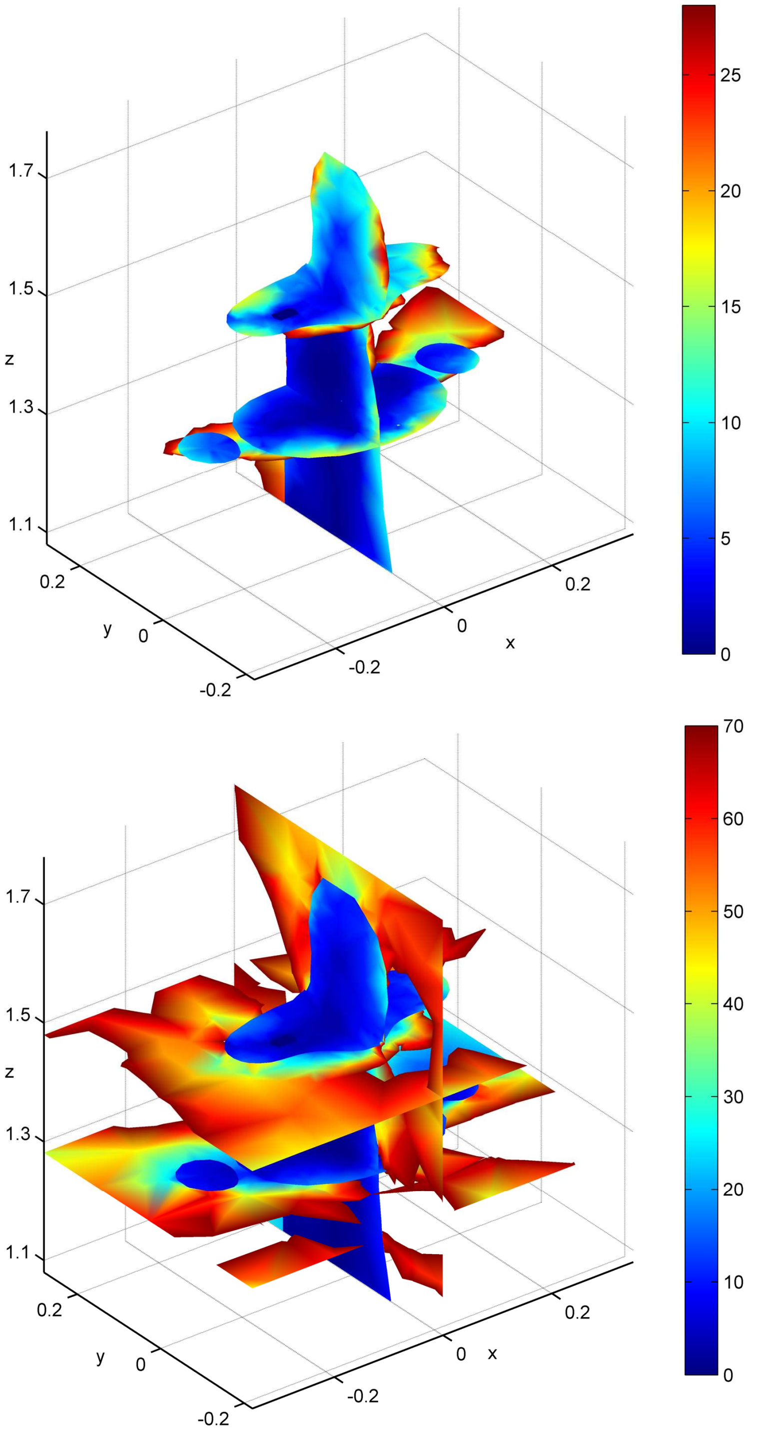
Po teh enačbah se izračuna električna poljska jakost, magnetna poljska jakost pa se nato izračuna iz dobljene vrednosti električne poljske jakosti po enačbi (7.12).

Za elektromagnetno polje 900 MHz veljajo enake mejne vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo kot pri 27 MHz: mejna vrednost za SAR za celotno telo je 0.08 Wkg^{-1}, lokalna vrednost (povprečje katerihkoli 10 g tkiva) pa znaša 2 Wkg^{-1} za glavo in trup ter 4 Wkg^{-1} za okončine. Za izvedene mejne vrednosti (*reference levels*) Smernic ICNIRP za prebivalstvo velja, da so vrednosti električne poljske jakosti omejene na 41 Vm^{-1}, vrednosti magnetne poljske jakosti na 0.111 Am^{-1} ter gostote pretoka moči na 4.5 Wm^{-2}. Za mejne vrednosti Uredbe za II območje velja, da so vrednosti električne poljske jakosti omejene na 12.9 Vm^{-1}, vrednosti magnetne poljske jakosti na 0.0345 Am^{-1} ter gostote pretoka moči na 0.45 Wm^{-2}. Pri ostalih modelih smo se držali pravila, da uporabimo mejne vrednosti Uredbe, ki so veljavne v Republiki Sloveniji. Glede na splošno razširjenost Smernic ICNIRP ter odstopanje pri tej frekvenci med mejnimi vrednostmi uredbe ter izvedenimi mejnimi vrednostmi ICNIRP smo se odločili, da za mejno vrednost v modelu uporabimo kar enako vrednost električnega polja kot pri 27 MHz, to je 28 Vm^{-1}, kar je ravno na sredini med mejno vrednostjo po Uredbi in izvedeno mejno vrednostjo Smernic ICNIRP. Za magnetno polje se robnih pogojev ne da nastavljati, saj se pri elektromagnetnem polju ena izmed veličin izračunava neposredno, druga pa s pomočjo prve. Glede na naravo model smo se seveda odločili, da se neposredno izračunava električna poljska jakost.

Na eni izmed stranic kvadra v ravnini *xy* smo za robne pogoje določili električno poljsko jakost v smeri *z*, na vseh drugih stranicah pa smo določili robni pogoj idealen magnetni prevodnik, zaradi česar je tangenicalna komponenta magnetne poljske jakosti na teh stranicah enaka 0.

7.5 Rezultati in razprava

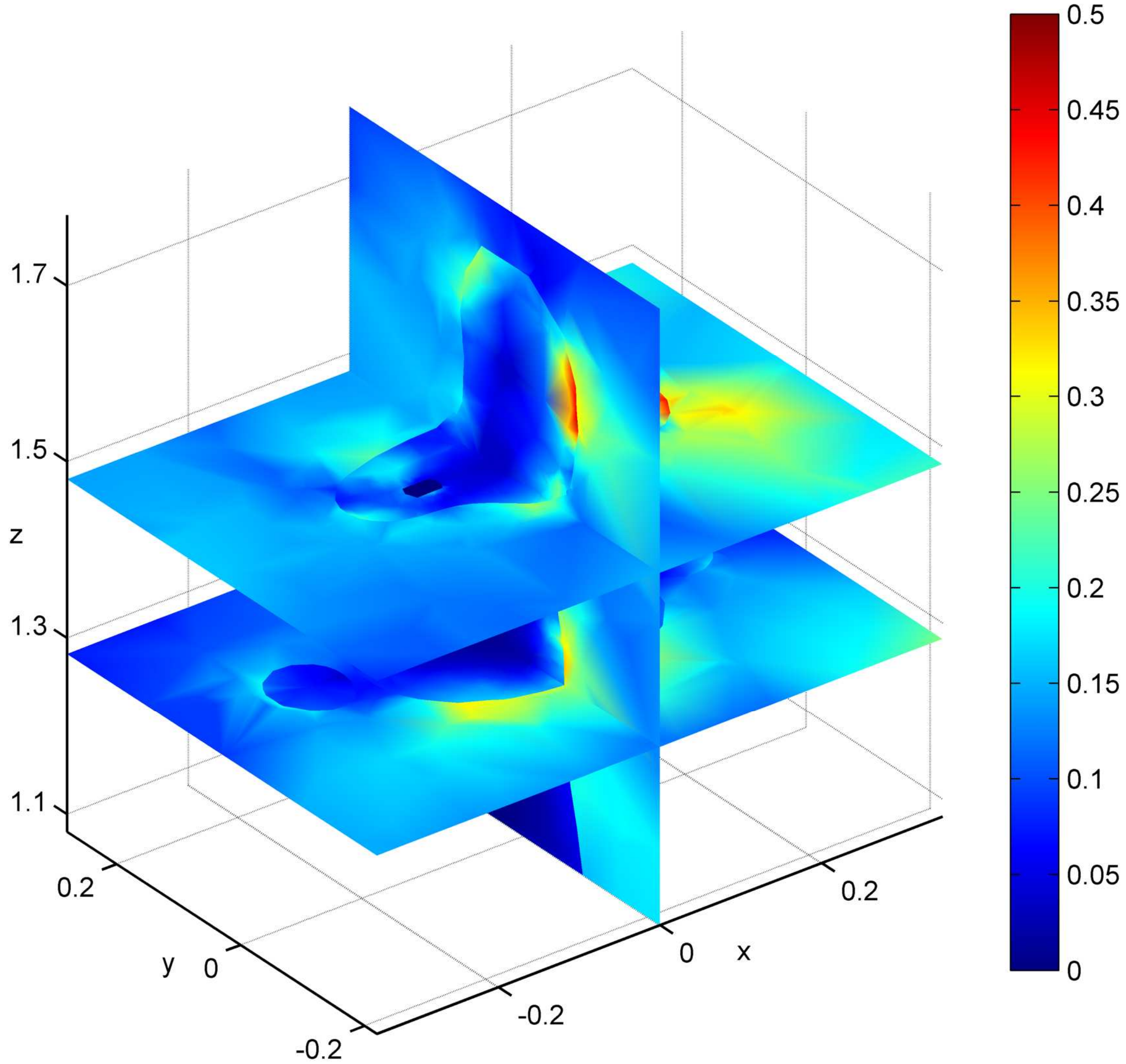
V modelu človeškega telesa, izpostavljenega elektromagnetnemu polju visokih frekvenc smo izračunali porazdelitev elektromagnetnega polja. Električna poljska jakost v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini yz pri *x* = 0 je predstavljena na Sliki 37 in sicer za barvni skali, enaki kot Sliki 30.



Slika 37: Električna poljska jakost v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju visokih frekvenc v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini *yz* pri *x* = 0. Barvni skali sta enaki kot na Sliki 30.

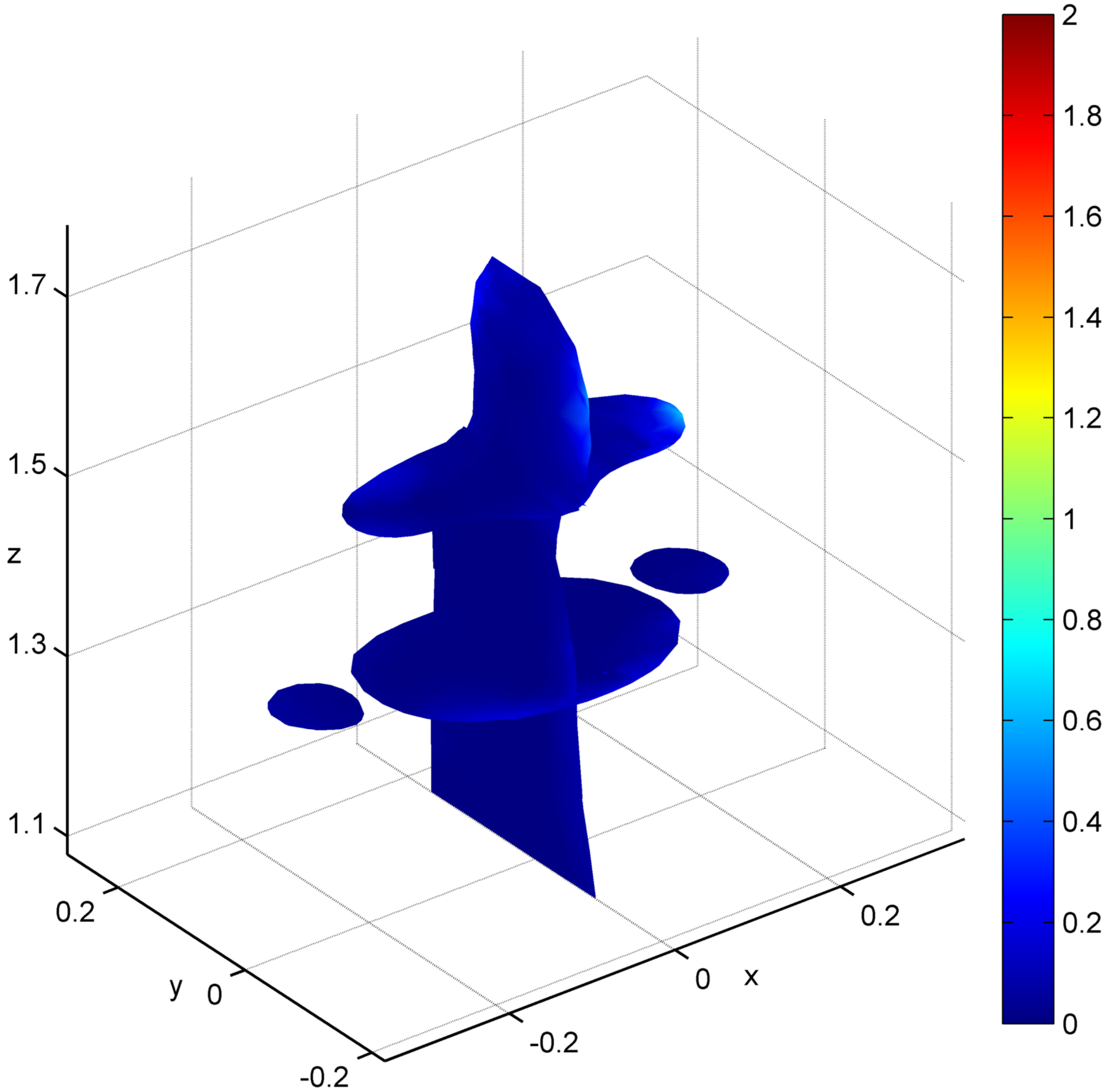
Iz rezultatov na Sliki 37 je razvidno, da se pojavljajo različne ojačitve in oslabitve v porazdelitvi električne poljske jakosti, ki nimajo več povezave zgolj z dielektričnimi lastnostmi snovi v modelu, ampak so to že pojavi zaradi harmoničnega elektromagnetnega polja v modelu. Prav tako je opazno, da je električna poljska jakost znotraj človeka zelo majhna.

Iz Slike 38, kjer je predstavljena magnetna poljska jakost v modelu v ravninah *xy* pri z = 1.282 ter 1.48 ter ravnini yz pri $x = 0$ pa je razvidno, da se magnetna poljska jakost v modelu občutno spreminja, četudi so feromagnetne lastnosti snovi v modelu homogene. Razlika s Sliko 29, kjer je predstavljena magnetna poljska jakost pri 27 MHz je očitna.

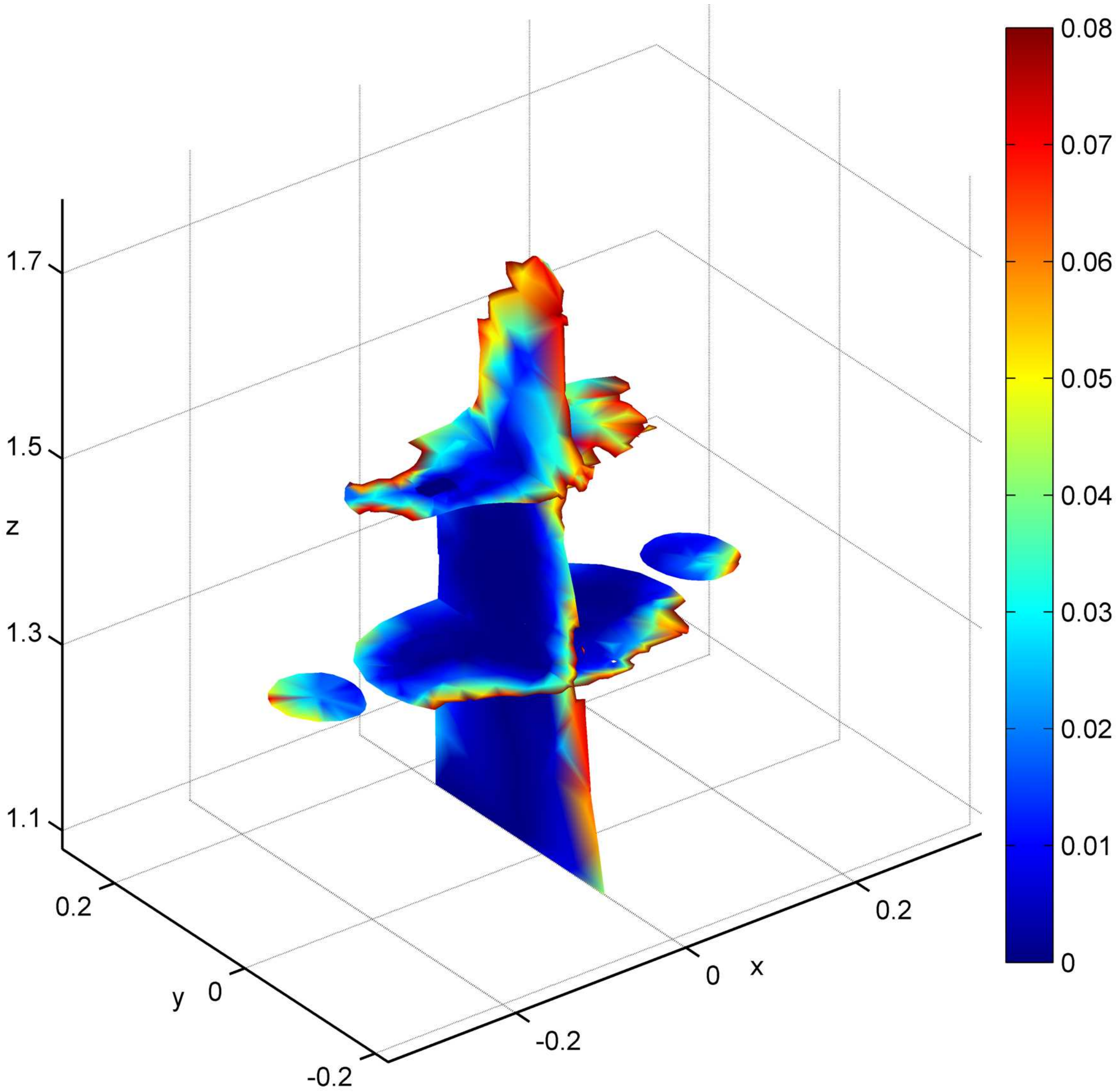


Slika 38: Magnetna poljska jakost v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju srednjih frekvenc v ravninah *xy* pri z = 1.282 ter 1.48 ter ravnini *yz* pri $x = 0$. Barvna skala v Am^{-1} sega do 0.5, mejna vrednost po Uredbi za II. območje je 0.0345 Am^{-1}, izvedena mejna vrednost Smernic ICNIRP za prebivalstvo pa znaša 0.111 Am^{-1}.

Na Sliki 39 je predstavljena porazdelitev SAR v modelu človeškega telesa. Barvna skala zavzema vrednosti do mejni vrednosti Smernic ICNIRP za prebivalstvo za lokalni SAR, ki znaša 2 Wkg^{-1}. V levem predelu spodnje prerezne ravnine, ki je tik pod koncem elektrode, na Sliki 39 ni opaziti povečanja SAR v okolici tik pod elektrodo, kakor je bilo to opaziti na Sliki 31, kar pomeni, da je vpliv srčnega spodbujevalnika in elektrod pri višjih frekvencah manjši.



Slika 39: SAR v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju visokih frekvenc v ravninah *xy* pri *z* = 1.282 ter 1.48 ter ravnini *xz* pri *x* = 0. Barvna skala v Wkg^{-1} obsega vrednosti do mejne vrednosti za lokalni SAR glede na Smernice ICNIRP za prebivalstvo.



Slika 40: SAR v modelu človeškega telesa s srčnim spodbujevalnikom v elektromagnetnem polju visokih frekvenc v ravninah *xy* pri $z = 1.282$ ter 1.48 ter ravnini *yz* pri $x = 0$. Barvna skala v Wkg^{-1} obsega vrednosti do mejne vrednosti za SAR za celotno telo glede na Smernice ICNIRP za prebivalstvo.

Vrednosti SAR so v 900 MHz modelu večje kot v 27 MHz modelu, kar je razvidno iz primerjave Slik 31 in 40, na katerih je prikazan SAR z barvno skalo, ki obsega vrednosti do mejne vrednosti za SAR za celotno telo glede na Smernice ICNIRP za prebivalstvo. Vendar je vpliv srčnega spodbujevalnika in elektrod na porazdelitev mnogo manjši in je šele na zadnji sliki komaj opazen, medtem ko je bil pri 27 MHz opazen že na Sliki 31, kjer je prikazan SAR z barvno skalo, ki obsega vrednosti do mejne vrednosti za lokalni SAR.

Določili smo največjo povprečno vrednost SAR v 10 gramih tkiva v območju, kjer se končuje elektroda ter v bližini srčnega podbujevalnika. Tako v modelu brez implanta kot tudi v modelu z implantom so bile povprečne vrednosti v 10 gramih tkiva zelo podobne in so znašale 0.015 Wkg^{-1}, kar je več kot 100 krat manj kot znaša mejna vrednost (*basic restrictions*) Smernic ICNIRP za prebivalstvo, ki znaša 2 Wkg^{-1}. Sicer je v neposredni okolici konca elektrode opaziti povečanje vrednosti SAR, ki doseže do 0.2 Wkg^{-1}, kar pa je vrednost SAR dosežena tudi v na nekaterih zunanjih predelih modela človeškega telesa.

8 Zaključek

V modelu človeškega telesa, izpostavljenega elektromagnetnemu polju nizkih (50 Hz), srednjih (27 MHz) in visokih (900 MHz) frekvenc smo izračunali porazdelitev elektromagnetnega polja. Vir elektromagnetnega polja v modelu je bil izbran tako, da je bila jakost elektromagnetnega polja v območju, kjer se je nahajal model človeškega telesa, zelo blizu mejnim vrednostim Uredbe.

Model človeškega telesa, izpostavljen elektromagnetnemu polju nizkih frekvenc, je vključeval mehko tkivo, ki ga je sestavljalo skupaj sedem objektov: glava, zgornji in spodnji del trupa ter po dve roki in nogi. Poleg mehkih tkiv je model vseboval tudi vse večje kosti v eni nogi: stegnenico, pogačico, golen in mečnico. V stegnenico smo dodali še kovinski implant: intramedularni žebelj, ki je eden izmed možnih fiksatorjev pri zlomih votlih kosti. Za intramedularni žebelj smo se odločili, ker je to verjetno največji kovinski implant, ki se ga vstavlja v človeško telo, poleg tega pa ostane v človeškem telesu več mesecev. Ostalih organov človeškega telesa v model nismo vključili, ker bi to onemogočilo reševanje modela, saj je bila gradnja mreže že v tako poenostavljenem modelu zahtevna. Poleg tega so drugi organi večinoma oddaljeni od noge in na rezultat ne bi imeli velikega vpliva. Edini organ, ki bi na prvi pogled lahko bil pomemben, je koža. Ta namreč pokriva celotno človeško telo. Ker je njena prevodnost zelo majhna v primerjavi s prevodnostjo drugih telesnih tkiv, je pomembna v primeru, ko prihaja do kontaktnega toka. Vendar je zrak v modelu neprevoden, model človeškega telesa pa lebdi nekaj centimetrov nad tlemi in je zato model človeškega telesa izoliran od tal. Ker električna prevodnost kože ni pomembna, in ker tudi relativna dielektričnost kože ni pomembna, saj je glede na literaturo [Gabriel et al,. 1996a] podobna relativni dielektričnosti ostalih tkiv, kože v takšen model ni potrebno vključiti. Če pa bi model človeškega telesa ozemljili, bi bila vloga kože pomembna na območju, kjer bi se model dotikal tal. Za izolirani model človeškega telesa smo se odločili, ker je običajno človek obut v slabo prevodno obuvalo, tako da je izolirani model človeka ustrezen približek.

Model človeškega telesa izpostavljen elektromagnetnemu polju srednjih in visokih frekvenc je bil sestavljen iz glave, zgornjega in spodnjega dela trupa, zgornjega dela rok in pljuč. Za vključitev pljuč smo se odločili, ker je njihova specifična prevodnost manjša od specifične prevodnosti okoliških tkiv. Na podlagi CT slik bolnice z vstavljenim srčnim spodbujevalnikom smo zgradili model elektrod in spodbujevalnika ter oboje po predhodni poravnavi z modelom človeškega telesa vstavili v model. Izračune smo opravili pri 27 MHz, kar ustreza frekvenci, pogosto uporabljeni v industriji, ter 900 MHz, kar ustreza frekvenci mobilnih omrežij.

Iz rezultatov je razvidno, da tako intramedularni žebelj kot tudi srčni spodbujevalnik z elektrodami povzročita povečanje elektromagnetnega polja na omejenem območju v modelu. Tako je gostota toka na mestu, kjer intramedularni žebelj izstopa iz kosti izrazito povečana, saj kljub izpolnjenim mejnim vrednostim Uredbe za II. območje gostota toka preseže mejne vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo. Po drugi strani je področje, kjer pride do izrazitega povečanja gostote toka omejeno na nekaj kubičnih centimetrov. Iz primerjave rezultatov modela z implantom in brez implanta ni opaznih sprememb v porazdelitvi gostote toka v ostalih delih telesa, le v nogi z implantom je gostota toka nekoliko manjša kot v odgovarjajoči nogi v modelu brez implanta. Vzrok je v dobri prevodnosti implanta, kar povzroči, da več toka teče po implantu in manj po tkivu ob njem. Ravno zaradi tega pa je ob koncu implanta gostota toka povečana. Opaznih sprememb v porazdelitvi gostote toka v drugih delih telesa ni. Podobno velja za srčni spodbujevalnik, saj je na koncu elektrod SAR občutno povečan, a ne preseže mejnih vrednosti Smernic ICNIRP. Vpliv implanta je pri višji frekvenci še manjši, saj se z višanjem frekvence manjša vdorna globina elektromagnetnega polja.

Dosedanji rezultati nakazujejo nadaljnje možnosti za izračune, in sicer je poleg različnih implantov mogoče izvesti več parametrizacij: glede na prevodnost implanta, glede na specifične prevodnosti in dielektričnosti tkiva; glede na frekvenco elektromagnetnega polja predvsem v območjih resonanc, lahko bi spreminjali orientacijo elektromagnetnega polja v modelu ter izračune opravili za ozemljene modele človeškega telesa.

Na podlagi rezultatov lahko potrdimo, da kovinski implanti pomembno vplivajo na porazdelitev elektromagnetnega polja v človeku. V določeni kombinaciji elektromagnetnega polja in implanta so kljub izpolnjenim mejnim vrednostim Uredbe za II. območje presežene mejne vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo. Vgotavljanje, ali to preseganje lahko predstavlja nevarnost za človeški organizem bi bilo glede majhno število različnih izračunanih kombinacij elektromagnetnih polj in implantov neverodostojno.

Razumevanje vpliva prevodnih implantov na porazdelitev elektromagnetnega polja v človeku je kompleksno in vsekakor ni namenjeno širšemu prebivalstvu. Vendar bi bilo potrebno in primerno tako zdravnike, ki se ukvarjajo z vstavljanjem takšnih implantov, kakor tudi bolnike, ki kovinske implante prejmejo, informirati o tem vplivu. V primeru srčnih spodbujevalnikov so bolniki o vplivu elektromagnetnih polj informirani, predvsem zaradi preprečevanja elektromagnetnih motenj in zagotavljanja elektromagnetne kompatibilnosti srčnega spodbujevalnika. V primeru drugih kovinskih implantov bolniki običajno niso informirani o njihovem vplivu na porazdelitev elektromagnetnega polja ter možnem lokalnem preseganju mejnih vrednosti (*basic restrictions*) Smernic ICNIRP za prebivalstvo.

9 Izvirni prispevki k razumevanju ožjega znanstvenega področja

9.1 Numerični izračuni elektromagnetnih polj v modelu človeka z upoštevanjem implantov

S pomočjo programskega paketa COMSOL Multiphysics smo zgradili model človeškega telesa z implantom. Geometrija modelov temelji na slikah iz baze VHDS ter slik, posnetih na bolnicah v okviru običajnega postopka zdravljenja. Slike smo digitalizirali in obdelali, tako da smo določili robove mehkih tkiv, kosti in implanta. Temu je sledila gradnja tridimenzionalne geometrije, kjer smo posebno pozornost namenili iskanju prave meje med ustrezno podrobnostjo in natančnostjo geometrije ter primerno preprostostjo modela, ki ga je bilo še mogoče rešiti. Celotna velikost modela je namreč omejena z zmogljivostjo algoritma za gradnjo mreže in računskimi zmogljivostmi računalnika. Lastnosti snovi v modelu smo določili na podlagi literature [Gabriel et al,. 1996a, Gabriel et al., 1996b], z robnimi pogoji v modelu pa določili razmere, kot jih lahko v najslabšem primeru pričakujemo v okolju.

9.2 Ovrednotenje vpliva implantov na povečanje elektromagnetnega polja v človeku

Biološki učinki elektromagnetnega polja na človeka so odvisni od gostote toka v tkivu, gostote magnetnega pretoka in specifične stopnje absorpcije (SAR), ki pove, kakšna je absorbirana moč elektromagnetnega polja na kilogram tkiva. Standardi, ki omejujejo jakost elektromagnetnega polja v življenjskem okolju, npr. Uredba o elektromagnetnem sevanju v naravnem in življenjskem okolju [Uradni list RS, 70/96] ali Priporočila 1999/519/EC Sveta Evrope Council recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz) [Official Journal of the Europena Communities, 59/1999] temeljijo na do sedaj poznanih škodljivih bioloških učinkih elektromagnetnega polja na človeka in omejujejo zunanje elektromagnetno polje na takšno vrednost, da je elektromagnetno polje v človeškem telesu nekajkrat nižje od praga, ki povzroči škodljive biološke učinke. Vendar standardi temeljijo na izračunih in meritvah na zdravem človeku brez implantov, zato je mogoče, da v primeru večjih implantov elektromagnetno polje v določenem predelu človeškega telesa preseže prag, ki povzroči škodljive biološke učinke. S primerjavo rezultatov modelov z implantom in brez smo ocenili vpliv implantov na povečanje tistih veličin elektromagnetnega polja, ki so pomembna za biološke učinke. Pri tem smo opazovali predvsem gostoto toka v tkivu ter SAR, ter območje v tkivu, kjer zaradi implanta gostota toka ali vrednost SAR preseže mejne vrednosti (*basic restrictions*), določene v Smernicah ICNIRP in Priporočilih 1999/519/EC.

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11 Dodatki

11.1 Program za gradnjo tridimenzionalne geometrije

```
function lg = gradnja(n)
% function lg = gradnja(n)
% funkcija iz slik v trenutni mapi zgradi geometrijo za COMSOL Multiphysics
% n je stevilo tock na vsaki krivulji
% Blaz Valic 16. 12. 2005

d=dir('*.tif');
d=d(length(d):-1:1); % obrni vrstni red, da so v vektorju najprej slike, ki
% lezijo najnizje a imajo zaradi nacina stevilcenja najvisje vrednosti

for i=1:length(d)
    slika=imread(d(i).name); % preberi sliko
    polozajZ(i)=2.730-str2num(d(i).name(4:7))/1000;
    % iz imena datoteke doloci njeno lego nad nivojem 0
    slika=(255-slika); % obrni vrednosti za belo iz 1 1 1 v 0 0 0
    slika=slika-10;
    % odstej zelo nizke vrednosti, ki so posledica napake zaradi stiskanja
    slika=slika(:,:,1)+slika(:,:,2)+slika(:,:,3);
    % sestej vse barve med seboj, da dobis cb sliko
    slika=slika(1:3:size(slika,1),1:3:size(slika,2));
    % iz slike vzemi vsako tretjo vrstico in stolpec, da bo locljivost 1 mm
    slika=slika*255; % pomnozi z 255, da dobis 1 bitno sliko
    interval=[0.000001 0.3]; % interval parametra funkcije flim2curv
    % podrobneje razlozeno nizje, parameter ima v lahko vrenosti med 0 in 1
    intervalpovp=sum(interval)/2; % sredina intervala
    [krivulja,r]=flim2curve(slika,{1,[]},'KeepFrac',intervalpovp);
    % prvi parameter je slika, drugi parameter je polje z dvema mestoma
    % {pragovna vrednost vektor vrednosti, pri katerih naj naredi krivulje}
    % cetrti parameter doloca, koliko tock bo imela krivulja
    N=geominfo(krivulja,'out',{'no'},'Od',0);
    % poglej, koliko je tock, ce uporabis za parameter sredino intervala
    while N~=n
        % z bisekcijo poisci tisto vrednost sredine intervala, da bo
        % stevilo tock krivulje enako zeljenemu stevilu tock krivulje
        if N<n
            interval(1)=intervalpovp;
        else
            interval(2)=intervalpovp;
        end
        intervalpovp=sum(interval)/2;
        [krivulja,r]=flim2curve(slika,{1,[]},'KeepFrac',intervalpovp);
        N=geominfo(krivulja,'out',{'no'},'Od',0);
    end
    [pkrivulja{i}]=scale(solid2(krivulja),0.001,0.001);
    % krivuljo pretvori v solid2 objekt in jo skrkaliraj iz mm v m
end

pozicija={[-[1024/3000 608/3000]'*ones(1,length(d)); polozajZ],[],[]};
% struktura, ki doloca, lego in orientacijo posamezne krivulje v prostoru
% prvi element je matrika 2*n, v prvi vrstici je premik slike po x osi,
% v drugi vrstic pa premik po y osi,
% s 3000 delimo da dobimo pozicijo v m (original je tocka velika 0.33 mm)
% drugi element strukture je premik po osi z
% ostala dva elementa strukture dolo•ata nagib krivulje
vozel=num2cell(ones(size(d)))';
% doloca, kateri vozli v krivulji se spajajo med seboj
lg=loft(pkrivulja,'loftedge',vozel,'Loftmethod','linear','loftsecpos',pozicija);
% COMSOL Multiphysics-ova funkcija za zdruzevanje krivulj
```

11.2 Program za gradnjo elektrod

```
function lg = gradnja_lead
% function lg = gradnja_lead
% funkcija iz slik v trenutni mapi zgradi geometrijo elektrod za COMSOL
Multiphysics
% Blaz Valic 21. 4. 2005

d=dir('*.tif');
d=d(length(d):-1:1); % obrni vrstni red, da so v vektorju najprej slike, ki
% lezijo najnizje a imajo zaradi nacina stevilcenja najvisje vrednosti
pixelsize=0.75; % velikost tocke na sliki
scalefactor=0.001*pixelsize; % faktor skaliranja, z 0.001 mnozimo, da dobimo m
r=0.0005;

for i=1:length(d)
    slika=imread(d(i).name); % preberi sliko
    slika=(255-slika); % obrni vrednosti za belo iz 1 1 1 v 0 0 0
    [slika,y]=max(slika);
    Y(i)=(max(y)-256)*scalefactor+0.025; % premik, da se pokrije z VHDS
    [slika,x]=max(slika);
    X(i)=-(x-256)*scalefactor+0.01; % premik, da se pokrije z VHDS
    Z(i)=1.67-str2num(d(i).name(5:8))/4000;
end

d=length(d);

% smerni vektorji posameznih odsekov
nX=X(2:d)-X(1:d-1);
nY=Y(2:d)-Y(1:d-1);
nZ=Z(2:d)-Z(1:d-1);
l=sqrt(nX.^2+nY.^2+nZ.^2); nX=nX./l; nY=nY./l; nZ=nZ./l;

%smerni vektorji ravnin na mestu loma krivulje
nTX=[nX(1) nX(2:d-1)+nX(1:d-2) nX(d-1)];
nTY=[nY(1) nY(2:d-1)+nY(1:d-2) nY(d-1)]+0.001; % mali premik da ni enkrat 0, ker
sicer zarije
nTZ=[nZ(1) nZ(2:d-1)+nZ(1:d-2) nZ(d-1)];
l=sqrt(nTX.^2+nTY.^2+nTZ.^2); nTX=nTX./l; nTY=nTY./l; nTZ=nTZ./l;

% dolocanje 3 tock v ravnini, prva je X Y Z, drugo si izberemo (X2,1,0), tretjo
% izracunamo iz vektorskega produkta
X2=-nTY./nTX;
Y2=ones(1,d);
Z2=zeros(1,d);
l=sqrt(X2.^2+Y2.^2+Z2.^2); X2=X2./l; Y2=Y2./l; Z2=Z2./l;
for i=1:d
    tocke(:,i)=cross([nTX(i) nTY(i) nTZ(i)],[X2(i) Y2(i) Z2(i)]);
end
X3=tocke(1,:); Y3=tocke(2,:); Z3=tocke(3,:);

% izris koordinatnih sistemov v prostoru
for i=1:d
    plot3([X(i) nTX(i)/100+X(i)],[Y(i) nTY(i)/100+Y(i)],[Z(i) nTZ(i)/100+Z(i)]);
    hold on
    plot3([X(i) X2(i)/100+X(i)],[Y(i) Y2(i)/100+Y(i)],[Z(i) Z2(i)/100+Z(i)]);
    plot3([X(i) X3(i)/100+X(i)],[Y(i) Y3(i)/100+Y(i)],[Z(i) Z3(i)/100+Z(i)]);
    axis equal
end
plot3(X,Y,Z,'r');
xlabel('x'); ylabel('y'); zlabel('z');

% tu pa jih pretvorimo v globalne koordinate
X2=X2+X; Y2=Y2+Y; Z2=Z2+Z;
X3=X3+X; Y3=Y3+Y; Z3=Z3+Z;

% preslikam smerni vektor posameznega odseka v koordinatni sistem ravnine
% in izracunam smer projekcije ter dolzino daljse osi elipse
pkrivulja{1}=solid2(circ2(r));
for i=2:d-1
    a(i)=r/dot([nTX(i) nTY(i) nTZ(i)],[nX(i) nY(i) nZ(i)]);
    phi(i)=asin(nX(i)/sqrt(nX(i)^2+nY(i)^2));
```

```
    if nX(i)<0
        phi(i)=phi(i)+sign(nY(i))*pi/2;
    end
    pkrivulja{i}=solid2(circ2(r));
    if (a(i)-r)/r>0.12 % z elipso nadomestimo samo vecja odstopanja
        pkrivulja{i}=solid2(ellip2(a(i), r, 'Rot', -phi(i)));
    end
end
pkrivulja{d}=solid2(circ2(r));

pozicija={[X; Y; Z],[nTX; nTY; nTZ],[]};
% struktura, ki doloca, lego in orientacijo posamezne krivulje v prostoru
% prvi element je matrika 3*n, v prvi vrstici je premik slike po x osi,
% v drugi vrstic pa premik po y osi in thretji premik po osi z
% ostala dva elementa strukture dolo•ata nagib in zasuk krivulje
try, load zamik; zamik=zamik(length(zamik):-1:1); catch, zamik=0; end
vozel=num2cell(ones(d,1)+zamik)'; % preberi zamik za spajanje
% doloca, kateri vozli v krivulji se spajajo med seboj
lg=loft(pkrivulja,'LoftSgnEdge',vozel,'LoftMethod','linear','loftsecpos',pozicija);
% COMSOL Multiphysics-ova funkcija za zdruzevanje krivulj
```

11.3 Smernice ICNIRP

Originalen naslov:

ICNIRP. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74: 494-522.

Slovenski prevod:

Smernice o omejevanju izpostavljenosti elektromagnetnemu sevanju:

Uporabljan izraz v tem dokumentu:

Smernice ICNIRP

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (UP TO 300 GHz)

International Commission on Non-Ionizing Radiation Protection*†

INTRODUCTION

In 1974, the International Radiation Protection Association (IRPA) formed a working group on non-ionizing radiation (NIR), which examined the problems arising in the field of protection against the various types of NIR. At the IRPA Congress in Paris in 1977, this working group became the International Non-Ionizing Radiation Committee (INIRC).

In cooperation with the Environmental Health Division of the World Health Organization (WHO), the IRPA/INIRC developed a number of health criteria documents on NIR as part of WHO's Environmental Health Criteria Programme, sponsored by the United Nations Environment Programme (UNEP). Each document includes an overview of the physical characteristics, measurement and instrumentation, sources, and applications of NIR, a thorough review of the literature on biological effects, and an evaluation of the health risks of exposure to NIR. These health criteria have provided the scientific database for the subsequent development of exposure limits and codes of practice relating to NIR.

At the Eighth International Congress of the IRPA (Montreal, 18–22 May 1992), a new, independent scientific organization—the International Commission on Non-Ionizing Radiation Protection (ICNIRP)—was established as a successor to the IRPA/INIRC. The functions of the Commission are to investigate the hazards that may be associated with the different forms of NIR, develop international guidelines on NIR exposure limits, and deal with all aspects of NIR protection.

Biological effects reported as resulting from exposure to static and extremely-low-frequency (ELF) electric and magnetic fields have been reviewed by UNEP/WHO/IRPA (1984, 1987). Those publications and a number of others, including UNEP/WHO/IRPA (1993) and Allen et al. (1991), provided the scientific rationale for these guidelines.

A glossary of terms appears in the Appendix.

PURPOSE AND SCOPE

The main objective of this publication is to establish guidelines for limiting EMF exposure that will provide protection against known adverse health effects. An adverse health effect causes detectable impairment of the health of the exposed individual or of his or her offspring; a biological effect, on the other hand, may or may not result in an adverse health effect.

Studies on both direct and indirect effects of EMF are described; direct effects result from direct interaction of fields with the body, indirect effects involve interactions with an object at a different electric potential from the body. Results of laboratory and epidemiological studies, basic exposure criteria, and reference levels for practical hazard assessment are discussed, and the guidelines presented apply to occupational and public exposure.

Guidelines on high-frequency and 50/60 Hz electromagnetic fields were issued by IRPA/INIRC in 1988 and 1990, respectively, but are superseded by the present guidelines which cover the entire frequency range of time-varying EMF (up to 300 GHz). Static magnetic fields are covered in the ICNIRP guidelines issued in 1994 (ICNIRP 1994).

In establishing exposure limits, the Commission recognizes the need to reconcile a number of differing expert opinions. The validity of scientific reports has to be considered, and extrapolations from animal experi-

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ments to effects on humans have to be made. The restrictions in these guidelines were based on scientific data alone; currently available knowledge, however, indicates that these restrictions provide an adequate level of protection from exposure to time-varying EMF. Two classes of guidance are presented:

- Basic restrictions: Restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields that are based directly on established health effects are termed “basic restrictions.” Depending upon the frequency of the field, the physical quantities used to specify these restrictions are current density (**J**), specific energy absorption rate (SAR), and power density (S). Only power density in air, outside the body, can be readily measured in exposed individuals.
- Reference levels: These levels are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Some reference levels are derived from relevant basic restrictions using measurement and/or computational techniques, and some address perception and adverse indirect effects of exposure to EMF. The derived quantities are electric field strength (**E**), magnetic field strength (**H**), magnetic flux density (**B**), power density (**S**), and currents flowing through the limbs (I_L). Quantities that address perception and other indirect effects are contact current (I_C) and, for pulsed fields, specific energy absorption (SA). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level. Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.

These guidelines do not directly address product performance standards, which are intended to limit EMF emissions under specified test conditions, nor does the document deal with the techniques used to measure any of the physical quantities that characterize electric, magnetic, and electromagnetic fields. Comprehensive descriptions of instrumentation and measurement techniques for accurately determining such physical quantities may be found elsewhere (NCRP 1981; IEEE 1992; NCRP 1993; DIN VDE 1995).

Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document but is available elsewhere (UNEP/WHO/IRPA 1993).

These guidelines will be periodically revised and updated as advances are made in identifying the adverse health effects of time-varying electric, magnetic, and electromagnetic fields.

QUANTITIES AND UNITS

Whereas electric fields are associated only with the presence of electric charge, magnetic fields are the result of the physical movement of electric charge (electric current). An electric field, **E**, exerts forces on an electric charge and is expressed in volt per meter (V m^{-1}). Similarly, magnetic fields can exert physical forces on electric charges, but only when such charges are in motion. Electric and magnetic fields have both magnitude and direction (i.e., they are vectors). A magnetic field can be specified in two ways—as magnetic flux density, **B**, expressed in tesla (T), or as magnetic field strength, **H**, expressed in ampere per meter (A m^{-1}). The two quantities are related by the expression:

$$\mathbf{B} = \mu\mathbf{H}, \tag{1}$$

where μ is the constant of proportionality (the magnetic permeability); in a vacuum and in air, as well as in non-magnetic (including biological) materials, μ has the value $4\pi \times 10^{-7}$ when expressed in henry per meter (H m^{-1}). Thus, in describing a magnetic field for protection purposes, only one of the quantities **B** or **H** needs to be specified.

In the far-field region, the plane-wave model is a good approximation of the electromagnetic field propagation. The characteristics of a plane wave are:

- The wave fronts have a planar geometry;
- The **E** and **H** vectors and the direction of propagation are mutually perpendicular;
- The phase of the **E** and **H** fields is the same, and the quotient of the amplitude of E/H is constant throughout space. In free space, the ratio of their amplitudes E/H = 377 ohm, which is the characteristic impedance of free space;
- Power density, **S**, i.e., the power per unit area normal to the direction of propagation, is related to the electric and magnetic fields by the expression:

$$\mathbf{S} = \mathbf{EH} = \mathrm{E}^2/377 = 377\mathrm{H}^2. \tag{2}$$

The situation in the near-field region is rather more complicated because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation as they do in the far field. In the near field, the electromagnetic field structure may be highly inhomogeneous, and there may be substantial variations from the plane-wave impedance of 377 ohms; that is, there may be almost pure E fields in some regions and almost pure H fields in others. Exposures in the near field are

Table 1. Electric, magnetic, electromagnetic, and dosimetric quantities and corresponding SI units.

Quantity	Symbol	Unit
Conductivity	σ	siemens per meter (S m^{-1})
Current	I	ampere (A)
Current density	$\mathbf{J}$	ampere per square meter (A m^{-2})
Frequency	f	hertz (Hz)
Electric field strength	$\mathbf{E}$	volt per meter (V m^{-1})
Magnetic field strength	$\mathbf{H}$	ampere per meter (A m^{-1})
Magnetic flux density	$\mathbf{B}$	tesla (T)
Magnetic permeability	μ	henry per meter (H m^{-1})
Permittivity	ϵ	farad per meter (F m^{-1})
Power density	$\mathbf{S}$	watt per square meter (W m^{-2})
Specific energy absorption	SA	joule per kilogram (J kg^{-1})
Specific energy absorption rate	SAR	watt per kilogram (W kg^{-1})

more difficult to specify, because both E and H fields must be measured and because the field patterns are morecomplicated; in this situation, power density is no longer an appropriate quantity to use in expressing exposure restrictions (as in the far field).

Exposure to time-varying EMF results in internal body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. The internal electric field and current density are related by Ohm's Law:

$$\mathbf{J} = \sigma \mathbf{E}, \qquad (3)$$

where σ is the electrical conductivity of the medium. The dosimetric quantities used in these guidelines, taking into account different frequency ranges and waveforms, are as follows:

- Current density, **J**, in the frequency range up to 10 MHz;
- Current, *I*, in the frequency range up to 110 MHz;
- Specific energy absorption rate, SAR, in the frequency range 100 kHz–10 GHz;
- Specific energy absorption, SA, for pulsed fields in the frequency range 300 MHz–10 GHz; and
- Power density, **S**, in the frequency range 10–300 GHz.

A general summary of EMF and dosimetric quantities and units used in these guidelines is provided in Table 1.

BASIS FOR LIMITING EXPOSURE

These guidelines for limiting exposure have been developed following a thorough review of all published scientific literature. The criteria applied in the course of the review were designed to evaluate the credibility of the various reported findings (Repacholi and Stolwijk 1991; Repacholi and Cardis 1997); only established effects were used as the basis for the proposed exposure restrictions. Induction of cancer from long-term EMF exposure was not considered to be established, and so these guidelines are based on short-term, immediate health effects such as stimulation of peripheral nerves and muscles, shocks and burns caused by touching conducting objects, and elevated tissue temperatures resulting from absorption of energy during exposure to EMF. In the case of potential long-term effects of exposure, such as an increased risk of cancer, ICNIRP concluded that available data are insufficient to provide a basis for setting exposure restrictions, although epidemiological research has provided suggestive, but unconvincing, evidence of an association between possible carcinogenic effects and exposure at levels of 50/60 Hz magnetic flux densities substantially lower than those recommended in these guidelines.

In-vitro effects of short-term exposure to ELF or ELF amplitude-modulated EMF are summarized. Transient cellular and tissue responses to EMF exposure have been observed, but with no clear exposure-response relationship. These studies are of limited value in the assessment of health effects because many of the responses have not been demonstrated *in vivo*. Thus, *in-vitro* studies alone were not deemed to provide data that could serve as a primary basis for assessing possible health effects of EMF.

COUPLING MECHANISMS BETWEEN FIELDS AND THE BODY

There are three established basic coupling mechanisms through which time-varying electric and magnetic fields interact directly with living matter (UNEP/WHO/IRPA 1993):

- coupling to low-frequency electric fields;
- coupling to low-frequency magnetic fields; and
- absorption of energy from electromagnetic fields.

Coupling to low-frequency electric fields

The interaction of time-varying electric fields with the human body results in the flow of electric charges (electric current), the polarization of bound charge (formation of electric dipoles), and the reorientation of electric dipoles already present in tissue. The relative magnitudes of these different effects depend on the electrical properties of the body—that is, electrical conductivity (governing the flow of electric current) and permittivity (governing the magnitude of polarization effects). Electrical conductivity and permittivity vary with the type of body tissue and also depend on the frequency of the applied field. Electric fields external to the body induce a surface charge on the body; this results in induced currents in the body, the distribution of which depends on exposure conditions, on the size and shape of the body, and on the body's position in the field.

Coupling to low-frequency magnetic fields

The physical interaction of time-varying magnetic fields with the human body results in induced electric fields and circulating electric currents. The magnitudes of the induced field and the current density are proportional to the radius of the loop, the electrical conductivity of the tissue, and the rate of change and magnitude of the magnetic flux density. For a given magnitude and frequency of magnetic field, the strongest electric fields are induced where the loop dimensions are greatest. The exact path and magnitude of the resulting current induced in any part of the body will depend on the electrical conductivity of the tissue.

The body is not electrically homogeneous; however, induced current densities can be calculated using anatomically and electrically realistic models of the body and computational methods, which have a high degree of anatomical resolution.

Absorption of energy from electromagnetic fields

Exposure to low-frequency electric and magnetic fields normally results in negligible energy absorption and no measurable temperature rise in the body. However, exposure to electromagnetic fields at frequencies above about 100 kHz can lead to significant absorption of energy and temperature increases. In general, exposure to a uniform (plane-wave) electromagnetic field results in a highly non-uniform deposition and distribution of energy within the body, which must be assessed by dosimetric measurement and calculation.

As regards absorption of energy by the human body, electromagnetic fields can be divided into four ranges (Durney et al. 1985):

- frequencies from about 100 kHz to less than about 20 MHz, at which absorption in the trunk decreases rapidly with decreasing frequency, and significant absorption may occur in the neck and legs;
- frequencies in the range from about 20 MHz to 300 MHz, at which relatively high absorption can occur in the whole body, and to even higher values if partial body (e.g., head) resonances are considered;
- frequencies in the range from about 300 MHz to several GHz, at which significant local, non-uniform absorption occurs; and
- frequencies above about 10 GHz, at which energy absorption occurs primarily at the body surface.

In tissue, SAR is proportional to the square of the internal electric field strength. Average SAR and SAR distribution can be computed or estimated from laboratory measurements. Values of SAR depend on the following factors:

- the incident field parameters, i.e., the frequency, intensity, polarization, and source–object configuration (near- or far-field);
- the characteristics of the exposed body, i.e., its size and internal and external geometry, and the dielectric properties of the various tissues; and
- ground effects and reflector effects of other objects in the field near the exposed body.

When the long axis of the human body is parallel to the electric field vector, and under plane-wave exposure conditions (i.e., far-field exposure), whole-body SAR reaches maximal values. The amount of energy absorbed depends on a number of factors, including the size of the exposed body. "Standard Reference Man" (ICRP 1994), if not grounded, has a resonant absorption frequency close to 70 MHz. For taller individuals the resonant absorption frequency is somewhat lower, and for shorter adults, children, babies, and seated individuals it may exceed 100 MHz. The values of electric field reference levels are based on the frequency-dependence of human absorption; in grounded individuals, resonant frequencies are lower by a factor of about 2 (UNEP/WHO/IRPA 1993).

For some devices that operate at frequencies above 10 MHz (e.g., dielectric heaters, mobile telephones), human exposure can occur under near-field conditions. The frequency-dependence of energy absorption under these conditions is very different from that described for far-field conditions. Magnetic fields may dominate for certain devices, such as mobile telephones, under certain exposure conditions.

The usefulness of numerical modeling calculations, as well as measurements of induced body current and tissue field strength, for assessment of near-field exposures has been demonstrated for mobile telephones, walkie-talkies, broadcast towers, shipboard communication sources, and dielectric heaters (Kuster and Balzano 1992; Dimbylow and Mann 1994; Jokela et al. 1994; Gandhi 1995; Tofani et al. 1995). The importance of these studies lies in their having shown that near-field exposure can result in high local SAR (e.g., in the head, wrists, ankles) and that whole-body and local SAR are strongly dependent on the separation distance between the high-frequency source and the body. Finally, SAR data obtained by measurement are consistent with data obtained from numerical modeling calculations. Whole-body average SAR and local SAR are convenient quantities for comparing effects observed under various exposure conditions. A detailed discussion of SAR can be found elsewhere (UNEP/WHO/IRPA 1993).

At frequencies greater than about 10 GHz, the depth of penetration of the field into tissues is small, and SAR is not a good measure for assessing absorbed energy; the incident power density of the field (in W m^{-2}) is a more appropriate dosimetric quantity.

INDIRECT COUPLING MECHANISMS

There are two indirect coupling mechanisms:

- contact currents that result when the human body comes into contact with an object at a different electric potential (i.e., when either the body or the object is charged by an EMF); and
- coupling of EMF to medical devices worn by, or implanted in, an individual (not considered in this document).

The charging of a conducting object by EMF causes electric currents to pass through the human body in contact with that object (Tenforde and Kaune 1987; UNEP/WHO/IRPA 1993). The magnitude and spatial distribution of such currents depend on frequency, the size of the object, the size of the person, and the area of contact; transient discharges—sparks—can occur when an individual and a conducting object exposed to a strong field come into close proximity.

BIOLOGICAL BASIS FOR LIMITING EXPOSURE (UP TO 100 KHZ)

The following paragraphs provide a general review of relevant literature on the biological and health effects of electric and magnetic fields with frequency ranges up to 100 kHz, in which the major mechanism of interaction is induction of currents in tissues. For the frequency range >0 to 1 Hz, the biological basis for the basic restrictions and reference levels are provided in ICNIRP (1994). More detailed reviews are available elsewhere (NRPB 1991, 1993; UNEP/WHO/IRPA 1993; Blank 1995; NAS 1996; Polk and Postow 1996; Ueno 1996).

Direct effects of electric and magnetic fields

Epidemiological studies. There have been many reviews of epidemiological studies of cancer risk in relation to exposure to power-frequency fields (NRPB 1992, 1993, 1994b; ORAU 1992; Savitz 1993; Heath 1996; Stevens and Davis 1996; Tenforde 1996; NAS 1996). Similar reviews have been published on the risk of adverse reproductive outcomes associated with exposure to EMF (Chernoff et al. 1992; Brent et al. 1993; Shaw and Croen 1993; NAS 1996; Tenforde 1996).

Reproductive outcome. Epidemiological studies on pregnancy outcomes have provided no consistent evidence of adverse reproductive effects in women working with visual display units (VDUs) (Bergqvist 1993; Shaw and Croen 1993; NRPB 1994a; Tenforde 1996). For example, meta-analysis revealed no excess risk of spontaneous abortion or malformation in combined studies comparing pregnant women using VDUs with women not using VDUs (Shaw and Croen 1993). Two other studies concentrated on actual measurements of the electric and magnetic fields emitted by VDUs; one reported a suggestion of an association between ELF magnetic fields and miscarriage (Lindbohm et al. 1992), while the other found no such association (Schnorr et al. 1991). A prospective study that included large numbers of cases, had high participation rates, and detailed exposure assessment (Bracken et al. 1995) reported that neither birth weight nor intra-uterine growth rate was related to any ELF field exposure. Adverse outcomes were not associated with higher levels of exposure. Exposure measurements included current-carrying capacity of power lines outside homes, 7-d personal exposure measurements, 24-h measurements in the home, and self-reported use of electric blankets, heated water beds, and VDUs. Most currently available information fails to support an association between occupational exposure to VDUs and harmful reproductive effects (NRPB 1994a; Tenforde 1996).

Residential cancer studies. Considerable controversy surrounds the possibility of a link between exposure to ELF magnetic fields and an elevated risk of cancer. Several reports on this topic have appeared since Wertheimer and Leeper reported (1979) an association between childhood cancer mortality and proximity of homes to power distribution lines with what the researchers classified as *high current configuration*. The basic hypothesis that emerged from the original study was that the contribution to the ambient residential 50/60 Hz magnetic fields from external sources such as power lines could be linked to an increased risk of cancer in childhood.

To date there have been more than a dozen studies on childhood cancer and exposure to power-frequency magnetic fields in the home produced by nearby power lines. These studies estimated the magnetic field exposure from short term measurements or on the basis of distance between the home and power line and, in most cases, the configuration of the line; some studies also took the load of the line into account. The findings relating to leukemia are the most consistent. Out of 13 studies (Wertheimer and Leeper 1979; Fulton et al. 1980; Myers et al. 1985; Tomenius 1986; Savitz et al. 1988; Coleman et al. 1989; London et al. 1991; Feychting and Ahlbom 1993; Olsen et al. 1993; Verkasalo et al. 1993; Michaelis et al. 1997; Linet et al. 1997; Tynes and Haldorsen 1997), all but five reported relative risk estimates of between 1.5 and 3.0.

Both direct magnetic field measurements and estimates based on neighboring power lines are crude proxy measures for the exposure that took place at various times before cases of leukemia were diagnosed, and it is not clear which of the two methods provides the more valid estimate. Although results suggest that indeed the magnetic field may play a role in the association with leukemia risk, there is uncertainty because of small sample numbers and because of a correlation between the magnetic field and proximity to power lines (Feychting et al. 1996).

Little is known about the etiology of most types of childhood cancer, but several attempts to control for potential confounders such as socioeconomic status and air pollution from motor vehicle exhaust fumes have had little effect on results. Studies that have examined the use of electrical appliances (primarily electric blankets) in relation to cancer and other health problems have reported generally negative results (Preston-Martin et al. 1988; Verreault et al. 1990; Vena et al. 1991, 1994; Li et al. 1995). Only two case-control studies have evaluated use of appliances in relation to the risk of childhood leukemia. One was conducted in Denver (Savitz et al. 1990) and suggested a link with prenatal use of electric blankets; the other, carried out in Los Angeles (London et al. 1991), found an association between leukemia and children using hair dryers and watching monochrome television.

The fact that results for leukemia based on proximity of homes to power lines are relatively consistent led the U.S. National Academy of Sciences Committee to conclude that children living near power lines appear to be at increased risk of leukemia (NAS 1996). Because of small numbers, confidence intervals in the individual studies are wide; when taken together, however, the results are consistent, with a pooled relative risk of 1.5 (NAS 1996). In contrast, short-term measurements of magnetic field in some of the studies provided no evidence of an association between exposure to 50/60 Hz fields and the risk of leukemia or any other form of cancer in children. The Committee was not convinced that this increase in risk was explained by exposure to magnetic fields, since there was no apparent association when exposure was estimated from magnetic field meter readings in the homes of both leukemia cases and controls. It was suggested that confounding by some unknown risk factor for childhood leukemia, associated with residence in the vicinity of power lines, might be the explanation, but no likely candidates were postulated.

After the NAS committee completed its review, the results of a study performed in Norway were reported (Tynes and Haldorsen 1997). This study included 500 cases of all types of childhood cancer. Each individual's exposure was estimated by calculation of the magnetic field level produced in the residence by nearby transmission lines, estimated by averaging over an entire year. No association between leukemia risk and magnetic fields for the residence at time of diagnosis was observed. Distance from the power line, exposure during the first year of life, mothers' exposure at time of conception, and exposure higher than the median level of the controls showed no association with leukemia, brain cancer, or lymphoma. However, the number of exposed cases was small.

Also, a study performed in Germany has been reported after the completion of the NAS review (Michaelis et al. 1997). This was a case-control study on childhood leukemia based on 129 cases and 328 controls. Exposure assessment comprised measurements of the magnetic field over 24 h in the child's bedroom at the residence where the child had been living for the longest period before the date of diagnosis. An elevated relative risk of 3.2 was observed for $>0.2\ \mu$T.

A large U.S. case-control study (638 cases and 620 controls) to test whether childhood acute lymphoblastic leukemia is associated with exposure to 60-Hz magnetic fields was published by Linet et al. (1997). Magnetic field exposures were determined using 24-h time-weighted average measurements in the bedroom and 30-s measurements in various other rooms. Measurements were taken in homes in which the child had lived for 70% of the 5 y prior to the year of diagnosis, or the corresponding period for the controls. Wire-codes were assessed for residentially stable case-control pairs in which both had not changed their residence during the years prior to diagnosis. The number of such pairs for which assessment could be made was 416. There was no indication of an association between wire-code category and leukemia. As for magnetic field measurements, the results are more intriguing. For the cut off point of 0.2 μT the unmatched and matched analyses gave relative risks of 1.2 and 1.5, respectively. For a cut off point of 0.3 μT, the unmatched relative risk estimate is 1.7 based on 45 exposed cases. Thus, the measurement results are suggestive of a positive association between magnetic fields and leukemia risk. This study is a major contribution in terms of its size, the number of subjects in high exposure categories, timing of measurements relative to the occurrence of the leukemia (usually within 24 mo after diagnosis), other measures used to obtain exposure data, and quality of analysis allowing for multiple potential confounders. Potential weaknesses include the procedure for control selection, the participation rates, and the methods used for statistical analysis of the data. The instruments used for measurements took no account of transient fields or higher order harmonics. The size of this study is such that its results, combined with those of other studies, would significantly weaken (though not necessarily invalidate) the previously observed association with wire code results.

Over the years there also has been substantial interest in whether there is an association between magnetic field exposure and childhood brain cancer, the second most frequent type of cancer found in children. Three recent studies completed after the NAS Committee's review fail to provide support for an association between brain cancer and children's exposure to magnetic fields, whether the source was power lines or electric blankets, or whether magnetic fields were estimated by calculations or by wire codes (Guénel et al. 1996; Preston-Martin et al. 1996a, b; Tynes and Haldorsen 1997).

Data on cancer in adults and residential magnetic field exposure are sparse (NAS 1996). The few studies published to date (Wertheimer and Leeper 1979; McDowall 1985; Seversen et al. 1988; Coleman et al. 1989; Schreiber et al. 1993; Feychting and Ahlbom 1994; Li et al. 1996; Verkasalo 1996; Verkasalo et al. 1996) all suffer to some extent from small numbers of exposed cases, and no conclusions can be drawn.

It is the view of the ICNIRP that the results from the epidemiological research on EMF field exposure and cancer, including childhood leukemia, are not strong enough in the absence of support from experimental research to form a scientific basis for setting exposure guidelines. This assessment is also in agreement with recent reviews (NRPB 1992, 1994b; NAS 1996; CRP 1997).

Occupational studies. A large number of epidemiological studies have been carried out to assess possible links between exposure to ELF fields and cancer risk among workers in electrical occupations. The first study of this type (Milham 1982) took advantage of a death certificate database that included both job titles and information on cancer mortality. As a crude method of assessing exposure, Milham classified job titles according to presumed magnetic field exposure and found an excess risk for leukemia among electrical workers. Subsequent studies (Savitz and Ahlbom 1994) made use of similar databases; the types of cancer for which elevated rates were noted varied across studies, particularly when cancer subtypes were characterized. Increased risks of various types of leukemia and nervous tissue tumors, and, in a few instances, of both male and female breast cancer, were reported (Demers et al. 1991; Matanoski et al. 1991; Tynes et al. 1992; Loomis et al. 1994). As well as producing somewhat inconsistent results, these studies suffered from very crude exposure assessment and from failure to control for confounding factors such as exposure to benzene solvent in the workplace.

Three recent studies have attempted to overcome some of the deficiencies in earlier work by measuring ELF field exposure at the workplace and by taking duration of work into consideration (Floderus et al. 1993; Thériault et al. 1994; Savitz and Loomis 1995). An elevated cancer risk among exposed individuals was observed, but the type of cancer of which this was true varied from study to study. Floderus et al. (1993) found a significant association with leukemia; an association was also noted by Thériault et al. (1994), but one that was weak and not significant, and no link was observed by Savitz and Loomis (1995). For subtypes of leukemia there was even greater inconsistency, but numbers in the analyses were small. For tumors of nervous tissue, Floderus et al. (1993) found an excess for glioblastoma (astrocytoma III–IV), while both Thériault et al. (1994) and Savitz and Loomis (1995) found only suggestive evidence for an increase in glioma (astrocytoma I–II). If there is truly a link between occupational exposure to magnetic fields and cancer, greater consistency and stronger associations would be expected of these recent studies based on more sophisticated exposure data.

Researchers have also investigated the possibility that ELF electric fields could be linked to cancer. The three utilities that participated in the Thériault et al. (1994) study of magnetic fields analyzed electric field data as well. Workers with leukemia at one of the utilities were reported to be more likely to have been exposed to electric fields than were control workers. In addition, the association was stronger in a group that had been exposed to high electric and magnetic fields combined (Miller et al. 1996). At the second utility, investigators reported no association between leukemia and higher cumulative exposure to workplace electric fields, but some of the analyses showed an association with brain cancer (Guénel et al. 1996). An association with colon cancer was also reported, yet in other studies of large populations of electric utility workers this type of cancer has not been found. At the third utility, no association between high electric fields and brain cancer or leukemia was observed, but this study was smaller and less likely to have detected small changes, if present (Baris et al. 1996).

An association between Alzheimer's disease and occupational exposure to magnetic fields has recently been suggested (Sobel and Davanipour 1996). However, this effect has not been confirmed.

Laboratory studies. The following paragraphs provide a summary and critical evaluation of laboratory studies on the biological effects of electric and magnetic fields with frequencies below 100 kHz. There are separate discussions on results obtained in studies of volunteers exposed under controlled conditions and in laboratory studies on cellular, tissue, and animal systems.

Volunteer studies. Exposure to a time-varying electric field can result in perception of the field as a result of the alternating electric charge induced on the body surface, which causes the body hairs to vibrate. Several studies have shown that the majority of people can perceive 50/60 Hz electric fields stronger than 20 kV m^{-1}, and that a small minority can perceive fields below 5 kV m^{-1} (UNEP/WHO/IRPA 1984; Tenforde 1991).

Small changes in cardiac function occurred in human volunteers exposed to combined 60-Hz electric and magnetic fields (9 kV m^{-1}, 20 μT) (Cook et al. 1992; Graham et al. 1994). Resting heart rate was slightly, but significantly, reduced (by 3–5 beats per minute) during or immediately after exposure. This response was absent on exposure to stronger (12 kV m^{-1}, 30 μT) or weaker (6 kV m^{-1}, 10 μT) fields and reduced if the subject was mentally alert. None of the subjects in these studies was able to detect the presence of the fields, and there were no other consistent results in a wide battery of sensory and perceptual tests.

No adverse physiological or psychological effects were observed in laboratory studies of people exposed to 50-Hz fields in the range 2–5 mT (Sander et al. 1982; Ruppe et al. 1995). There were no observed changes in blood chemistry, blood cell counts, blood gases, lactate levels, electrocardiogram, electroencephalogram, skin temperature, or circulating hormone levels in studies by Sander et al. (1982) and Graham et al. (1994). Recent studies on volunteers have also failed to show any effect of exposure to 60-Hz magnetic fields on the nocturnal melatonin level in blood (Graham et al. 1996, 1997; Selmaoui et al. 1996).

Sufficiently intense ELF magnetic fields can elicit peripheral nerve and muscle tissue stimulation directly, and short magnetic field pulses have been used clinically to stimulate nerves in the limbs in order to check the integrity of neural pathways. Peripheral nerve and muscle stimulation has also been reported in volunteers exposed to 1-kHz gradient magnetic fields in experimental magnetic resonance imaging systems. Threshold magnetic flux densities were several millitesla, and corresponding induced current densities in the peripheral tissues were about 1 A m^{-2} from pulsed fields produced by rapidly switched gradients. Time-varying magnetic fields that induce current densities above 1 A m^{-2} in tissue lead to neural excitation and are capable of producing irreversible biological effects such as cardiac fibrillation (Tenforde and Kaune 1987; Reilly 1989). In a study involving electromyographic recordings from the human arm (Polson et al. 1982), it was found that a pulsed field with dB/dt greater than 10^4 T s^{-1} was needed to stimulate the median nerve trunk. The duration of the magnetic stimulus has also been found to be an important parameter in stimulation of excitable tissues.

Thresholds lower than 100 mA m^{-2} can be derived from studies of visual and mental functions in human volunteers. Changes in response latency for complex reasoning tests have been reported in volunteers subjected to weak power-frequency electric currents passed through electrodes attached to the head and shoulders; current densities were estimated to lie between 10 and 40 mA m^{-2} (Stollery 1986, 1987). Finally, many studies have reported that volunteers experienced faint flickering visual sensations, known as magnetic phosphenes, during exposure to ELF magnetic fields above 3–5 mT (Silny 1986). These visual effects can also be induced by the direct application of weak electric currents to the head. At 20 Hz, current densities of about 10 mA m^{-2} in the retina have been estimated as the threshold for induction of phosphenes, which is above the typical endogenous current densities in electrically excitable tissues. Higher thresholds have been observed for both lower and higher frequencies (Lövsund et al. 1980; Tenforde 1990).

Studies have been conducted at 50 Hz on visually evoked potentials that exhibited thresholds for effects at flux densities of 60 mT (Silny 1986). Consistent with this result, no effects on visually evoked potentials were obtained by either Sander et al. (1982), using a 50-Hz, 5-mT field, or Graham et al. (1994), using combined 60-Hz electric and magnetic fields up to 12 kV m^{-1} and 30 μT, respectively.

Cellular and animal studies. Despite the large number of studies undertaken to detect biological effects of ELF electric and magnetic fields, few systematic studies have defined the threshold field characteristics that produce significant perturbations of biological functions. It is well established that induced electric current can stimulate nerve and muscle tissue directly once the induced current density exceeds threshold values (UNEP/WHO/IRPA 1987; Bernhardt 1992; Tenforde 1996). Current densities that are unable to stimulate excitable tissues directly may nevertheless affect ongoing electrical activity and influence neuronal excitability. The activity of the central nervous system is known to be sensitive to the endogenous electric fields generated by the action of adjacent nerve cells, at levels below those required for direct stimulation.

Many studies have suggested that the transduction of weak electrical signals in the ELF range involves interactions with the cell membrane, leading to cytoplasmic biochemical responses that in turn involve changes in cellular functional and proliferative states. From simple models of the behavior of single cells in weak fields it has been calculated that an electrical signal in the extracellular field must be greater than approximately 10–100 mV m^{-1} (corresponding to an induced current density of about 2–20 mA m^{-2}) in order to exceed the level of endogenous physical and biological noise in cellular membranes (Astumian et al. 1995). Existing evidence also suggests that several structural and functional properties of membranes may be altered in response to induced ELF fields at or below 100 mV m^{-1} (Sienkiewicz et al. 1991; Tenforde 1993). Neuroendocrine alterations (e.g., suppression of nocturnal melatonin synthesis) have been reported in response to induced electrical fields of 10 mV m^{-1} or less, corresponding to induced current densities of approximately 2 mA m^{-2} or less (Tenforde 1991, 1996). However, there is no clear evidence that these biological interactions of low-frequency fields lead to adverse health effects.

Induced electric fields and currents at levels exceeding those of endogenous bioelectric signals present in tissue have been shown to cause a number of physiological effects that increase in severity as the induced current density is increased (Bernhardt 1979; Tenforde 1996). In the current density range 10–100 mA m^{-2}, tissue effects and changes in brain cognitive functions have been reported (NRPB 1992; NAS 1996). When induced current density exceeds 100 to several hundred mA m^{-2} for frequencies between about 10 Hz and 1 kHz, thresholds for neuronal and neuromuscular stimulation are exceeded. The threshold current densities increase progressively at frequencies below several hertz and above 1 kHz. Finally, at extremely high current densities, exceeding 1 A m^{-2}, severe and potentially life-threatening effects such as cardiac extrasystoles, ventricular fibrillation, muscular tetanus, and respiratory failure may occur. The severity and the probability of irreversibility of tissue effects becomes greater with chronic exposure to induced current densities above the level 10 to 100 mA m^{-2}. It therefore seems appropriate to limit human exposure to fields that induce current densities no greater than 10 mA m^{-2} in the head, neck, and trunk at frequencies of a few hertz up to 1 kHz.

It has been postulated that oscillatory magnetomechanical forces and torques on biogenic magnetite particles in brain tissue could provide a mechanism for the transduction of signals from ELF magnetic fields. Kirschvink et al. (1992b) proposed a model in which ELF magnetic forces on magnetite particles are visualized as producing the opening and closing of pressure-sensitive ion channels in membranes. However, one difficulty with this model is the sparsity of magnetite particles relative to the number of cells in brain tissue. For example, human brain tissue has been reported to contain a few million magnetite particles per gram, distributed in 10^5 discrete clusters of 5–10 particles (Kirschvink et al. 1992a). The number of cells in brain tissue thus exceeds the number of magnetite particles by a factor of about 100, and it is difficult to envisage how oscillating magnetomechanical interactions of an ELF field with magnetite crystals could affect a significant number of pressure-sensitive ion channels in the brain. Further studies are clearly needed to reveal the biological role of magnetite and the possible mechanisms through which this mineral could play a role in the transduction of ELF magnetic signals.

An important issue in assessing the effects of electromagnetic fields is the possibility of teratogenic and developmental effects. On the basis of published scientific evidence, it is unlikely that low-frequency fields have adverse effects on the embryonic and postnatal development of mammalian species (Chernoff et al. 1992; Brent et al. 1993; Tenforde 1996). Moreover, currently available evidence indicates that somatic mutations and genetic effects are unlikely to result from exposure to electric and magnetic fields with frequencies below 100 kHz (Cridland 1993; Sienkiewicz et al. 1993).

There are numerous reports in the literature on the *in-vitro* effects of ELF fields on cell membrane properties (ion transport and interaction of mitogens with cell surface receptors) and changes in cellular functions and growth properties (e.g., increased proliferation and alterations in metabolism, gene expression, protein biosynthesis, and enzyme activities) (Cridland 1993; Sienkiewicz et al. 1993; Tenforde 1991, 1992, 1993, 1996). Considerable attention has focused on low-frequency field effects on Ca^{++} transport across cell membranes and the intracellular concentration of this ion (Walleczek and Liburdy 1990; Liburdy 1992; Walleczek 1992), messenger RNA and protein synthesis patterns (Goodman et al. 1983; Goodman and Henderson 1988, 1991; Greene et al. 1991; Phillips et al. 1992), and the activity of enzymes such as ornithine decarboxylase (ODC) that are related to cell proliferation and tumor promotion (Byus et al. 1987, 1988; Litovitz et al. 1991, 1993). However, before these observations can be used for defining exposure limits, it is essential to establish both their reproducibility and their relevance to cancer or other adverse health outcomes. This point is underscored by the fact that there have been difficulties in replicating some of the key observations of field effects on gene expression and protein synthesis (Lacy-Hulbert et al. 1995; Saffer and Thurston 1995). The authors of these replication studies identified several deficiencies in the earlier studies, including poor temperature control, lack of appropriate internal control samples, and the use of low-resolution techniques for analyzing the production of messenger RNA transcripts. The transient increase in ODC activity reported in response to field exposure is small in magnitude and not associated with *de novo* synthesis of the enzyme (unlike chemical tumor promoters such as phorbol esters) (Byus et al. 1988). Studies on ODC have mostly involved cellular preparations; more studies are needed to show whether there are effects on ODC *in vivo*, although there is one report suggesting effects on ODC in a rat mammary tumor promotion assay (Mevissen et al. 1995).

There is no evidence that ELF fields alter the structure of DNA and chromatin, and no resultant mutational and neoplastic transformation effects are expected. This is supported by results of laboratory studies designed to detect DNA and chromosomal damage, mutational events, and increased transformation frequency in response to ELF field exposure (NRPB 1992; Murphy et al. 1993; McCann et al. 1993; Tenforde 1996). The lack of effects on chromosome structure suggests that ELF fields, if they have any effect on the process of carcinogenesis, are more likely to act as promoters than initiators, enhancing the proliferation of genetically altered cells rather than causing the initial lesion in DNA or chromatin. An influence on tumor development could be mediated through epigenetic effects of these fields, such as alterations in cell signalling pathways or gene expression. The focus of recent studies has therefore been on detecting possible effects of ELF fields on the promotion and progression phases of tumor development following initiation by a chemical carcinogen.

Studies on *in-vitro* tumor cell growth and the development of transplanted tumors in rodents have provided no strong evidence for possible carcinogenic effects of exposure to ELF fields (Tenforde 1996). Several studies of more direct relevance to human cancer have involved *in-vivo* tests for tumor-promoting activity of ELF magnetic fields on skin, liver, brain, and mammary tumors in rodents. Three studies of skin tumor promotion (McLean et al. 1991; Rannug et al. 1993a, 1994) failed to show any effect of either continuous or intermittent exposure to power-frequency magnetic fields in promoting chemically induced tumors. At a 60-Hz field strength of 2 mT, a co-promoting effect with a phorbol ester was reported for mouse skin tumor development in the initial stages of the experiment, but the statistical significance of this was lost by completion of the study in week 23 (Stuchly et al. 1992). Previous studies by the same investigators had shown that 60-Hz, 2-mT field exposure did not promote the growth of DMBA-initiated skin cells (McLean et al. 1991).

Experiments on the development of transformed liver foci initiated by a chemical carcinogen and promoted by phorbol ester in partially hepatectomized rats revealed no promotion or co-promotion effect of exposure to 50-Hz fields ranging in strength from 0.5 to 50 μT (Rannug et al. 1993b, c).

Studies on mammary cancer development in rodents treated with a chemical initiator have suggested a cancer-promoting effect of exposure to power-frequency magnetic fields in the range 0.01–30 mT (Beniashvili et al. 1991; Löscher et al. 1993; Mevissen et al. 1993, 1995; Baum et al. 1995; Löscher and Mevissen 1995). These observations of increased tumor incidence in rats exposed to magnetic fields have been hypothesized to be related to field-induced suppression of pineal melatonin and a resulting elevation in steroid hormone levels and breast cancer risk (Stevens 1987; Stevens et al. 1992). However, replication efforts by independent laboratories are needed before conclusions can be drawn regarding the implications of these findings for a promoting effect of ELF magnetic fields on mammary tumors. It should also be noted that recent studies have found no evidence for a significant effect of exposure to ELF magnetic fields on melatonin levels in humans (Graham et al. 1996, 1997; Selmaoui et al. 1996).

Indirect effects of electric and magnetic fields

Indirect effects of electromagnetic fields may result from physical contact (e.g., touching or brushing against) between a person and an object, such as a metallic structure in the field, at a different electric potential. The result of such contact is the flow of electric charge (contact current) that may have accumulated on the object or on the body of the person. In the frequency range up to approximately 100 kHz, the flow of electric current from an object in the field to the body of the individual may result in the stimulation of muscles and/or peripheral nerves. With increasing levels of current this may be manifested as perception, pain from electric shock and/or burn, inability to release the object, difficulty in breathing and, at very high currents, cardiac ventricular fibrillation (Tenforde and Kaune 1987). Threshold values for these effects are frequency-dependent, with the lowest threshold occurring at frequencies between 10 and 100 Hz. Thresholds for peripheral nerve responses remain low for frequencies up to several kHz. Appropriate engineering and/or administrative controls, and even the wearing of personal protective clothing, can prevent these problems from occurring.

Spark discharges can occur when an individual comes into very close proximity with an object at a different electric potential, without actually touching it (Tenforde and Kaune 1987; UNEP/WHO/IRPA 1993). When a group of volunteers, who were electrically insulated from the ground, each held a finger tip close to a grounded object, the threshold for perception of spark discharges was as low as 0.6–1.5 kV m^{-1} in 10% of cases. The threshold field level reported as causing annoyance under these exposure conditions is about 2.0–3.5 kV m^{-1}. Large contact currents can result in muscle contraction. In male volunteers, the 50th percentile threshold for being unable to release a charged conductor has been reported as 9 mA at 50/60 Hz, 16 mA at 1 kHz, about 50 mA at 10 kHz, and about 130 mA at 100 kHz (UNEP/WHO/IRPA 1993).

The threshold currents for various indirect effects of fields with frequencies up to 100 kHz are summarized in Table 2 (UNEP/WHO/IRPA 1993).

Table 2. Ranges of threshold currents for indirect effects, including children, women, and men.

Indirect effect	Threshold current (mA) at frequency: 50/60 Hz	1 kHz	100 kHz
Touch perception	0.2–0.4	0.4–0.8	25–40
Pain on finger contact	0.9–1.8	1.6–3.3	33–55
Painful shock/let-go threshold	8–16	12–24	112–224
Severe shock/breathing difficulty	12–23	21–41	160–320

Summary of biological effects and epidemiological studies (up to 100 kHz)

With the possible exception of mammary tumors, there is little evidence from laboratory studies that power-frequency magnetic fields have a tumor-promoting effect. Although further animal studies are needed to clarify the possible effects of ELF fields on signals produced in cells and on endocrine regulation—both of which could influence the development of tumors by promoting the proliferation of initiated cells—it can only be concluded that there is currently no convincing evidence for carcinogenic effects of these fields and that these data cannot be used as a basis for developing exposure guidelines.

Laboratory studies on cellular and animal systems have found no established effects of low-frequency fields that are indicative of adverse health effects when induced current density is at or below 10 mA m^{-2}. At higher levels of induced current density (10–100 mA m^{-2}), more significant tissue effects have been consistently observed, such as functional changes in the nervous system and other tissue effects (Tenforde 1996).

Data on cancer risk associated with exposure to ELF fields among individuals living close to power lines are apparently consistent in indicating a slightly higher risk of leukemia among children, although more recent studies question the previously observed weak association. The studies do not, however, indicate a similarly elevated risk of any other type of childhood cancer or of any form of adult cancer. The basis for the hypothetical link between childhood leukemia and residence in close proximity to power lines is unknown; if the link is not related to the ELF electric and magnetic fields generated by the power lines, then unknown risk factors for leukemia would have to be linked to power lines in some undetermined manner. In the absence of support from laboratory studies, the epidemiological data are insufficient to allow an exposure guideline to be established.

There have been reports of an increased risk of certain types of cancer, such as leukemia, nervous tissue tumors, and, to a limited extent, breast cancer, among electrical workers. In most studies, job titles were used to classify subjects according to presumed levels of magnetic field exposure. A few more recent studies, however, have used more sophisticated methods of exposure assessment; overall, these studies suggested an increased risk of leukemia or brain tumors but were largely inconsistent with regard to the type of cancer for which risk is increased. The data are insufficient to provide a basis for ELF field exposure guidelines. In a large number of epidemiological studies, no consistent evidence of adverse reproductive effects have been provided.

Measurement of biological responses in laboratory studies and in volunteers has provided little indication of adverse effects of low-frequency fields at levels to which people are commonly exposed. A threshold current density of 10 mA m^{-2} at frequencies up to 1 kHz has been estimated for minor effects on nervous system functions. Among volunteers, the most consistent effects of exposure are the appearance of visual phosphenes and a minor reduction in heart rate during or immediately after exposure to ELF fields, but there is no evidence that these transient effects are associated with any long-term health risk. A reduction in nocturnal pineal melatonin synthesis has been observed in several rodent species following exposure to weak ELF electric and magnetic fields, but no consistent effect has been reported in humans exposed to ELF fields under controlled conditions. Studies involving exposures to 60-Hz magnetic fields up to 20 μT have not reported reliable effects on melatonin levels in blood.

BIOLOGICAL BASIS FOR LIMITING EXPOSURE (100 kHz–300 GHz)

The following paragraphs provide a general review of relevant literature on the biological effects and potential health effects of electromagnetic fields with frequencies of 100 kHz to 300 GHz. More detailed reviews can be found elsewhere (NRPB 1991; UNEP/WHO/IRPA 1993; McKinlay et al. 1996; Polk and Postow 1996; Repacholi 1998).

Direct effects of electromagnetic fields

Epidemiological studies. Only a limited number of studies have been carried out on reproductive effects and cancer risk in individuals exposed to microwave radiation. A summary of the literature was published by UNEP/WHO/IRPA (1993).

Reproductive outcomes. Two extensive studies on women treated with microwave diathermy to relieve the pain of uterine contractions during labor found no evidence for adverse effects on the fetus (Daels 1973, 1976). However, seven studies on pregnancy outcomes among workers occupationally exposed to microwave radiation and on birth defects among their offspring produced both positive and negative results. In some of the larger epidemiological studies of female plastic welders and physiotherapists working with shortwave diathermy devices, there were no statistically significant effects on rates of abortion or fetal malformation (Källen et al. 1982). By contrast, other studies on similar populations of female workers found an increased risk of miscarriage and birth defects (Larsen et al. 1991; Ouellet-Hellstrom and Stewart 1993). A study of male radar workers found no association between microwave exposure and the risk of Down's syndrome in their offspring (Cohen et al. 1977).

Overall, the studies on reproductive outcomes and microwave exposure suffer from very poor assessment of exposure and, in many cases, small numbers of subjects. Despite the generally negative results of these studies, it will be difficult to draw firm conclusions on reproductive risk without further epidemiological data on highly exposed individuals and more precise exposure assessment.

Cancer studies. Studies on cancer risk and microwave exposure are few and generally lack quantitative exposure assessment. Two epidemiological studies of radar workers in the aircraft industry and in the U.S. armed forces found no evidence of increased morbidity or mortality from any cause (Barron and Baraff 1958; Robinette et al. 1980; UNEP/WHO/IRPA 1993). Similar results were obtained by Lillienfeld et al. (1978) in a study of employees in the U.S. embassy in Moscow, who were chronically exposed to low-level microwave radiation. Selvin et al. (1992) reported no increase in cancer risk among children chronically exposed to radiation from a large microwave transmitter near their homes. More recent studies have failed to show significant increases in nervous tissue tumors among workers and military personnel exposed to microwave fields (Beall et al. 1996; Grayson 1996). Moreover, no excess total mortality was apparent among users of mobile telephones (Rothman et al. 1996a, b), but it is still too early to observe an effect on cancer incidence or mortality.

There has been a report of increased cancer risk among military personnel (Szmigielski et al. 1988), but the results of the study are difficult to interpret because neither the size of the population nor the exposure levels are clearly stated. In a later study, Szmigielski (1996) found increased rates of leukemia and lymphoma among military personnel exposed to EMF fields, but the assessment of EMF exposure was not well defined. A few recent studies of populations living near EMF transmitters have suggested a local increase in leukemia incidence (Hocking et al. 1996; Dolk et at. 1997a, b), but the results are inconclusive. Overall, the results of the small number of epidemiological studies published provide only limited information on cancer risk.

Laboratory studies. The following paragraphs provide a summary and critical evaluation of laboratory studies on the biological effects of electromagnetic fields with frequencies in the range 100 kHz–300 GHz. There are separate discussions on results of studies of volunteers exposed under controlled conditions and of laboratory studies on cellular, tissue, and animal systems.

Volunteer studies. Studies by Chatterjee et al. (1986) demonstrated that, as the frequency increases from approximately 100 kHz to 10 MHz, the dominant effect of exposure to a high-intensity electromagnetic field changes from nerve and muscle stimulation to heating. At 100 kHz the primary sensation was one of nerve tingling, while at 10 MHz it was one of warmth on the skin. In this frequency range, therefore, basic health protection criteria should be such as to avoid stimulation of excitable tissues and heating effects. At frequencies from 10 MHz to 300 GHz, heating is the major effect of absorption of electromagnetic energy, and temperature rises of more than 1–2 °C can have adverse health effects such as heat exhaustion and heat stroke (ACGIH 1996). Studies on workers in thermally stressful environments have shown worsening performance of simple tasks as body temperature rises to a level approaching physiological heat stress (Ramsey and Kwon 1988).

A sensation of warmth has been reported by volunteers experiencing high-frequency current of about 100–200 mA through a limb. The resulting SAR value is unlikely to produce a localized temperature increment of more than 1°C in the limbs (Chatterjee et al. 1986; Chen and Gandhi 1988; Hoque and Gandhi 1988), which has been suggested as the upper limit of temperature increase that has no detrimental health effects (UNEP/WHO/IRPA 1993). Data on volunteers reported by Gandhi et al. (1986) for frequencies up to 50 MHz and by Tofani et al. (1995) for frequencies up to 110 MHz (the upper limit of the FM broadcast band) support a reference level for limb current of 100 mA to avoid excessive heating effects (Dimbylow 1997).

There have been several studies of thermoregulatory responses of resting volunteers exposed to EMF in magnetic resonance imaging systems (Shellock and Crues 1987; Magin et al. 1992). In general, these have demonstrated that exposure for up to 30 min, under conditions in which whole-body SAR was less than 4 W kg^{-1}, caused an increase in the body core temperature of less than 1°C.

Cellular and animal studies. There are numerous reports on the behavioral and physiological responses of laboratory animals, including rodents, dogs, and nonhuman primates, to thermal interactions of EMF at frequencies above 10 MHz. Thermosensitivity and thermoregulatory responses are associated both with the hypothalamus and with thermal receptors located in the skin and in internal parts of the body. Afferent signals reflecting temperature change converge in the central nervous system and modify the activity of the major neuroendocrine control systems, triggering the physiological and behavioral responses necessary for the maintenance of homeostasis.

Exposure of laboratory animals to EMF producing absorption in excess of approximately 4 W kg^{-1} has revealed a characteristic pattern of thermoregulatory response in which body temperature initially rises and then stabilizes following the activation of thermoregulatory mechanisms (Michaelson 1983). The early phase of this response is accompanied by an increase in blood volume due to movement of fluid from the extracellular space into the circulation and by increases in heart rate and intraventricular blood pressure. These cardiodynamic changes reflect thermoregulatory responses that facilitate the conduction of heat to the body surface. Prolonged exposure of animals to levels of microwave radiation that raise the body temperature ultimately lead to failure of these thermoregulatory mechanisms.

Several studies with rodents and monkeys have also demonstrated a behavioral component of thermoregulatory responses. Decreased task performance by rats and monkeys has been observed at SAR values in the range 1–3 W kg^{-1} (Stern et al. 1979; Adair and Adams 1980; de Lorge and Ezell 1980; D'Andrea et al. 1986). In monkeys, altered thermoregulatory behavior starts when the temperature in the hypothalamic region rises by as little as 0.2–0.3°C (Adair et al. 1984). The hypothalamus is considered to be the control center for normal thermoregulatory processes, and its activity can be modified by a small local temperature increase under conditions in which rectal temperature remains constant.

At levels of absorbed electromagnetic energy that cause body temperature rises in excess of 1–2°C, a large number of physiological effects have been characterized in studies with cellular and animal systems (Michaelson and Elson 1996). These effects include alterations in neural and neuromuscular functions; increased blood-brain barrier permeability; ocular impairment (lens opacities and corneal abnormalities); stress-associated changes in the immune system; hematological changes; reproductive changes (e.g., reduced sperm production); teratogenicity; and changes in cell morphology, water and electrolyte content, and membrane functions.

Under conditions of partial-body exposure to intense EMF, significant thermal damage can occur in sensitive tissues such as the eye and the testis. Microwave exposure of 2–3 h duration has produced cataracts in rabbits' eyes at SAR values from 100–140 W kg^{-1}, which produced lenticular temperatures of 41–43°C (Guy et al. 1975). No cataracts were observed in monkeys exposed to microwave fields of similar or higher intensities, possibly because of different energy absorption patterns in the eyes of monkeys from those in rabbits. At very high frequencies (10–300 GHz), absorption of electromagnetic energy is confined largely to the epidermal layers of the skin, subcutaneous tissues, and the outer part of the eye. At the higher end of the frequency range, absorption is increasingly superficial. Ocular damage at these frequencies can be avoided if the microwave power density is less than 50 W m^{-2} (Sliney and Wolbarsht 1980; UNEP/WHO/IRPA 1993).

There has been considerable recent interest in the possible carcinogenic effects of exposure to microwave fields with frequencies in the range of widely used communications systems, including hand-held mobile telephones and base transmitters. Research findings in this area have been summarized by ICNIRP (1996). Briefly, there are many reports suggesting that microwave fields are not mutagenic, and exposure to these fields is therefore unlikely to initiate carcinogenesis (NRPB 1992; Cridland 1993; UNEP/WHO/IRPA 1993). By contrast, some recent reports suggest that exposure of rodents to microwave fields at SAR levels of the order of 1 W kg^{-1} may produce strand breaks in the DNA of testis and brain tissues (Sarkar et al. 1994; Lai and Singh 1995, 1996), although both ICNIRP (1996) and Williams (1996) pointed out methodological deficiencies that could have significantly influenced these results.

In a large study of rats exposed to microwaves for up to 25 mo, an excess of primary malignancies was noted in exposed rats relative to controls (Chou et al. 1992). However, the incidence of benign tumors did not differ between the groups, and no specific type of tumor was more prevalent in the exposed group than in stock rats of the same strain maintained under similar specific-pathogen-free conditions. Taken as a whole, the results of this study cannot be interpreted as indicating a tumor-initiating effect of microwave fields.

Several studies have examined the effects of microwave exposure on the development of pre-initiated tumor cells. Szmigielski et al. (1982) noted an enhanced growth rate of transplanted lung sarcoma cells in rats exposed to microwaves at high power densities. It is possible that this resulted from a weakening of the host immune defense in response to thermal stress from the microwave exposure. Recent studies using athermal levels of microwave irradiation have found no effects on the development of melanoma in mice or of brain glioma in rats (Santini et al. 1988; Salford et al. 1993).

Repacholi et al. (1997) have reported that exposure of 100 female, *Eμ-pim1* transgenic mice to 900-MHz fields, pulsed at 217 Hz with pulse widths of 0.6 μs for up to 18 mo, produced a doubling in lymphoma incidence compared with 101 controls. Because the mice were free to roam in their cages, the variation in SAR was wide (0.01–4.2 W kg^{-1}). Given that the resting metabolic rate of these mice is 7–15 W kg^{-1}, only the upper end of the exposure range may have produced some slight heating. Thus, it appears that this study suggests a non-thermal mechanism may be acting, which needs to be investigated further. However, before any assumptions can be made about health risk, a number of questions need to be addressed. The study needs to be replicated, restraining the animals to decrease the SAR exposure variation and to determine whether there is a dose response. Further study is needed to determine whether the results can be found in other animal models in order to be able to generalize the results to humans. It is also essential to assess whether results found in transgenic animals are applicable to humans.

Special considerations for pulsed and amplitude-modulated waveforms

Compared with continuous-wave (CW) radiation, pulsed microwave fields with the same average rate of energy deposition in tissues are generally more effective in producing a biological response, especially when there is a well-defined threshold that must be exceeded to elicit the effect (ICNIRP 1996). The “microwave hearing” effect is a well known example of this (Frey 1961; Frey and Messenger 1973; Lin 1978): people with normal hearing can perceive pulse-modulated fields with frequencies between about 200 MHz and 6.5 GHz. The auditory sensation has been variously described as a buzzing, clicking, or popping sound, depending on the modulation characteristics of the field. The microwave hearing effects have been attributed to a thermoelastic interaction in the auditory cortex of the brain, with a threshold for perception of about 100–400 mJ m^{-2} for pulses of duration less than 30 μs at 2.45 GHz (corresponding to an SA of 4–16 mJ kg^{-1}). Repeated or prolonged exposure to microwave auditory effects may be stressful and potentially harmful.

Some reports suggest that retina, iris, and corneal endothelium of the primate eye are sensitive to low levels of pulsed microwave radiation (Kues et al. 1985; UNEP/WHO/IRPA 1993). Degenerative changes in light-sensitive cells of the retina were reported for absorbed energy levels as low as 26 mJ kg^{-1}. After administration of timolol maleate, which is used in the treatment of glaucoma, the threshold for retinal damage by pulsed fields dropped to 2.6 mJ kg^{-1}. However, an attempt in an independent laboratory to partially replicate these findings for CW fields (i.e., not pulsed) was unsuccessful (Kamimura et al. 1994), and it is therefore impossible at present to assess the potential health implications of the initial findings of Kues et al. (1985).

Exposure to intense pulsed microwave fields has been reported to suppress the startle response in conscious mice and to evoke body movements (NRPB 1991; Sienkiewicz et al. 1993; UNEP/WHO/IRPA 1993). The threshold specific energy absorption level at midbrain that evoked body movements was 200 J kg^{-1} for 10 μs pulses. The mechanism for these effects of pulsed microwaves remains to be determined but is believed to be related to the microwave hearing phenomenon. The auditory thresholds for rodents are about an order of magnitude lower than for humans, that is 1–2 mJ kg^{-1} for pulses <30 μs in duration. Pulses of this magnitude have also been reported to affect neurotransmitter metabolism and the concentration of the neural receptors involved in stress and anxiety responses in different regions of the rat brain.

The issue of athermal interactions of high-frequency EMF has centered largely on reports of biological effects of amplitude modulated (AM) fields under *in-vitro* conditions at SAR values well below those that produce measurable tissue heating. Initial studies in two independent laboratories led to reports that VHF fields with amplitude modulation at extremely low frequencies (6–20 Hz) produced a small, but statistically significant, release of Ca^{++} from the surfaces of chick brain cells (Bawin et al. 1975; Blackman et al. 1979). A subsequent attempt to replicate these findings, using the same type of AM field, was unsuccessful (Albert et al. 1987). A number of other studies of the effects of AM fields on Ca^{++} homeostasis have produced both positive and negative results. For example, effects of AM fields on Ca^{++} binding to cell surfaces have been observed with neuroblastoma cells, pancreatic cells, cardiac tissue, and cat brain cells, but not with cultured rat nerve cells, chick skeletal muscle, or rat brain cells (Postow and Swicord 1996).

Amplitude-modulated fields have also been reported to alter brain electrical activity (Bawin et al. 1974), inhibit T-lymphocyte cytotoxic activity (Lyle et al. 1983), decrease the activities of non-cyclic-AMP-dependent kinase in lymphocytes (Byus et al. 1984), and cause a transient increase in the cytoplasmic activity of ornithine decarboxylase, an essential enzyme for cell proliferation (Byus et al. 1988; Litovitz et al. 1992). In contrast, no effects have been observed on a wide variety of other cellular systems and functional end-points, including lymphocyte capping, neoplastic cell transformation, and various membrane electrical and enzymatic properties (Postow and Swicord 1996). Of particular relevance to the potential carcinogenic effects of pulsed fields is the observation by Balcer-Kubiczek and Harrison (1991) that neoplastic transformation was accelerated in C3H/10T1/2 cells exposed to 2,450-MHz microwaves that were pulse-modulated at 120 Hz. The effect was dependent on field strength but occurred only when a chemical tumor-promoter, TPA, was present in the cell culture medium. This finding suggests that pulsed microwaves may exert co-carcinogenic effects in combination with a chemical agent that increases the rate of proliferation of transformed cells. To date, there have been no attempts to replicate this finding, and its implication for human health effects is unclear.

Interpretation of several observed biological effects of AM electromagnetic fields is further complicated by the apparent existence of "windows" of response in both the power density and frequency domains. There are no accepted models that adequately explain this phenomenon, which challenges the traditional concept of a monotonic relationship between the field intensity and the severity of the resulting biological effects.

Overall, the literature on athermal effects of AM electromagnetic fields is so complex, the validity of reported effects so poorly established, and the relevance of the effects to human health is so uncertain, that it is impossible to use this body of information as a basis for setting limits on human exposure to these fields.

Indirect effects of electromagnetic fields

In the frequency range of about 100 kHz–110 MHz, shocks and burns can result either from an individual touching an ungrounded metal object that has acquired a charge in a field or from contact between a charged individual and a grounded metal object. It should be noted that the upper frequency for contact current (110 MHz) is imposed by a lack of data on higher frequencies rather than by the absence of effects. However, 110 MHz is the upper frequency limit of the FM broadcast band. Threshold currents that result in biological effects ranging in severity from perception to pain have been measured in controlled experiments on volunteers (Chatterjee et al. 1986; Tenforde and Kaune 1987; Bernhardt 1988); these are summarized in Table 3. In general, it has been shown that the threshold currents that produce perception and pain vary little over the frequency range 100 kHz–1 MHz and are unlikely to vary significantly over the frequency range up to about 110 MHz. As noted earlier for lower frequencies, significant variations between the sensitivities of men, women, and children also exist for higher frequency fields. The data in Table 3 represent the range of 50th percentile values for people of different sizes and different levels of sensitivity to contact currents.

Table 3. Ranges of threshold currents for indirect effects, including children, women, and men.

Indirect effect	Threshold current (mA) at frequency: 100 kHz	Threshold current (mA) at frequency: 1 MHz
Touch perception	25–40	25–40
Pain on finger contact	33–55	28–50
Painful shock/let-go threshold	112–224	Not determined
Severe shock/breathing difficulty	160–320	Not determined

Summary of biological effects and epidemiological studies (100 kHz–300 GHz)

Available experimental evidence indicates that the exposure of resting humans for approximately 30 min to EMF producing a whole-body SAR of between 1 and 4 W kg^{-1} results in a body temperature increase of less than 1 °C. Animal data indicate a threshold for behavioral responses in the same SAR range. Exposure to more intense fields, producing SAR values in excess of 4 W kg^{-1}, can overwhelm the thermoregulatory capacity of the body and produce harmful levels of tissue heating. Many laboratory studies with rodent and non-human primate models have demonstrated the broad range of tissue damage resulting from either partial-body or whole-body heating producing temperature rises in excess of 1–2°C. The sensitivity of various types of tissue to thermal damage varies widely, but the threshold for irreversible effects in even the most sensitive tissues is greater than 4 W kg^{-1} under normal environmental conditions. These data form the basis for an occupational exposure restriction of 0.4 W kg^{-1}, which provides a large margin of safety for other limiting conditions such as high ambient temperature, humidity, or level of physical activity.

Both laboratory data and the results of limited human studies (Michaelson and Elson 1996) make it clear that thermally stressful environments and the use of drugs or alcohol can compromise the thermoregulatory capacity of the body. Under these conditions, safety factors should be introduced to provide adequate protection for exposed individuals.

Data on human responses to high-frequency EMF that produce detectable heating have been obtained from controlled exposure of volunteers and from epidemiological studies on workers exposed to sources such as radar, medical diathermy equipment, and heat sealers. They are fully supportive of the conclusions drawn from laboratory work, that adverse biological effects can be caused by temperature rises in tissue that exceed 1°C. Epidemiological studies on exposed workers and the general public have shown no major health effects associated with typical exposure environments. Although there are deficiencies in the epidemiological work, such as poor exposure assessment, the studies have yielded no convincing evidence that typical exposure levels lead to adverse reproductive outcomes or an increased cancer risk in exposed individuals. This is consistent with the results of laboratory research on cellular and animal models, which have demonstrated neither teratogenic nor carcinogenic effects of exposure to athermal levels of high-frequency EMF.

Exposure to pulsed EMF of sufficient intensity leads to certain predictable effects such as the microwave hearing phenomenon and various behavioral responses. Epidemiological studies on exposed workers and the general public have provided limited information and failed to demonstrate any health effects. Reports of severe retinal damage have been challenged following unsuccessful attempts to replicate the findings.

A large number of studies of the biological effects of amplitude-modulated EMF, mostly conducted with low levels of exposure, have yielded both positive and negative results. Thorough analysis of these studies reveals that the effects of AM fields vary widely with the exposure parameters, the types of cells and tissues involved, and the biological end-points that are examined. In general, the effects of exposure of biological systems to athermal levels of amplitude-modulated EMF are small and very difficult to relate to potential health effects. There is no convincing evidence of frequency and power density windows of response to these fields.

Shocks and burns can be the adverse indirect effects of high-frequency EMF involving human contact with metallic objects in the field. At frequencies of 100 kHz–110 MHz (the upper limit of the FM broadcast band), the threshold levels of contact current that produce effects ranging from perception to severe pain do not vary significantly as a function of the field frequency. The threshold for perception ranges from 25 to 40 mA in individuals of different sizes, and that for pain from approximately 30 to 55 mA; above 50 mA there may be severe burns at the site of tissue contact with a metallic conductor in the field.

GUIDELINES FOR LIMITING EMF EXPOSURE

Occupational and general public exposure limitations

The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions. By contrast, the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals. In many cases, members of the public are unaware of their exposure to EMF. Moreover, individual members of the public cannot reasonably be expected to take precautions to minimize or avoid exposure. It is these considerations that underlie the adoption of more stringent exposure restrictions for the public than for the occupationally exposed population.

Basic restrictions and reference levels

Restrictions on the effects of exposure are based on established health effects and are termed basic restrictions. Depending on frequency, the physical quantities used to specify the basic restrictions on exposure to EMF are current density, SAR, and power density. Protection against adverse health effects requires that these basic restrictions are not exceeded.

Reference levels of exposure are provided for comparison with measured values of physical quantities; compliance with all reference levels given in these guidelines will ensure compliance with basic restrictions. If measured values are higher than reference levels, it does not necessarily follow that the basic restrictions have been exceeded, but a more detailed analysis is necessary to assess compliance with the basic restrictions.

General statement on safety factors

There is insufficient information on the biological and health effects of EMF exposure of human populations and experimental animals to provide a rigorous basis for establishing safety factors over the whole frequency range and for all frequency modulations. In addition, some of the uncertainty regarding the appropriate safety factor derives from a lack of knowledge regarding the appropriate dosimetry (Repacholi 1998). The following general variables were considered in the development of safety factors for high-frequency fields:

- effects of EMF exposure under severe environmental conditions (high temperature, etc.) and/or high activity levels; and
- the potentially higher thermal sensitivity in certain population groups, such as the frail and/or elderly, infants and young children, and people with diseases or taking medications that compromise thermal tolerance.

The following additional factors were taken into account in deriving reference levels for high-frequency fields:

- differences in absorption of electromagnetic energy by individuals of different sizes and different orientations relative to the field; and
- reflection, focusing, and scattering of the incident field, which can result in enhanced localized absorption of high-frequency energy.

Basic restrictions

Different scientific bases were used in the development of basic exposure restrictions for various frequency ranges:

- Between 1 Hz and 10 MHz, basic restrictions are provided on current density to prevent effects on nervous system functions;
- Between 100 kHz and 10 GHz, basic restrictions on SAR are provided to prevent whole-body heat stress and excessive localized tissue heating; in the 100 kHz–10 MHz range, restrictions are provided on both current density and SAR; and
- Between 10 and 300 GHz, basic restrictions are provided on power density to prevent excessive heating in tissue at or near the body surface.

In the frequency range from a few Hz to 1 kHz, for levels of induced current density above 100 mA m^{-2}, the thresholds for acute changes in central nervous system excitability and other acute effects such as reversal of the visually evoked potential are exceeded. In view of the safety considerations above, it was decided that, for frequencies in the range 4 Hz to 1 kHz, occupational exposure should be limited to fields that induce current densities less than 10 mA m^{-2}, i.e., to use a safety factor of 10. For the general public an additional factor of 5 is applied, giving a basic exposure restriction of 2 mA m^{-2}. Below 4 Hz and above 1 kHz, the basic restriction on induced current density increases progressively, corresponding to the increase in the threshold for nerve stimulation for these frequency ranges.

Established biological and health effects in the frequency range from 10 MHz to a few GHz are consistent with responses to a body temperature rise of more than 1°C. This level of temperature increase results from exposure of individuals under moderate environmental conditions to a whole-body SAR of approximately 4 W kg^{-1} for about 30 min. A whole-body average SAR of 0.4 W kg^{-1} has therefore been chosen as the restriction that provides adequate protection for occupational exposure. An additional safety factor of 5 is introduced for exposure of the public, giving an average whole-body SAR limit of 0.08 W kg^{-1}.

The lower basic restrictions for exposure of the general public take into account the fact that their age and health status may differ from those of workers.

In the low-frequency range, there are currently few data relating transient currents to health effects. The ICNIRP therefore recommends that the restrictions on current densities induced by transient or very short-term peak fields be regarded as instantaneous values which should not be time-averaged.

The basic restrictions for current densities, whole-body average SAR, and localized SAR for frequencies between 1 Hz and 10 GHz are presented in Table 4, and those for power densities for frequencies of 10–300 GHz are presented in Table 5.

REFERENCE LEVELS

Where appropriate, the reference levels are obtained from the basic restrictions by mathematical modeling and by extrapolation from the results of laboratory investigations at specific frequencies. They are given for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. Tables 6 and 7 summarize the reference levels for occupational exposure and exposure of the general public, respectively, and the reference levels are illustrated in Figs. 1 and 2. The reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded.

For low-frequency fields, several computational and measurement methods have been developed for deriving field-strength reference levels from the basic restrictions.

Table 4. Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz.[a]

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localized SAR (head and trunk) (W kg^{-1})	Localized SAR (limbs) (W kg^{-1})
Occupational exposure	up to 1 Hz	40	—	—	—
	1–4 Hz	$40/f$	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	$f/100$	—	—	—
	100 kHz–10 MHz	$f/100$	0.4	10	20
	10 MHz–10 GHz	—	0.4	10	20
General public exposure	up to 1 Hz	8	—	—	—
	1–4 Hz	$8/f$	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	$f/500$	—	—	—
	100 kHz–10 MHz	$f/500$	0.08	2	4
	10 MHz–10 GHz	—	0.08	2	4

[a] Note:

1. f is the frequency in hertz.
2. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm^2 perpendicular to the current direction.
3. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ ($\sim$1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
4. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.
5. All SAR values are to be averaged over any 6-min period.
6. Localized SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.
7. For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. Additionally, for pulsed exposures in the frequency range 0.3 to 10 GHz and for localized exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 10 mJ kg^{-1} for workers and 2mJ kg^{-1} for the general public, averaged over 10 g tissue.

Table 5. Basic restrictions for power density for frequencies between 10 and 300 GHz.[a]

Exposure characteristics	Power density (W m^{-2})
Occupational exposure	50
General public	10

[a] Note:

1. Power densities are to be averaged over any 20 cm^2 of exposed area and any $68/f^{1.05}$-min period (where f is in GHz) to compensate for progressively shorter penetration depth as the frequency increases.
2. Spatial maximum power densities, averaged over 1 cm^2, should not exceed 20 times the values above.

The simplifications that have been used to date did not account for phenomena such as the inhomogeneous distribution and anisotropy of the electrical conductivity and other tissue factors of importance for these calculations.

The frequency dependence of the reference field levels is consistent with data on both biological effects and coupling of the field.

Magnetic field models assume that the body has a homogeneous and isotropic conductivity and apply simple circular conductive loop models to estimate induced currents in different organs and body regions, e.g., the head, by using the following equation for a pure sinusoidal field at frequency f derived from Faraday's law of induction:

$$J = \pi R f \sigma \mathrm{B}, \tag{4}$$

where B is the magnetic flux density and R is the radius of the loop for induction of the current. More complex models use an ellipsoidal model to represent the trunk or the whole body for estimating induced current densities at the surface of the body (Reilly 1989, 1992).

If, for simplicity, a homogeneous conductivity of 0.2 S m^{-1} is assumed, a 50-Hz magnetic flux density of 100 μT generates current densities between 0.2 and 2 mA m^{-2} in the peripheral area of the body (CRP 1997). According to another analysis (NAS 1996), 60-Hz exposure levels of 100 μT correspond to average current densities of 0.28 mA m^{-2} and to maximum current densities of approximately 2 mA m^{-2}. More realistic calculations based on anatomically and electrically refined models (Xi and Stuchly 1994) resulted in maximum current densities exceeding 2 mA m^{-2} for a 100-μT field at 60 Hz. However, the presence of biological cells affects the spatial pattern of induced currents and fields, resulting in significant differences in both magnitude (a factor of 2 greater) and patterns of flow of the induced current compared with those predicted by simplified analyses (Stuchly and Xi 1994).

Electric field models must take into account the fact that, depending on the exposure conditions and the size, shape, and position of the exposed body in the field, the surface charge density can vary greatly, resulting in a variable and non-uniform distribution of currents inside the body. For sinusoidal electric fields at frequencies below about 10 MHz, the magnitude of the induced current density inside the body increases with frequency. The induced current density distribution varies inversely with the body cross-section and may be relatively high in the neck and ankles. The exposure level of 5 kV m^{-1} for exposure of the general public corresponds, under worst-case conditions, to an induced current density of about 2 mA m^{-2} in the neck and trunk of the body if the E-field vector is parallel to the body axis (ILO 1994; CRP 1997). However, the current density induced by 5 kV m^{-1} will comply with the basic restrictions under realistic worst-case exposure conditions.

For purposes of demonstrating compliance with the basic restrictions, the reference levels for the electric and magnetic fields should be considered separately and not additively. This is because, for protection purposes, the currents induced by electric and magnetic fields are not additive.

For the specific case of occupational exposures at frequencies up to 100 kHz, the derived electric fields can be increased by a factor of 2 under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.

At frequencies above 10 MHz, the derived electric and magnetic field strengths were obtained from the whole-body SAR basic restriction using computational and experimental data. In the worst case, the energy coupling reaches a maximum between 20 MHz and several hundred MHz. In this frequency range, the derived reference levels have minimum values. The derived magnetic field strengths were calculated from the electric field strengths by using the far-field relationship between E and H (E/H = 377 ohms). In the near-field, the SAR frequency dependence curves are no longer valid; moreover, the contributions of the electric and magnetic field components have to be considered separately. For a conservative approximation, field exposure levels can be used for near-field assessment since the coupling of energy from the electric or magnetic field contribution cannot exceed the SAR restrictions. For a less conservative assessment, basic restrictions on the whole-body average and local SAR should be used.

Reference levels for exposure of the general public have been obtained from those for occupational exposure by using various factors over the entire frequency range. These factors have been chosen on the basis of effects that are recognized as specific and relevant for the various frequency ranges. Generally speaking, the factors follow the basic restrictions over the entire frequency range, and their values correspond to the mathematical relation between the quantities of the basic restrictions and the derived levels as described below:

- In the frequency range up to 1 kHz, the general public reference levels for electric fields are one-half of the values set for occupational exposure. The value of 10 kV m^{-1} for a 50-Hz or 8.3 kV m^{-1} for a 60-Hz occupational exposure includes a sufficient safety margin to prevent stimulation effects from contact currents under all possible conditions. Half of this value was chosen for the general public reference levels, i.e.,

Table 6. Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values).[a]

Frequency range	E-field strength ($V\ m^{-1}$)	H-field strength ($A\ m^{-1}$)	B-field (μT)	Equivalent plane wave power density S_{eq} ($W\ m^{-2}$)
up to 1 Hz	—	1.63×10^5	2×10^5	—
1–8 Hz	20,000	$1.63 \times 10^5/f^2$	$2 \times 10^5/f^2$	—
8–25 Hz	20,000	$2 \times 10^4/f$	$2.5 \times 10^4/f$	—
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	—
0.82–65 kHz	610	24.4	30.7	—
0.065–1 MHz	610	$1.6/f$	$2.0/f$	—
1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	—
10–400 MHz	61	0.16	0.2	10
400–2,000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$0.01f^{1/2}$	$f/40$
2–300 GHz	137	0.36	0.45	50

[a] Note:

1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any 6-min period.
4. For peak values at frequencies up to 100 kHz see Table 4, note 3.
5. For peak values at frequencies exceeding 100 kHz see Figs. 1 and 2. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1,000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
6. For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any $68/f^{1.05}$-min period (f in GHz).
7. No E-field value is provided for frequencies <1 Hz, which are effectively static electric fields. Electric shock from low impedance sources is prevented by established electrical safety procedures for such equipment.

Table 7. Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values).[a]

Frequency range	E-field strength ($V\ m^{-1}$)	H-field strength ($A\ m^{-1}$)	B-field (μT)	Equivalent plane wave power density S_{eq} ($W\ m^{-2}$)
up to 1 Hz	—	3.2×10^4	4×10^4	—
1–8 Hz	10,000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$	—
8–25 Hz	10,000	$4{,}000/f$	$5{,}000/f$	—
0.025–0.8 kHz	$250/f$	$4/f$	$5/f$	—
0.8–3 kHz	$250/f$	5	6.25	—
3–150 kHz	87	5	6.25	—
0.15–1 MHz	87	$0.73/f$	$0.92/f$	—
1–10 MHz	$87/f^{1/2}$	$0.73/f$	$0.92/f$	—
10–400 MHz	28	0.073	0.092	2
400–2,000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	$0.0046f^{1/2}$	$f/200$
2–300 GHz	61	0.16	0.20	10

[a] Note:

1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2, and B^2 are to averaged over any 6-min period.
4. For peak values at frequencies up to 100 kHz see Table 4, note 3.
5. For peak values at frequencies exceeding 100 kHz see Figs. 1 and 2. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width does not exceed 1,000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
6. For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any $68/f^{1.05}$-min period (f in GHz).
7. No E-field value is provided for frequencies <1 Hz, which are effectively static electric fields. perception of surface electric charges will not occur at field strengths less than 25 kVm^{-1}. Spark discharges causing stress or annoyance should be avoided.

5 kV m^{-1} for 50 Hz or 4.2 kV m^{-1} for 60 Hz, to prevent adverse indirect effects for more than 90% of exposed individuals;

- In the low-frequency range up to 100 kHz, the general public reference levels for magnetic fields are set at a factor of 5 below the values set for occupational exposure;
- In the frequency range 100 kHz–10 MHz, the general public reference levels for magnetic fields have been increased compared with the limits given in the 1988 IRPA guideline. In that guideline, the magnetic field strength reference levels were calculated from the electric field strength reference levels by using the far-field

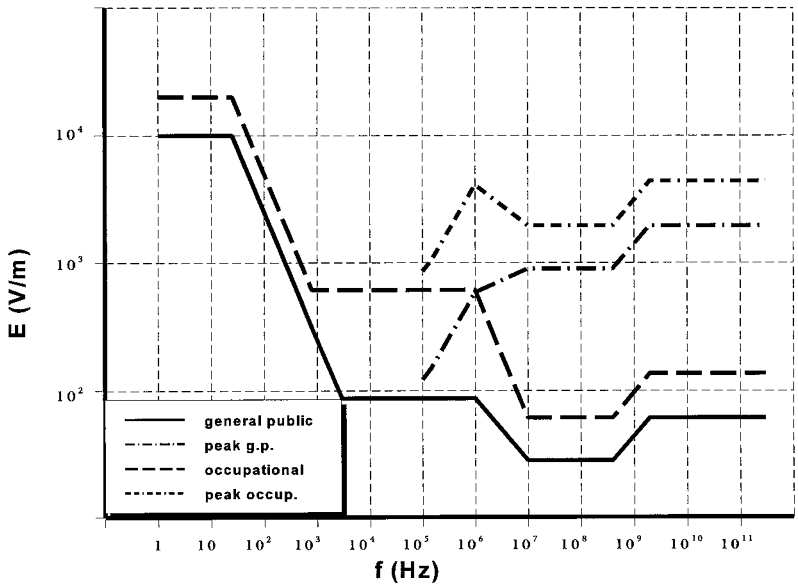

Fig. 1. Reference levels for exposure to time varying electric fields (compare Tables 6 and 7).

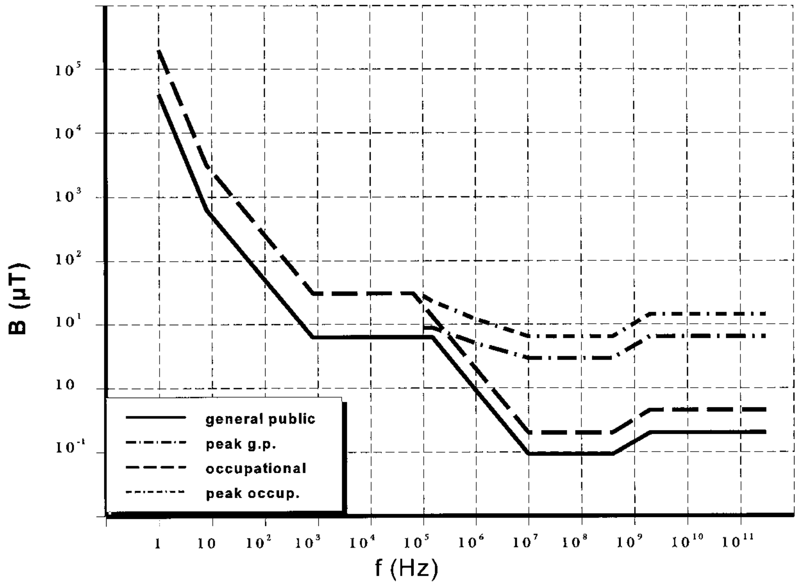

Fig. 2. Reference levels for exposure to time varying magnetic fields (compare Tables 6 and 7).

formula relating E and H. These reference levels are too conservative, since the magnetic field at frequencies below 10 MHz does not contribute significantly to the risk of shocks, burns, or surface charge effects that form a major basis for limiting occupational exposure to electric fields in that frequency range;

- In the high-frequency range 10 MHz–10 GHz, the general public reference levels for electric and magnetic fields are lower by a factor of 2.2 than those set for occupational exposure. The factor of 2.2 corresponds to the square root of 5, which is the safety factor between the basic restrictions for occupational exposure and those for general public exposure. The square root is used to relate the quantities "field strength" and "power density;"

- In the high-frequency range 10–300 GHz, the general public reference levels are defined by the power density, as in the basic restrictions, and are lower by a factor of 5 than the occupational exposure restrictions;
- Although little information is available on the relation between biological effects and peak values of pulsed fields, it is suggested that, for frequencies exceeding 10 MHz, S_{eq} as averaged over the pulse width should not exceed 1,000 times the reference levels or that field strengths should not exceed 32 times the field strength reference levels given in Tables 6 and 7 or shown in Figs. 1 and 2. For frequencies between about 0.3 GHz and several GHz, and for localized exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion the specific absorption from pulses must limited. In this frequency range, the threshold SA of 4–16 mJ kg^{-1} for producing this effect corresponds, for 30-μs pulses, to peak SAR values of 130–520 W kg^{-1} in the brain. Between 100 kHz and 10 MHz, peak values for the field strengths in Figs. 1 and 2 are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz.
- In Tables 6 and 7, as well as in Figs. 1 and 2, different frequency break-points occur for occupational and general public derived reference levels. This is a consequence of the varying factors used to derive the general public reference levels, while generally keeping the frequency dependence the same for both occupational and general public levels.

REFERENCE LEVELS FOR CONTACT AND INDUCED CURRENTS

Up to 110 MHz, which includes the FM radio transmission frequency band, reference levels for contact current are given above which caution must be exercised to avoid shock and burn hazards. The point contact reference levels are presented in Table 8. Since the threshold contact currents that elicit biological responses in children and adult women are approximately one-half and two-thirds, respectively, of those for adult men, the reference levels for contact current for the general public are set lower by a factor of 2 than the values for occupational exposure.

For the frequency range 10–110 MHz, reference levels are provided for limb currents that are below the basic restrictions on localized SAR (see Table 9).

SIMULTANEOUS EXPOSURE TO MULTIPLE FREQUENCY FIELDS

It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects. Additivity should be examined separately for the effects of thermal and electrical stimulation, and the basic restrictions below should be met. The formulae below apply to relevant frequencies under practical exposure situations.

For electrical stimulation, relevant for frequencies up to 10 MHz, induced current densities should be added according to

$$\sum_{i=1\text{ Hz}}^{10\text{ MHz}} \frac{J_i}{J_{L,i}} \leq 1. \qquad (5)$$

For thermal effects, relevant above 100 kHz, SAR and power density values should be added according to:

$$\sum_{i=100\text{ kHz}}^{10\text{ GHz}} \frac{SAR_i}{SAR_L} + \sum_{i>10\text{ GHz}}^{300\text{ GHz}} \frac{S_i}{S_L} \leq 1, \qquad (6)$$

where

J_i = the current density induced at frequency i;
$J_{L,\,i}$ = the induced current density restriction at frequency i as given in Table 4;
SAR_i = the SAR caused by exposure at frequency i;
SAR_L = the SAR limit given in Table 4;
S_L = the power density limit given in Table 5; and
S_i = the power density at frequency i.

For practical application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied.

Table 8. Reference levels for time varying contact currents from conductive objects.[a]

Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational exposure	up to 2.5 kHz	1.0
	2.5–100 kHz	0.4*f*
	100 kHz–110 MHz	40
General public exposure	up to 2.5 kHz	0.5
	2.5–100 kHz	0.2*f*
	100 kHz–110 MHz	20

[a] *f* is the frequency in kHz.

Table 9. Reference levels for current induced in any limb at frequencies between 10 and 110 MHz.[a]

Exposure characteristics	Current (mA)
Occupational exposure	100
General public	45

[a] Note:
1. The public reference level is equal to the occupational reference level divided by $\sqrt{5}$.
2. For compliance with the basic restriction on localized SAR, the square root of the time-averaged value of the square of the induced current over any 6-min period forms the basis of the reference levels.

For induced current density and electrical stimulation effects, relevant up to 10 MHz, the following two requirements should be applied to the field levels:

$$\sum_{i=1\ \mathrm{Hz}}^{1\ \mathrm{MHz}} \frac{E_i}{E_{L,i}} + \sum_{i>1\ \mathrm{MHz}}^{10\ \mathrm{MHz}} \frac{E_i}{a} \leq 1, \qquad (7)$$

and

$$\sum_{j=1\ \mathrm{Hz}}^{65\ \mathrm{kHz}} \frac{H_j}{H_{L,j}} + \sum_{j>65\ \mathrm{kHz}}^{10\ \mathrm{MHz}} \frac{H_j}{b} \leq 1, \qquad (8)$$

where

E_i = the electric field strength at frequency i;
$E_{L,\,i}$ = the electric field reference level from Tables 6 and 7;
H_j = the magnetic field strength at frequency j;
$H_{L,\,j}$ = the magnetic field reference level from Tables 6 and 7;
a = 610 V m^{-1} for occupational exposure and 87 V m^{-1} for general public exposure; and
b = 24.4 A m^{-1} (30.7 μT) for occupational exposure and 5 A m^{-1} (6.25 μT) for general public exposure.

The constant values a and b are used above 1 MHz for the electric field and above 65 kHz for the magnetic field because the summation is based on induced current densities and should not be mixed with thermal considerations. The latter forms the basis for $E_{L,i}$ and $H_{L,j}$ above 1 MHz and 65 kHz, respectively, found in Tables 6 and 7.

For thermal considerations, relevant above 100 kHz, the following two requirements should be applied to the field levels:

$$\sum_{i=100\ \mathrm{kHz}}^{1\ \mathrm{MHz}} \left(\frac{E_i}{c}\right)^2 + \sum_{i>1\ \mathrm{MHz}}^{300\ \mathrm{GHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1, \qquad (9)$$

and

$$\sum_{j=100\ \mathrm{kHz}}^{1\ \mathrm{MHz}} \left(\frac{H_j}{d}\right)^2 + \sum_{j>1\ \mathrm{MHz}}^{300\ \mathrm{GHz}} \left(\frac{H_j}{H_{L,j}}\right)^2 \leq 1, \qquad (10)$$

where

E_i = the electric field strength at frequency i;
$E_{L,\,i}$ = the electric field reference level from Tables 6 and 7;
H_j = the magnetic field strength at frequency j;
$H_{L,\,i}$ = the magnetic field reference level from Tables 6 and 7;
c = 610/f V m^{-1} (f in MHz) for occupational exposure and 87/$f^{1/2}$ V m^{-1} for general public exposure; and
d = 1.6/f A m^{-1} (f in MHz) for occupational exposure and 0.73/f for general public exposure.

For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{k=10\ \mathrm{MHz}}^{110\ \mathrm{MHz}} \left(\frac{I_k}{I_{L,k}}\right)^2 \leq 1 \qquad \sum_{n=1\ \mathrm{Hz}}^{110\ \mathrm{MHz}} \frac{I_n}{I_{C,n}} \leq 1, \qquad (11)$$

where

I_k = the limb current component at frequency k;
$I_{L,\,k}$ = the reference level of limb current (see Table 9);
I_n = the contact current component at frequency n; and
$I_{C,\,n}$ = the reference level of contact current at frequency n (see Table 8).

The above summation formulae assume worst-case conditions among the fields from the multiple sources. As a result, typical exposure situations may in practice require less restrictive exposure levels than indicated by the above formulae for the reference levels.

PROTECTIVE MEASURES

ICNIRP notes that the industries causing exposure to electric and magnetic fields are responsible for ensuring compliance with all aspects of the guidelines.

Measures for the protection of workers include engineering and administrative controls, personal protection programs, and medical surveillance (ILO 1994). Appropriate protective measures must be implemented when exposure in the workplace results in the basic restrictions being exceeded. As a first step, engineering controls should be undertaken wherever possible to reduce device emissions of fields to acceptable levels. Such controls include good safety design and, where necessary, the use of interlocks or similar health protection mechanisms.

Administrative controls, such as limitations on access and the use of audible and visible warnings, should be used in conjunction with engineering controls. Personal protection measures, such as protective clothing, though useful in certain circumstances, should be regarded as a last resort to ensure the safety of the worker; priority should be given to engineering and administrative controls wherever possible. Furthermore, when such items as insulated gloves are used to protect individuals from high-frequency shock and burns, the basic restrictions must not be exceeded, since the insulation protects only against indirect effects of the fields.

With the exception of protective clothing and other personal protection, the same measures can be applied to the general public whenever there is a possibility that the general public reference levels might be exceeded. It is also essential to establish and implement rules that will prevent:

- interference with medical electronic equipment and devices (including cardiac pacemakers);

- detonation of electro-explosive devices (detonators); and
- fires and explosions resulting from ignition of flammable materials by sparks caused by induced fields, contact currents, or spark discharges.

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APPENDIX

Glossary

Absorption. In radio wave propagation, attenuation of a radio wave due to dissipation of its energy, i.e., conversion of its energy into another form, such as heat.

Athermal effect. Any effect of electromagnetic energy on a body that is not a heat-related effect.

Blood-brain barrier. A functional concept developed to explain why many substances that are transported by blood readily enter other tissues but do not enter the brain; the "barrier" functions as if it were a continuous membrane lining the vasculature of the brain. These brain capillary endothelial cells form a nearly continuous barrier to entry of substances into the brain from the vasculature.

Conductance. The reciprocal of resistance. Expressed in siemens (S).

Conductivity, electrical. The scalar or vector quantity which, when multiplied by the electric field strength, yields the conduction current density; it is the reciprocal of resistivity. Expressed in siemens per meter ($S\ m^{-1}$).

Continuous wave. A wave whose successive oscillations are identical under steady-state conditions.

Current density. A vector of which the integral over a given surface is equal to the current flowing through the surface; the mean density in a linear conductor is equal to the current divided by the cross-sectional area of the conductor. Expressed in ampere per square meter ($A\ m^{-2}$).

Depth of penetration. For a plane wave electromagnetic field (EMF), incident on the boundary of a good conductor, depth of penetration of the wave is the depth at which the field strength of the wave has been reduced to 1/e, or to approximately 37% of its original value.

Dielectric constant. See permittivity.

Dosimetry. Measurement, or determination by calculation, of internal electric field strength or induced current density, of the specific energy absorption, or specific energy absorption rate distribution, in humans or animals exposed to electromagnetic fields.

Electric field strength. The force (E) on a stationary unit positive charge at a point in an electric field; measured in volt per meter ($V\ m^{-1}$).

Electromagnetic energy. The energy stored in an electromagnetic field. Expressed in joule (J).

ELF. Extremely low frequency; frequency below 300 Hz.

EMF. Electric, magnetic, and electromagnetic fields.

Far field. The region where the distance from a radiating antenna exceeds the wavelength of the radiated EMF; in the far-field, field components (E and H) and the direction of propagation are mutually perpendicular, and the shape of the field pattern is independent of the distance from the source at which it is taken.

Frequency. The number of sinusoidal cycles completed by electromagnetic waves in 1 s; usually expressed in hertz (Hz).

Impedance, wave. The ratio of the complex number (vector) representing the transverse electric field at a point to that representing the transverse magnetic field at that point. Expressed in ohm (Ω).

Magnetic field strength. An axial vector quantity, H, which, together with magnetic flux density, specifies a magnetic field at any point in space, and is expressed in ampere per meter ($A\ m^{-1}$).

Magnetic flux density. A vector field quantity, B, that results in a force that acts on a moving charge or charges, and is expressed in tesla (T).

Magnetic permeability. The scalar or vector quantity which, when multiplied by the magnetic field strength, yields magnetic flux density; expressed in henry per meter (H m^{-1}). *Note:* For isotropic media, magnetic permeability is a scalar; for anisotropic media, it is a tensor quantity.

Microwaves. Electromagnetic radiation of sufficiently short wavelength for which practical use can be made of waveguide and associated cavity techniques in its transmission and reception. *Note:* The term is taken to signify radiations or fields having a frequency range of 300 MHz–300 GHz.

Near field. The region where the distance from a radiating antenna is less than the wavelength of the radiated EMF. *Note:* The magnetic field strength (multiplied by the impedance of space) and the electric field strength are unequal and, at distances less than one-tenth of a wavelength from an antenna, vary inversely as the square or cube of the distance if the antenna is small compared with this distance.

Non-ionizing radiation (NIR). Includes all radiations and fields of the electromagnetic spectrum that do not normally have sufficient energy to produce ionization in matter; characterized by energy per photon less than about 12 eV, wavelengths greater than 100 nm, and frequencies lower than 3×10^{15} Hz.

Occupational exposure. All exposure to EMF experienced by individuals in the course of performing their work.

Permittivity. A constant defining the influence of an isotropic medium on the forces of attraction or repulsion between electrified bodies, and expressed in farad per metre (F m^{-1}); *relative permittivity* is the permittivity of a material or medium divided by the permittivity of vacuum.

Plane wave. An electromagnetic wave in which the electric and magnetic field vectors lie in a plane perpendicular to the direction of wave propagation, and the magnetic field strength (multiplied by the impedance of space) and the electric field strength are equal.

Power density. In radio wave propagation, the power crossing a unit area normal to the direction of wave propagation; expressed in watt per square meter (W m^{-2}).

Public exposure. All exposure to EMF experienced by members of the general public, excluding occupational exposure and exposure during medical procedures.

Radiofrequency (RF). Any frequency at which electromagnetic radiation is useful for telecommunication. *Note:* In this publication, radiofrequency refers to the frequency range 300 Hz –300 GHz.

Resonance. The change in amplitude occurring as the frequency of the wave approaches or coincides with a natural frequency of the medium; whole-body absorption of electromagnetic waves presents its highest value, i.e., the resonance, for frequencies (in MHz) corresponding approximately to $114/L$, where L is the height of the individual in meters.

Root mean square (rms). Certain electrical effects are proportional to the square root of the mean of the square of a periodic function (over one period). This value is known as the effective, or root-mean-square (rms) value, since it is derived by first squaring the function, determining the mean value of the squares obtained, and taking the square root of that mean value.

Specific energy absorption. The energy absorbed per unit mass of biological tissue, (SA) expressed in joule per kilogram (J kg^{-1}); specific energy absorption is the time integral of specific energy absorption rate.

Specific energy absorption rate (SAR). The rate at which energy is absorbed in body tissues, in watt per kilogram (W kg^{-1}); SAR is the dosimetric measure that has been widely adopted at frequencies above about 100 kHz.

Wavelength. The distance between two successive points of a periodic wave in the direction of propagation, at which the oscillation has the same phase.

■ ■

11.4 Uredba

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Uredba

E.01/1 *(Uradni list RS, št. 70/96)*

Na podlagi prvega in drugega odstavka 27. člena zakona o varstvu okolja (Uradni list RS, št. 32/93 in 1/96) in 21. člena zakona o Vladi Republike Slovenije (Uradni list RS, št. 4/93 in 23/96) izdaja Vlada Republike Slovenije

Uredbo o elektromagnetnem sevanju v naravnem in življenjskem okolju

I. SPLOŠNE DOLOČBE

1. člen

Ta uredba določa v zvezi z elektromagnetnim sevanjem v okolju (v nadaljnjem besedilu: sevanje) mejne vrednosti veličin elektromagnetnega polja v okolju, stopnje varstva pred sevanjem v posameznih območjih naravnega in življenjskega okolja, način določanja in vrednotenja obremenitve okolja zaradi sevanja ter ukrepe za zmanjševanje in preprečevanje čezmernega sevanja.

Določbe te uredbe veljajo za sevanje zunaj nadzorovanih območij, ki ga v posameznih območjih naravnega in življenjskega okolja povzročajo stalne ali občasne emisije enega ali več virov obremenjevanja okolja s sevanjem (v nadaljnjem besedilu: vir sevanja) razen za sevanje naprav, ki so namenjene diagnostiki ali zdravljenju v zdravstvu, in za sevanje premičnih ali prenosnih oddajnih ali radarskih sistemov za obrambne potrebe ter za zaščito, reševanje in pomoč.

2. člen

Pojmi imajo po tej uredbi naslednji pomen:

1 Elektromagnetno sevanje je sevanje, ki pri uporabi ali obratovanju vira sevanja v njegovi bližnji ali daljni okolici povzroča elektromagnetno polje, in je tveganje za škodljive učinke za človeka in živo naravo. Bližnje polje je elektromagnetno polje v neposredni bližini vira sevanja, kjer elektromagnetno polje nima značilnosti ravnega valovanja. Daljno polje je elektromagnetno polje na vplivnem področju vira sevanja, vendar toliko daleč od vira, da že ima značilnost ravnega valovanja.

2 Vir sevanja je visokonapetostni transformator, razdelilna transformatorska postaja, nadzemni ali podzemni vod za prenos električne energije, odprt oddajni sistem za brezžično komunikacijo, radijski ali televizijski oddajnik, radar ali druga naprava ali objekt, katerega uporaba ali obratovanje obremenjuje okolje z:

- nizkofrekvenčnim elektromagnetnim sevanjem od 0 Hz do vključno 10 kHz (v nadaljnjem besedilu: nizkofrekvenčni vir sevanja) in je nazivna napetost, pri kateri vir sevanja obratuje, večja od 1kV ali
- visokofrekvenčnim elektromagnetnim sevanjem od 10 kHz do vključno 300 GHz in je njegova največja oddajna moč večja od 100 W (v nadaljnjem besedilu: visokofrekvenčni vir sevanja).

Amaterska radijska postaja ni vir sevanja.

3 Obstoječi vir sevanja je vir sevanja, ki je bil v uporabi ali je obratoval na dan začetka veljavnosti te uredbe ali za katerega je bilo skladno s predpisi pred začetkom veljavnosti te uredbe pridobljeno gradbeno dovoljenje.

4 Rekonstrukcija vira sevanja je vsak poseg v vir sevanja, s katerim se bistveno spremenijo glavne tehnične značilnosti, način uporabe ali obratovanja ali zmogljivost vira in ima za posledico spremembo moči, jakosti ali vrste elektromagnetnega polja.

5 Nadzemni vod je električni vod z vodniki nad zemljo, običajno podprtimi z izolatorji in ustreznimi podporniki.

6 Amaterska radijska postaja je radijska postaja po predpisih o radioamaterski dejavnosti.

7 Nadzorovano območje je ograjeno in označeno območje okrog vira sevanja, kjer je vstop dovoljen samo osebju, ki vir upravlja ali vzdržuje.

8 Nemoteno elektromagnetno polje (v nadaljnjem besedilu: nemoteno polje) je zaradi sevanja povzročeno elektromagnetno polje na vplivnem področju vira sevanja, kadar niso prisotni premikajoči se objekti ali osebe. V nemotenem polju je izbran kraj meritev veličin elektromagnetnega polja.

9 Električna poljska jakost E (v nadaljnjem besedilu: električna poljska jakost) je veličina elektromagnetnega polja, ki opisuje električno polje, povzročeno zaradi vira sevanja, in se izraža v voltih na meter (V/m).

10 Gostota magnetnega pretoka B (v nadaljnjem besedilu: gostota magnetnega pretoka) je veličina elektromagnetnega polja, ki opisuje magnetno polje, povzročeno zaradi vira sevanja, in se izraža v teslih (T).

11 Magnetna poljska jakost H (v nadaljnjem besedilu: magnetna poljska jakost) je veličina elektromagnetnega polja, ki je povezana z gostoto magnetnega pretoka preko permeabilnosti in se izraža **v** amperih na meter (A/m).

12 Gostota pretoka moči S (v nadaljnjem besedilu: gostota pretoka moči) je moč elektromagnetnega polja, ki ji je izpostavljena površina, postavljena pravokotno na smer elektromagnetnega valovanja in se izraža v watih na kvadratni meter (W/m^2).

13 Mejna vrednost veličine elektromagnetnega polja (v nadaljnjem besedilu: mejna vrednost) je vrednost veličine, določena s to uredbo za posamezno območje naravnega ali življenskega okolja, na podlagi katere se določa čezmerna obremenitev okolja zaradi sevanja in se izraža kot:

- mejna efektivna vrednost električne poljske jakosti in gostote magnetnega pretoka ter mejna temenska vrednost električne poljske jakosti in gostote magnetnega pretoka za elektromagnetno polje, ki je posledica emisije nizkofrekvenčnih virov sevanja,
- mejna efektivna vrednost električne in magnetne poljske jakosti ter mejna vrednost povprečne

vrednosti gostote pretoka moči za elektromagnetno polje, ki je posledica emisije visokofrekvenčnih virov sevanja,

- mejna temenska vrednost električne in magnetne poljske jakosti ter mejna temenska vrednost gostote pretoka moči za primere impulznega elektromagnetnega polja, ki je posledica emisije visokofrekvenčnih virov sevanja.

14 Efektivna vrednost veličin elektromagnetnega polja se določa za periodična polja in je za eliptično polarizirano elektromagnetno polje enaka:

$$E = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

kjer so E_x, E_y in E_z efektivne vrednosti komponent električne poljske jakosti. Enako velja tudi za magnetno poljsko jakost.

15 Povprečna vrednost gostote pretoka moči se določa za periodična elektromagnetna sevanja in je enaka povprečni vrednosti produkta električne in magnetne poljske jakosti, izračunane za čas najdaljše periode elektromagnetnega sevanja kot posledice vira sevanja.

16 Temenska vrednost veličin elektromagnetnega polja je največja trenutna vrednost, ki jo doseže veličina. Če gre za impulzna elektromagnetna sevanja, je temenska vrednost veličine največja vrednost veličine v času trajanja impulza brez upoštevanja konic in drugih nezaželenih delov impulza, ki ne presegajo 5 % celotne energije impulza.

17 Prve meritve so meritve, ki se izvedejo pri prvem zagonu novega ali rekonstruiranega vira sevanja.

18 Občasne meritve so meritve elektromagnetnega polja, povzročenega zaradi uporabe ali obratovanja virov sevanja, ki se opravljajo v predpisanih časovnih presledkih v okviru predpisanega obratovalnega monitoringa.

3. člen

Stopnji varstva pred sevanjem, določeni glede na občutljivost posameznega območja naravnega ali življenjskega okolja (v nadaljnjem besedilu: območje) za učinke elektromagnetnega polja, ki jih povzročajo viri sevanja, sta I. in II. stopnja.

I stopnja varstva pred sevanjem velja za I. območje, ki potrebuje povečano varstvo pred sevanjem. I. območje je območje bolnišnic, zdravilišč, okrevališč ter turističnih objektov, namenjenih bivanju in rekreaciji, čisto stanovanjsko območje, območje objektov vzgojnovarstvenega in izobraževalnega programa ter programa osnovnega zdravstvenega varstva, območje igrišč ter javnih parkov, javnih zelenih in rekreacijskih površin, trgovsko-poslovno-stanovanjsko območje, ki je hkrati namenjeno bivanju in obrtnim ter podobnim proizvodnim dejavnostim, javno središče, kjer se opravljajo upravne, trgovske, storitvene ali gostinske dejavnosti, ter tisti predeli območja, namenjenega kmetijski dejavnosti, ki so hkrati namenjeni bivanju (v nadaljnjem besedilu: I. območje).

II stopnja varstva pred sevanjem velja za II. območje, kjer je dopusten poseg v okolje, ki je zaradi sevanja bolj moteč. II. območje je zlasti območje brez stanovanj, namenjeno industrijski ali obrtni ali drugi podobni proizvodni dejavnosti, transportni, skladiščni ali servisni dejavnosti ter vsa druga območja, ki niso v prejšnjem odstavku določena kot I. območje (v nadaljnjem besedilu: II. območje).

II stopnja varstva pred sevanjem velja tudi na površinah, ki so v I. območju namenjene javnemu cestnemu ali železniškemu prometu.

II. MEJNE VREDNOSTI ZA NIZKOFREKVENČNE VIRE SEVANJA

4. člen

Mejne efektivne vrednosti električne poljske jakosti kot posledice obratovanja ali uporabe nizkofrekvenčnih virov sevanja so za I. in II. območje določene v tabeli 1.

Tabela 1: Mejne efektivne vrednosti električne poljske jakosti

Frekvenčno območje (Hz)	Mejna efektivna vrednost električne poljske jakosti ($E_{RL,i}$) (kV/m)	
	I. območje - za nove in rekonstruirane vire sevanja	II. območje - za nove in rekonstruirane vire sevanja in I. in II. območje - za obstoječe vire sevanja
> 0 =< 0,1	0,7 (1)	14 (1)
> 0,1 =< 60	0,5	10
> 60 =< 1.500	30/f (2)	600/f (2)
> 1.500 =< 10.000	0,04	0,4

(1) - za frekvenčno območje od 0 do 0,1 Hz mejni vrednosti veljata za temenske vrednosti električne poljske jakosti.

(2) - f je frekvenca, izražena v Hz.

Mejne efektivne vrednosti gostote magnetnega pretoka kot posledice obratovanja ali uporabe nizkofrekvenčnih virov sevanja so za I. in II. območje določene v tabeli 2.

Tabela 2: Mejne efektivne vrednosti gostote magnetnega pretoka

Frekvenčno območje (Hz)	Mejna efektivna gostote magnetnega pretoka ($B_{RL,i}$) (mT)	
	I. območje - za nove in rekonstruirane vire sevanja	II. območje - za nove in rekonstruirane vire sevanja in I. in II. območje - za obstoječe vire sevanja
> 0 =< 0,1	4 (1)	40 (1)
> 0,1 =< 1,15	2,8	28
> 1,15 =< 1.500	0,5/f (2)	5/f (2)
> 1.500 =< 10.000	0,002	0,021

(1) - za frekvenčno območje od 0 do 0,1 Hz mejni

vrednosti veljata za temenske vrednosti gostote magnetnega pretoka

(2) - f je frekvenca, izražena v Hz.

III. MEJNE VREDNOSTI ZA VISOKOFREKVENČNE VIRE SEVANJA

5. člen

Mejne efektivne vrednosti električne in magnetne poljske jakosti ter povprečne vrednosti gostote pretoka moči kot posledice obratovanja ali uporabe visokofrekvenčnih virov sevanja so za I. območje določene v tabeli 3.

Tabela 3: Mejne efektivne vrednosti za I. območje

Frekvenčno območje (MHz)	Mejna efektivna vrednost električne poljske jakosti ($L_{E,i}$) (V/m)	Mejna efektivna vrednost magnetne poljske jakosti ($L_{H,i}$) (A/m)	Mejna povprečna vrednost gostote pretoka moči ($L_{S,i}$) (W/m^2)
> 0,01 =< 0,042	126	5,3	-
> 0,042 =< 0,68	126	0,22/f (1)	-
> 0,68 =< 10	86/f (1)	0,22/f (1)	-
> 10 =< 400	8,6	0,022	0,2
> 400 =< 2.000	$0{,}43.\sqrt{f}$ (1)	$1{,}15.10^{-3}\sqrt{f}$ (1)	f/2000 (1)
> 2.000 =< 150.000	19	0,05	1
> 150.000 =< 300.000	$0{,}05.\sqrt{f}$ (1)	$1{,}32.10^{-3}\sqrt{f}$ (1)	$0{,}67.10^{-5}.f$ (1)

(1) - f je frekvenca, izražena v MHz.

Mejne vrednosti, določene v tabeli 3, veljajo tudi za elektromagnetno polje, ki je posledica obratovanja ali uporabe rekonstruiranega visokofrekvenčnega vira sevanja.

Mejne efektivne vrednosti električne in magnetne poljske jakosti ter gostote pretoka moči kot posledice obratovanja ali uporabe visokofrekvenčnih virov sevanja so za II. območje določene v tabeli 4.

Tabela 4: Mejne efektivne vrednosti za II. območje

Frekvenčno območje (MHz)	Mejna efektivna vrednost električne poljske jakosti ($L_{E,i}$) (V/m)	Mejna efektivna vrednost magnetne poljske jakosti ($L_{H,i}$) (A/m)	Mejna povprečna vrednost gostote pretoka moči ($L_{S,i}$) (W/m^2)
> 0,01 =< 0,042	400	16,8	-
> 0,042 =< 0,68	400	0,7/f (1)	-
> 0,68 =< 10	275/f (1)	0,7/f (1)	-
> 10 =< 400	27,5	0,07	2
> 400 =< 2.000	$1{,}37.\sqrt{f}$ (1)	$3{,}64.10^{-3}\sqrt{f}$ (1)	f/200 (1)
> 2.000 =< 150.000	61.4	0,163	10
> 150.000 =< 300.000	$0{,}158.\sqrt{f}$ (1)	$4{,}21.10^{-3}\sqrt{f}$ (1)	$6{,}67.10^{-5}.f$ (1)

(1) - f je frekvenca, izražena v MHz.

Mejne vrednosti, določene v tabeli 4, veljajo tudi za elektromagnetno polje, ki je posledica obratovanja ali uporabe rekonstruiranega visokofrekvenčnega vira sevanja.

6. člen

Mejne efektivne vrednosti električne in magnetne poljske jakosti ter gostote pretoka moči kot posledice obratovanja ali uporabe obstoječih visokofrekvenčnih virov sevanja v I. in II. območju so določene v tabeli 4 prejšnjega člena.

7. člen

Mejne vrednosti za temenske vrednosti električne poljske jakosti, magnetne poljske jakosti in gostote pretoka moči kot posledice obratovanja ali uporabe visokofrekvenčnih virov sevanja, ki veljajo pri izpostavljenosti impulznim elektromagnetnim poljem s časom trajanja manj kot 100 µs, so za I. območje določene v tabeli 5.

Tabela 5: Mejne vrednosti za izpostavljenost impulznim elektromagnetnim poljem na I. območju

Frekvenčno območje (MHz)	Temenska vrednost električne poljske jakosti (V/m)	Temenska vrednost magnetne poljske jakosti (A/m)	Temenska vrednost gostote pretoka moči (W/m^2)
> 0,01 =< 0,25	612	25	-
> 0,25 =<4,16	612	6,3/f (1)	-
> 4,16 =< 10	2510/f (1)	6,3/f (1)	-
> 10 =< 400	236	0,63	158
> 400 =< 2.000	12.$\sqrt{f}$ (1)	0,03.$\sqrt{f}$ (1)	0,39.f (1)
> 2.000 =< 150.000	561	1,31	793
> 150.000 =< 300.000	1,44.$\sqrt{f}$ (1)	0,003.$\sqrt{f}$ (1)	0,005.f (1)

(1) - f je frekvenca, izražena v MHz.

Mejne vrednosti, določene v tabeli 5, veljajo tudi za impulzno elektromagnetno polje, ki je posledica obratovanja ali uporabe rekonstruiranega visokofrekvenčnega vira sevanja.

Mejne vrednosti za temenske vrednosti električne poljske jakosti, magnetne poljske jakosti in gostote pretoka moči kot posledice obratovanja ali uporabe visokofrekvenčnih virov sevanja, ki veljajo pri izpostavljenosti impulznim elektromagnetnim poljem, so za II. območje določene v tabeli 6.

Tabela 6: Mejne vrednosti za izpostavljenost impulznim elektromagnetnim poljem na II. območju

Frekvenčno območje (MHz)	Temenska vrednost električne poljske jakosti (V/m)	Temenska vrednost magnetne poljske jakosti (A/m)	Temenska vrednost gostote pretoka moči (W/m^2)
> 0,01 =< 0,25	1.936	80	-
> 0,25 =<4,16	1.936	20/f (1)	-
> 4,16 =< 10	7.940/f (1)	20/f (1)	-
> 10 =< 400	749	2	1.588
> 400 =< 2.000	39,7.$\sqrt{f}$ (1)	0,1$\sqrt{f}$ (1)	3,97.f (1)
> 2.000 =< 150.000	1.775	4,17	7.934
> 150.000 =< 300.000	4,58.$\sqrt{f}$ (1)	0,0115$\sqrt{f}$ (1)	0,053.f (1)

(1) - f je frekvenca, izražena v MHz.

Mejne vrednosti, določene v tabeli 6, veljajo tudi za impulzno elektromagnetno polje, ki je posledica obratovanja ali uporabe rekonstruiranega visokofrekvenčnega vira sevanja.

8. člen

Mejne vrednosti za temenske vrednosti električne poljske jakosti, magnetne poljske jakosti in gostote pretoka kot posledice obratovanja ali uporabe obstoječih visokofrekvenčnih virov sevanja v I. in II. območju pri izpostavljenosti impulznim elektromagnetnim poljem so določene v tabeli 6 prejšnjega člena.

IV. DOLOČANJE IN VREDNOTENJE OBREMENITVE S SEVANJEM

9. člen

Celotna obremenitev območja s sevanjem kot posledice obratovanja ali uporabe vseh virov sevanja se ugotavlja tako, da se na kraju meritev izmerijo in vrednotijo veličine elektromagnetnega polja, za katere so s to uredbo določene mejne vrednosti. Celotna obremenitev območja s sevanjem zaradi nizkofrekvenčnih virov sevanja in zaradi visokofrekvenčnih virov sevanja se ugotavlja ločeno. Če so med visokofrekvenčnimi viri sevanja, ki obremenjujejo območje, tudi viri z impulznim načinom delovanja, se obremenitev območja zaradi izpostavljenosti impulznim elektromagnetnim poljem vrednoti posebej.

10. člen

Obremenitev območja s sevanjem kot posledice obratovanja ali uporabe posameznega vira sevanja se ugotavlja tako, da se na kraju meritev izmerijo in vrednotijo veličine elektromagnetnega polja, za katere so s to uredbo določene mejne vrednosti, pri čemer se za frekvenčno območje, v katerem obravnavani vir seva, ne upoštevajo deleži elektromagnetnega polja, ki so na kraju meritev posledica emisije vseh drugih pomembnih virov sevanja.

Če je za posamezni vir sevanja predpisan računski postopek vrednotenja veličin elektromagnetnega polja, kot posledice obratovanja ali uporabe posameznega vira sevanja, se lahko namesto iz rezultatov meritev vrednotijo veličine elektromagnetnega polja na kraju imisije na podlagi podatkov o obratovanju vira sevanja, ko ta s sevanjem najbolj obremenjuje okolje. Računske postopke za izračun veličin elektromagnetnega polja na kraju imisije za posamezni vir sevanja predpiše minister, pristojen za okolje.

Nizkofrekvenčni vir sevanja je pomemben vir sevanja, če njegovo obratovanje ali uporaba na kraju meritev pomeni, da je:

- efektivna vrednost električne poljske jakosti ali gostote magnetnega pretoka oziroma
- temenska vrednost električne poljske jakosti ali gostote magnetnega pretoka, če gre za frekvenčno območje od 0 do 0,1 Hz,

najmanj v enem frekvenčnem območju večja od 20% vrednosti, ki je kot mejna vrednost za nove nizkofrekvenčne vire sevanja določena s to uredbo.

Visokofrekvenčni vir sevanja je pomemben vir sevanja, če njegovo obratovanje ali uporaba na kraju meritev pomeni, da je:

- efektivna vrednost električne ali magnetne poljske jakosti oziroma
- temenska vrednost, če gre za impulzno sevanje,

najmanj za eno frekvenčno območje večja od 20 % vrednosti, ki je kot mejna vrednost za nove visokofrekvenčne vire sevanja določena s to uredbo.

11. člen

Obremenitev območja s sevanjem, ki je posledica obratovanja ali uporabe enega ali več nizkofrekvenčnih virov sevanja, je čezmerna , če so izpolnjeni pogoji iz priloge 1, ki je sestavni del te uredbe.

Če se ugotavlja celotna obremenitev območja, kjer obratuje ali se uporablja najmanj en obstoječi nizkofrekvenčni vir sevanja, ki je po določbah drugega odstavka prejšnjega člena pomemben vir sevanja, se za izračun čezmernosti obremenitve iz priloge 1 upoštevajo mejne vrednosti električne poljske jakosti in gostote magnetnega pretoka, ki v tabelah 1 in 2 iz 4. člena te uredbe veljajo za obstoječe nizkofrekvenčne vire sevanja.

12. člen

Obremenitev območja s sevanjem, ki je posledica obratovanja ali uporabe enega ali več visokofrekvenčnih virov sevanja, je čezmerna, če so izpolnjeni pogoji iz priloge 2, ki je sestavni del te uredbe.

Če se ugotavlja celotna obremenitev območja, kjer obratuje ali se uporablja najmanj en obstoječi visokofrekvenčni vir sevanja, ki je po določbah tretjega odstavka 10. člena te uredbe pomemben vir sevanja, se za izračun čezmernosti obremenitve iz priloge 2 upoštevajo mejne vrednosti veličin elektromagnetnega polja, ki po 6. členu te uredbe veljajo za obstoječe visokofrekvenčne vire sevanja.

13. člen

Obremenitev območja s sevanjem, ki je posledica obratovanja ali uporabe enega ali več visokofrekvenčnih virov sevanja, je pri izpostavljenosti impulznim elektromagnetnim poljem čezmerna, če so izpolnjeni pogoji iz priloge 4, ki je sestavni del te uredbe.

Če se ugotavlja celotna obremenitev območja, kjer obratuje ali se uporablja najmanj en obstoječi visokofrekvenčni vir sevanja, ki je po določbah tretjega odstavka 10. člena te uredbe pomemben vir sevanja, se za izračun čezmernosti obremenitve iz prejšnjih odstavkov upoštevajo mejne vrednosti veličin elektromagnetnega polja, ki po 8. členu te uredbe veljajo za obstoječe visokofrekvenčne vire sevanja.

14. člen

Vir sevanja povzroča na kraju meritve čezmerno obremenitev, če je ob neupoštevanju vseh drugih pomembnih virov sevanja celotna obremenitev območja, določena na način iz 11., 12. ali 13. člena te uredbe, čezmerna.

V. UKREPI ZMANJŠEVANJA SEVANJA

15. člen

Nov poseg v okolje ali rekonstrukcija objekta ali naprave, ki je vir sevanja, ne sme povzročiti čezmerne obremenitve iz 14. člena te uredbe.

Nov poseg v okolje ali rekonstrukcija objekta ali naprave, ki je vir sevanja, ne sme povzročiti čezmerne celotne obremenitve območja s sevanjem, če s predpisi določene mejne vrednosti na tem območju še niso presežene.

Nov poseg v okolje ali rekonstrukcija objekta ali naprave ne sme povzročiti povečanja celotne obremenitve območja s sevanjem, če je celotna obremenitev območja zaradi sevanja že čezmerna.

Rekonstrukcija obstoječega podzemnega ali nadzemnega voda za prenos električne energije v I. območju lahko povzroči čezmerno obremenitev za vir sevanja iz 14. člena te uredbe in čezmerno celotno obremenitev območja s sevanjem, če se ta ne ugotavlja skladno z določbami drugega odstavka 11. člena te uredbe in če se zaradi obratovanja nadzemnega voda ne poveča obremenitev na vplivnem območju vira sevanja v nobenem od bivalnih ali drugih prostorov v zgradbah, v katerih se ljudje zadržujejo.

Če se čezmerna celotna obremenitev območja s sevanjem ugotavlja skladno z določbami drugega odstavka 11. člena te uredbe, lahko rekonstrukcija iz prejšnjega odstavka povzroča čezmerno obremenitev za vir sevanja iz 14. člena te uredbe s tem, da se zaradi obratovanja vira sevanja ne poveča obremenitev na vplivnem območju vira sevanja v nobenem od bivalnih ali drugih prostorov v zgradbah, v katerih se ljudje zadržujejo.

Ne glede na obremenitev prostorov iz prejšnjih dveh odstavkov s sevanjem pred rekonstrukcijo podzemnega ali nadzemnega voda v njih zaradi obratovanja rekonstruiranega vira sevanja efektivna električna poljska jakost ne sme presegati vrednosti 1,8 kV/m in efektivna vrednost gostote magnetnega pretoka vrednosti 15 µT.

16. člen

Nov objekt ali naprava ali objekt ali naprava v rekonstrukciji, ki je vir sevanja, mora za pridobitev dovoljenja za poseg v prostor izpolnjevati te pogoje:

- elektromagnetno polje, ki je posledica uporabe ali obratovanja vira, ne sme povzročati čezmerne obremenitve s sevanjem in
- kjer je obremenitev zaradi sevanja že čezmerna, morajo biti pri uporabi ali obratovanju obravnavanega vira zagotovljeni ukrepi varstva pred sevanjem, ki zagotavljajo izpolnjenost pogoja iz tretjega odstavka prejšnjega člena.

Za izračun obremenitve območja s sevanjem zaradi obratovanja vira sevanja iz prejšnjega odstavka se uporabljajo računski postopki iz drugega odstavka 10. člena te uredbe.

Za objekt ali napravo iz prvega odstavka tega člena, pri kateri se na podlagi zakona presojajo vplivi na okolje, se skladnost s pogoji iz prejšnjega odstavka ugotavlja v postopku za izdajo okoljevarstvenega soglasja.

Za objekt ali napravo iz prvega odstavka tega člena, za katero okoljevarstveno soglasje ni potrebno, mora investitor v zahtevi za dovoljenje za poseg v prostor kot osnovne podatke o namenu in zmogljivosti objekta ali naprave posredovati tudi strokovno oceno obremenitve okolja zaradi sevanja kot posledice uporabe ali obratovanja tega vira sevanja.

Strokovno oceno iz prejšnjega odstavka izdela pravna ali fizična oseba, pooblaščena za izdelavo poročil o vplivih na okolje.

17. člen

Investitor mora pri novem ali rekonstruiranem objektu ali napravi, ki je vir sevanja, zagotoviti prve meritve tistih veličin elektromagnetnega polja kot posledice obremenitve območja zaradi sevanja iz vira, za katere so s to uredbo določene mejne vrednosti

Lastnik ali upravljavec vira sevanja mora kot obratovalni monitoring zagotavljati občasne meritve tistih veličin elektromagnetnega polja kot posledice obremenitve območja s sevanjem iz vira, za katere so s to uredbo določene mejne vrednosti

Obratovalnega monitoringa iz prejšnjega odstavka ni treba zagotavljati za:

- nizkofrekvenčni vir sevanja na II. območju,
- nizkofrekvenčni vir sevanja na I. območju, katerega nazivna napetost je manjša od 110 kV,
- visokofrekvenčni vir sevanja, katerega največja oddajna moč ne presega 600 W, in
- visokofrekvenčni vir sevanja, katerega največja oddajna moč ne presega 50 kW, če gre za visokofrekvenčni vir sevanja, ki obremenjuje okolje z impulznim elektromagnetnim poljem.

Prve in občasne meritve iz prvega in drugega odstavka tega člena se izvajajo na način in v obsegu, določenima s predpisi o prvih meritvah in obratovalnem monitoringu za vire sevanja.

18. člen

Ministrstvo, pristojno za varstvo okolja, lahko na podlagi vloge lastnika ali upravljavca odobri za vir sevanja spremembo programa obratovalnega monitoringa, če ugotovi, da je lahko pogostost meritev manjša, ker je obremenjevanje okolja s sevanjem enako vse koledarsko leto.

Vloga iz prejšnjega odstavka mora vsebovati poročilo o meritvah veličin elektromagnetnega polja in mnenje izvajalca obratovalnega monitoringa o upravičenosti zahtevane spremembe programa.

Inšpektor, pristojen za varstvo okolja, lahko lastniku ali upravljavcu odredi za vir sevanja spremembo programa obratovalnega monitoringa, če ugotovi, da mora biti pogostost meritev večja, ker se obremenjevanje okolja s sevanjem zaradi uporabe ali obratovanja vira spreminja v obdobju med dvema občasnima meritvama ali ker je zaradi obratovanja vira sevanja obremenitev območja s sevanjem občasno čezmerna.

19. člen

Pri načrtovanju, gradnji ali rekonstrukciji vira sevanja mora investitor izbrati tehnične rešitve in upoštevati dognanja in rešitve, ki zagotavljajo, da mejne vrednosti niso presežene, in hkrati omogočajo najnižjo tehnično dosegljivo obremenitev okolja zaradi sevanja.

Povzročitelj obremenitve okolja s sevanjem mora zagotoviti ograditev bližnjega polja okrog vira sevanja, če vira sevanja ni mogoče namestiti tako, da je onemogočen dostop na območje čezmerne obremenitve okolja zaradi sevanja ali če čezmerne obremenitve okolja zaradi sevanja na tem območju kot posledice obratovanja ali uporabe vira ni mogoče preprečiti z drugimi ukrepi varstva pred sevanjem.

Povzročitelj obremenitve s sevanjem mora inšpektoratu, pristojnemu za varstvo okolja, prijaviti vsako nepravilno obratovanje vira sevanja, ki povzroči čezmerno obremenitev okolja zaradi sevanja. Zemeljski stiki, kratki stiki ter delovanje različnih zaščit se pri napravah in objektih za prenos električne energije v nizkofrekvenčnem območju ne štejejo za nepravilno obratovanje vira sevanja.

20. člen

Amaterske radijske postaje ni dopustno upravljati tako, da:

- največja oddajna moč postaje presega 1,5 kW,
- letni obratovalni čas postaje na I. območju presega 700 ur in
- je aktivni del antene radijske postaje, katere največja oddajna moč presega 250 W, več kot 5 m oddaljen od najbližjega bivalnega ali drugega prostora v zgradbah, kjer se ljudje zadržujejo.

VI. NADZOR

21. člen

Nadzor nad izvajanjem te uredbe opravlja inšpektorat, pristojen za varstvo okolja.

VII. KAZENSKE DOLOČBE

22. člen

Z denarno kaznijo najmanj 200.000 SIT se kaznuje za prekršek gospodarska družba ali druga pravna oseba ali posameznik, ki stori prekršek v zvezi s samostojnim opravljanjem dejavnosti, če ravna v nasprotju z:

- drugim odstavkom 17. člena,
- drugim in tretjim odstavkom 19. člena te uredbe.

Z denarno kaznijo najmanj 50.000 SIT se kaznuje za prekršek iz prejšnjega odstavka tudi odgovorna oseba gospodarske družbe ali druge pravne osebe.

Z denarno kaznijo najmanj 50.000 SIT se kaznuje upravljavec amaterske radijske postaje, če ravna v nasprotju z 20. členom te uredbe.

VIII. PREHODNE IN KONČNE DOLOČBE

23. člen

Povzročitelji čezmerne obremenitve okolja s sevanjem morajo prilagoditi obstoječe vire sevanja zahtevam te uredbe v štiriindvajsetih mesecih po njeni uveljavitvi.

24. člen

Do uveljavitve predpisa o vrstah posegov v okolje, za katere je presoja vplivov na okolje obvezna, se izpolnjevanje pogojev za vse objekte in naprave iz prvega odstavka 16. člena te uredbe ugotavlja na način, določen v tretjem odstavku 16. člena te uredbe.

Do določitve pooblaščenih pravnih ali fizičnih oseb iz četrtega odstavka 16. člena te uredbe strokovno oceno iz tretjega odstavka 16. člena te uredbe izdela Uprava Republike Slovenije za varstvo narave.

25. člen

Ta uredba začne veljati petnajsti dan po objavi v Uradnem listu Republike Slovenije.

Št.353-06/96-4/1-8
Ljubljana, dne 21. november 1996

Vlada Republike Slovenije
dr. Janez Drnovšek l. r.
Predsednik

Priloga 1

Izračun čezmerne obremenitve zaradi sevanja nizkofrekvenčnih virov sevanja.

Obremenitev območja s sevanjem je čezmerna, če na kraju meritev za električno poljsko jakost in gostoto magnetnega pretoka kot posledice obratovanja ali uporabe enega ali več nizkofrekvenčnih virov sevanja najmanj pri eni frekvenci velja:

$$\sum_i E_i / E_{RL,i} > 1 \qquad 0 < \mathrm{f} \le 60\mathrm{Hz}$$

$$\sum_j B_j / B_{RL,j} > 1$$

$$\sum_i E_i / E_{RL,i} + \sum_j B_j / B_{RL,j} > 1 \qquad 60\mathrm{Hz} < \mathrm{f} \le 10\ \mathrm{kHz}$$

kjer je:

E_i - temenska vrednost električne poljske jakosti za frekvenčno območje od 0 do 0,1 Hz oziroma efektivna vrednost električne poljske jakosti za preostala frekvenčna območja,

Bj - temenska vrednost gostote magnetnega pretoka za frekvenčno območje od 0 do 0,1 Hz oziroma efektivna vrednost gostote magnetnega pretoka za preostala frekvenčna območja,

$E_{RL,i}$ - i-temu frekvenčnemu območju ustrezna mejna vrednost električne poljske jakosti iz tabele 1 v 4. členu te uredbe,

$B_{RL,j}$ - j-temu frekvenčnemu območju ustrezna mejna vrednost gostote magnetnega pretoka iz tabele 2 v 4. členu te uredbe.

Pri izračunu iz prejšnjega odstavka se upoštevajo samo deleži pri frekvencah, za katere velja:

- $E_i / E_{max} \ge 0,2$ in
- $B_j / B_{max} \ge 0,2$,

kjer sta E_{max} in B_{max} največja od vseh E_i in B_j, ki prispevajo k elektromagnetnemu polju zaradi sevanja.

Priloga 2

Izračun čezmerne obremenitve zaradi sevanja visokofrekvenčnih virov sevanja.

Obremenitev območja s sevanjem je čezmerna, če na kraju meritev za električno poljsko jakost, magnetno poljsko jakost in gostoto pretoka moči kot posledice obratovanja ali uporabe enega ali več visokofrekvenčnih virov sevanja najmanj pri eni frekvenci velja:

$$\sum_i \frac{E_i}{L_{E,i}} + \sum_j \frac{H_j}{L_{H,j}} > 1 \qquad 10\ \mathrm{kHz} < \mathrm{f} \le 680\ \mathrm{kHz}$$

$$\sum_i \left(\frac{E_i}{L_{E,i}}\right)^2 > 1 \quad \text{ter} \quad \sum_j \left(\frac{H_j}{L_{H,j}}\right)^2 > 1 \qquad 680\ \mathrm{kHz} < \mathrm{f} \le 300\ \mathrm{GHz}$$

$$\sum_i \frac{S_i}{L_{S,i}} > 1 \qquad 10\ \mathrm{MHz} < \mathrm{f} \le 300\ \mathrm{GHz}$$

kjer je:

E_i - efektivna vrednost električne poljske jakosti i-tega vira oziroma i-te frekvence, če vir seva pri več frekvencah,

H_j - efektivna vrednost magnetne poljske jakosti j-tega vira oziroma j-te frekvence, če vir seva pri več frekvencah,

S_j - povprečna vrednost gostote pretoka moči i-tega vira oziroma i-te frekvence, če vir seva pri več frekvencah,

$L_{E,i}$, $L_{H,i}$, $L_{S,i}$ - i-temu frekvenčnemu območju ustrezna mejna vrednost električne, magnetne poljske jakosti in povprečne vrednosti gostote pretoka moči iz tabele 3 in 4 v 5. členu te uredbe.

Če je kraj meritve izpostavljen sevanju, ki traja manj kot 6 minut in je posledica obratovanja ali uporabe enega ali več visokofrekvenčnih virov sevanja, ki sevajo pri frekvencah večjih od 680 kHz, je ne glede na določbe prejšnjega odstavka obremenitev območja čezmerna, če za časovna povprečja iz prvega odstavka priloge 3, ki je sestavni del te uredbe, velja:

$$\sum_i \left(\frac{E_{pov,i}}{L_{E,i}}\right)^2 > 1 \quad \text{ter} \quad \sum_j \left(\frac{H_{pov,j}}{L_{H,j}}\right)^2 > 1 \qquad 680\ \mathrm{kHz} < \mathrm{f} \le 300\ \mathrm{GHz}$$

$$\sum_{\mathrm{i}} \frac{S_{pov,i}}{L_{S,i}} > 1 \qquad 10\ \mathrm{MHz} < \mathrm{f} \le 300\ \mathrm{GHz}$$

kjer je:

$E_{pov,i}$ - časovno povprečje efektivne vrednosti električne poljske jakosti iz prvega odstavka priloge 3 i-tega vira oziroma i-te frekvence, če vir seva pri več frekvencah,

$H_{pov,i}$ - časovno povprečje efektivne vrednosti magnetne poljske jakosti iz prvega odstavka priloge 3 j-tega vira oziroma j-te frekvence, če vir seva pri več frekvencah,

$S_{pov,i}$ - časovno povprečje povprečne vrednosti gostote pretoka moči i-tega vira oziroma i-te frekvence, če vir seva pri več frekvencah,

$L_{E,i}$, $L_{H,i}$, $L_{S,i}$ - i-temu frekvenčnemu območju ustrezna mejna vrednost električne, magnetne poljske jakosti in povprečne vrednosti gostote pretoka moči iz tabele 3 in 4 v 5. členu te uredbe.

Če je kraj meritve izpostavljen sevanju, ki traja manj kot 100 ms in je posledica obratovanja ali uporabe enega ali več visokofrekvenčnih virov sevanja, ki sevajo pri frekvencah manjših ali enaki 680 kHz, je ne glede na določbe prvega odstavka tega člena obremenitev območja čezmerna, če za časovna povprečja iz drugega odstavka priloge 3 velja:

$$\sum_i \frac{E_{pov,i}}{L_{E,i}} + \sum_j \frac{H_{pov,j}}{L_{H,j}} > 1 \qquad 10\ \mathrm{kHz} < f \leq 680\ \mathrm{kHz}$$

kjer je:

$E_{pov,i}$ - časovno povprečje efektivne vrednosti električne poljske jakosti iz drugega odstavka priloge 3 i-tega vira oziroma i-te frekvence, če vir seva pri več frekvencah,

$H_{pov,i}$ - časovno povprečje efektivne vrednosti magnetne poljske jakosti iz drugega odstavka priloge 3 j-tega vira oziroma j-te frekvence, če vir seva pri več frekvencah,

$L_{E,i}$ $L_{H,i}$ - i-temu frekvenčnemu področju ustrezna mejna vrednost električne in magnetne poljske jakosti iz tabele 3 in 4 v 5. členu te uredbe.

Pri izračunu iz prejšnjih odstavkov se upoštevajo samo deleži pri tistih frekvencah ali tistih virih, za katere velja:

- $E_i / E_{max} \geq 0{,}2$ in
- $H_j / H_{max} \geq 0{,}2$,

kjer sta E_{max} in H_{max} največja od vseh E_i in H_j, ki prispevajo k elektromagnetnemu polju zaradi sevanja.

Priloga 3

Izračun časovnih povprečij pri izpostavljenosti sevanju, ki je krajša od 6 minut

Če je čas izpostavljenosti sevanju krajši od 6 minut in je frekvenca večja od 680 kHz, se izračuna:

- časovno povprečje efektivne vrednosti za električno poljsko jakost po enačbi:

$$E_{pov} = \sqrt{\frac{1}{T_2} \sum_n E_n^2 t_n}$$

- časovno povprečje efektivne vrednosti za magnetno poljsko jakost po enačbi:

$$H_{pov} = \sqrt{\frac{1}{T_2} \sum_n H_n^2 t_n} \quad \text{in}$$

- časovno povprečje povprečne vrednosti gostote pretoka moči po enačbi:

$$S_{pov} = \frac{1}{T_2} \sum_n S_n t_{ni}$$

Če je čas izpostavljenosti sevanju krajši od 100 ms in so frekvence manjše ali enake 680 kHz, se izračuna časovno povprečje efektivne vrednosti za električno poljsko jakost po enačbi:

$$E_{pov} = \frac{1}{T_1} \sum_n E_n t_{ni}$$

in časovno povprečje efektivne vrednosti za magnetno poljsko jakost po enačbi:

$$H_{pov} = \frac{1}{T_1} \sum_n H_n t_n$$

Oznake v enačbah iz prejšnjih odstavkov pomenijo:

E_{pov} - časovno povprečje efektivne vrednosti električne poljske jakosti,

H_{pov} - časovno povprečje magnetne poljske jakosti,

S_{pov} - časovno povprečje povprečne vrednosti gostote pretoka moči,

E_n - efektivna vrednost električne poljske jakosti v času n-te izpostavljenosti sevanju,

H_n - efektivna vrednost magnetne poljske jakosti v času n-te izpostavljenosti sevanju,

S_n - povprečna vrednost gostote pretoka moči v času n-te izpostavljenosti sevanju,

t_n - čas trajanja n-te izpostavljenosti sevanju,

T_1 - čas povprečenja, enak 100 ms, in

T_2 - čas povprečenja, enak 6 minut.

11.5 Priporočila 1999/519/EC

Originalen naslov:

Council recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). 1999. Official Journal of the Europena Communities, L199.

Slovenski prevod:

Priporočila Sveta Evrope o omejevanju izpostavljenosti prebivalstva elektromagnetnemu sevanju (0 Hz to 300 GHz).

Uporabljan izraz v tem dokumentu:

Priporočila 1999/519/EC

II

(Acts whose publication is not obligatory)

COUNCIL

COUNCIL RECOMMENDATION

of 12 July 1999

on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)

(1999/519/EC)

THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 152(4), second subparagraph,

Having regard to the proposal from the Commission,

Having regard to the opinion of the European Parliament (1),

Whereas:

(1) In accordance with point (p) of Article 3 of the Treaty, Community action must include a contribution to the attainment of a high level of health protection; the Treaty also makes provision for protecting the health of workers and of consumers;

(2) In its resolution of 5 May 1994 on combating the harmful effects of non-ionising radiation (2), the European Parliament called on the Commission to propose legislative measures seeking to limit the exposure of workers and the public to non-ionising electromagnetic radiation;

(3) Community minimum requirements for the protection of health and safety of workers in relation to electromagnetic fields exist for work with display screen equipment (3); Community measures were introduced to encourage improvements in the safety and health at work of pregnant workers and workers who have recently given birth or are breastfeeding (4) which oblige, *inter alia*, employers to assess activities which involve a specific risk of exposure to non-ionising radiation; minimum requirements have been proposed for the protection of workers from physical agents (5) which include measures against non-ionising radiation; whereas, therefore, this recommendation does not address the protection of workers against occupational exposure to electromagnetic fields;

(4) It is imperative to protect members of the general public within the Community against established adverse health effects that may result as a consequence of exposure to electromagnetic fields;

(5) Measures with regard to electromagnetic fields should afford all Community citizens a high level of protection; provisions by Member States in this area should be based on a commonly agreed framework, so as to contribute to ensuring consistency of protection throughout the Community;

(6) In accordance with the principle of subsidiarity, any new measure taken in an area which does not fall within the exclusive competence of the Community, such as non-ionising radiation protection of the public, may be taken up by the Community only if, by reason of the scale or effects of the proposed action, the objectives proposed can be better achieved by the Community than by Member States;

(7) Actions on limiting the exposure of the general public to electromagnetic fields should be balanced with the other health, safety and security benefits that devices emitting electromagnetic fields bring to the quality of life, in such areas as telecommunications, energy and public security;

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(1) OJC 175, 21.6.1999.

(2) OJ C 205, 25.7.1994, p. 439.

(3) OJ L 156, 21.6.1990, p. 14.

(4) OJ L 348, 28.11.1992, p. 1.

(5) OJC 77, 18.3.1993, p. 12 and,OJC 230, 19.8.1994, p.3.

(8) There is a need to establish by means of recommendations addressed to Member States a Community framework with regard to exposure to electromagnetic fields with the objective of protecting the public;

(9) This recommendation has as its objective the protection of the health of the public and it therefore applies, in particular, to relevant areas where members of the public spend significant time in relation to the effects covered by this recommendation;

(10) The Community framework, which draws on the large body of scientific documentation that already exists, must be based on the best available scientific data and advice in this area and should comprise basic restrictions and reference levels on exposure to electromagnetic fields; recalling that only established effects have been used as the basis for the recommended limitation of exposure; advice on this matter has been given by the International Commission on Non-Ionising Radiation Protection (ICNIRP) and has been endorsed by the Commission's Scientific Steering Committee; the framework should be regularly reviewed and reassessed in the light of new knowledge and developments in technology and applications of sources and practices giving rise to exposure to electromagnetic fields;

(11) Such basic restrictions and reference levels should apply to all radiations emitted by electromagnetic fields with the exception of optical radiation and ionising radiation; for optical radiation the relevant scientific data and advice still require further consideration, and for ionising radiation Community provisions already exist;

(12) In order to assess compliance with the basic restrictions provided in this recommendation, the national and European bodies for standardisation (e.g. Cenelec, CEN) should be encouraged to develop standards within the framework of Community legislation for the purposes of the design and testing of equipment;

(13) Adherence to the recommended restrictions and reference levels should provide a high level of protection as regards the established health effects that may result from exposure to electromagnetic fields but such adherence may not necessarily avoid interference problems with, or effects on the functioning of, medical devices such as metallic protheses, cardiac pacemakers and defibrillators, cochlear implants and other implants; interference problems with pacemakers may occur at levels below the recommended reference levels and should therefore be the object of appropriate precautions which, however, are not within the scope of this recommendation and are dealt with in the context of legislation on electromagnetic compatibility and medical devices;

(14) In accordance with the principle of proportionality, this recommendation provides general principles and methods for the protection of members of the public while leaving it to the Member States to provide for detailed rules as regards the sources and practices which give rise to exposure to electromagnetic fields and the classification, as work-related or not, of conditions of exposure of individuals, in accordance with Community provisions concerning the safety and health protection of workers;

(15) Member States may, in accordance with the Treaty, provide for a higher level of protection than that set out in this recommendation;

(16) Measures by the Member States in this area, whether binding or non-binding, and the way in which they have taken account of this recommendation should be the object of reports at national and Community level;

(17) In order to increase awareness of the risks of, and measures of protection against, electromagnetic fields, Member States should promote the dissemination of information and rules of practice in this field, in particular with regard to the design, installation and use of equipment, so as to aim at obtaining levels of exposure that do not exceed the recommended restrictions;

(18) Attention should be paid to achieving appropriate communication and understanding regarding the risks related to electromagnetic fields, while taking into account public perceptions of such risks;

(19) The Member States should take note of progress made in scientific knowledge and technology with respect to non-ionising radiation protection, taking into account the aspect of precaution, and should provide for regular scrutiny and review with an assessment being made at regular intervals in the light of guidance issued by competent international organisations, such as the International Commission on Non-Ionising Radiation Protection,

HEREBY RECOMMENDS THAT:

I. For the purpose of this recommendation Member States should assign to the physical quantities listed in Annex I.A the meanings given to them therein.

II. Member States, in order to provide for a high level of health protection against exposure to electromagnetic fields, should:

(a) adopt a framework of basic restrictions and reference levels using Annex I.B as the basis;

(b) implement measures according to this framework, in respect of sources or practices giving rise to electromagnetic exposure of the general public when the time of exposure is significant with the exception of exposure for medical purposes where the risks and benefits of exposure, above the basic restrictions, must be properly weighed;

(c) aim to achieve respect of the basic restrictions given in Annex II for public exposure.

III. Member States, in order to facilitate and promote respect of the basic restrictions given in Annex II:

(a) should take into account the reference levels given in Annex III for exposure assessment purposes or, when they exist, as far as they are recognised by the Member State, European or national standards based on agreed scientifically proven measurement and calculation procedures designed to evaluate compliance with the basic restrictions;

(b) should evaluate situations involving sources of more than one frequency in accordance with the formulae set out in Annex IV, both in terms of basic restrictions and reference levels;

(c) may take into account criteria, where appropriate, such as duration of the exposure, exposed parts of the body, age and health status of the public.

IV. Member States should consider both the risks and benefits in deciding whether action is required or not, pursuant to this recommendation, when deciding on policy or adopting measures on exposure of members of the public to electromagnetic fields.

V. Member States, in order to increase understanding of risks and protection against exposure to electromagnetic fields should provide, in an appropriate format, information to the public on the health impact of electromagnetic fields and the measures taken to address them.

VI. Member States, in order to enhance knowledge about the health effects of electromagnetic fields, should promote and review research relevant to electromagnetic fields and human health in the context of their national research programmes, taking into account Community and international research recommendations and efforts from the widest possible range of sources.

VII. Member States, in order to contribute to the establishment of a consistent system of protection against risks of exposure to electromagnetic fields, should prepare reports on the experience obtained with measures that they take in the field covered by this recommendation and should inform the Commission thereof after a period of three years following the adoption of this recommendation, indicating how it has been taken into account in these measures,

HEREBY INVITES the Commission to

1. Work towards the establishment of European standards as referred to in section III(a), including methods of calculation and measure.
2. Encourage research into long and short-term effects of exposure to electromagnetic fields at all relevant frequencies in the implementation of the current research framework programme.
3. Continue to participate in the work of international organisations competent in this field and promote the establishment of an international consensus in guidelines and advice on protective and preventive measures.
4. Keep the matters covered by this recommendation under review, with a view to its revision and updating, taking into account also possible effects, which are currently the object of research, including relevant aspects of precaution and to prepare a report, within five years, taking into account the reports of the Member States and the latest scientific data and advice.

Done at Brussels, 12 July 1999.

For the Council

The President

S. NIINISTÖ

ANNEX I

DEFINITIONS

For the purposes of this recommendation, the term electromagnetic fields (EMF) includes static fields, extremely low frequency (ELF) fields and radiofrequency (RF) fields, including microwaves, encompassing the frequency range of 0 Hz to 300 GHz.

A. Physical quantities

In the context of EMF exposure, eight physical quantities are commonly used:

Contact current (I_C) between a person and an object is expressed in amperes (A). A conductive object in an electric field can be charged by the field.

Current density (J) is defined as the current flowing through a unit cross section perpendicular to its direction in a volume conductor such as the human body or part of it, expressed in amperes per square metre (A/m^2).

Electric field strength is a vector quantity (E) that corresponds to the force exerted on a charged particle regardless of its motion in space. It is expressed in volts per metre (V/m).

Magnetic field strength is a vector quantity (H), which, together with the magnetic flux density, specifies a magnetic field at any point in space. It is expressed in amperes per metre (A/m).

Magnetic flux density is a vector quantity (B), resulting in a force that acts on moving charges, it is expressed in teslas (T). In free space and in biological materials, magnetic flux density and magnetic field strength can be interchanged using the equivalence $1 \text{ A m}^{-1} = 4\pi \ 10^{-7}$ T.

Power density (S) is the appropriate quantity used for very high frequencies, where the depth of penetration in the body is low. It is the radiant power incident perpendicular to a surface, divided by the area of the surface and is expressed in watts per square metre (W/m^2).

Specific energy absorption (SA) is defined as the energy absorbed per unit mass of biological tissue, expressed in joules per kilogram (J/kg). In this recommendation it is used for limiting non-thermal effects from pulsed microwave radiation.

Specific energy absorption rate (SAR) averaged over the whole body or over parts of the body, is defined as the rate at which energy is absorbed per unit mass of body tissue and is expressed in watts per kilogram (W/kg). Whole body SAR is a widely accepted measure for relating adverse thermal effects to RF exposure. Besides the whole body average SAR, local SAR values are necessary to evaluate and limit excessive energy deposition in small parts of the body resulting from special exposure conditions. Examples of such conditions are: a grounded individual exposed to RF in the low MHz range and individuals exposed in the near field of an antenna.

Of these quantities, magnetic flux density, contact current, electric and magnetic field strengths and power density can be measured directly.

B. Basic restrictions and reference levels

For the application of restrictions based on the assessment of possible health effects of electromagnetic fields, differentiation should be made between basic restrictions and reference levels.

Note:

These basic restrictions and reference levels for limiting exposure have been developed following a thorough review of all published scientific literature. The criteria applied in the course of the review were designed to evaluate the credibility of the various reported findings; only established effects were used as a basis for the proposed exposure restrictions. Induction of cancer from long-term EMF exposure was not considered to be established. However, since there are safety factors of about 50 between the threshold values for acute effects and the basis restrictions, this recommendation implicitly covers possible long-term effects in the whole frequency range.

Basic restrictions. Restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields which are based directly on established health effects and biological considerations are termed ‘basic restrictions’. Depending upon the frequency of the field, the physical quantities used to specify these restrictions are magnetic flux density (B), current density (J), specific energy absorption rate (SAR), and power density (S). Magnetic flux density and power density can be readily measured in exposed individuals.

Reference levels. These levels are provided for practical exposure-assessment purposes to determine whether the basic restrictions are likely to be exceeded. Some reference levels are derived from relevant basic restrictions using measurements and/or computational techniques and some reference levels address perception and adverse indirect effects of exposure to EMFs. The derived quantities are electric field strength (E), magnetic field strength (H), magnetic flux density (B), power density (S), and limb current (I_L). Quantities that address perception and other indirect effects are (contact) current (I_C) and, for pulsed fields, specific energy absorption (SA). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level. Respect of the reference level will ensure respect of the relevant basic restriction. If the measured value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. Under such circumstances, however, there is a need to establish whether there is respect of the basic restriction.

Quantitative restrictions on static electric fields are not given in this recommendation. However, it is recommended that annoying perception of surface electric charges and spark discharges causing stress or annoyance should be avoided.

Some quantities such as magnetic flux density (B) and power density (S) serve both as basic restrictions and reference levels, at certain frequencies (see Annexes II and III).

ANNEX II

BASIC RESTRICTIONS

Depending on frequency, the following physical quantities (dosimetric/exposimetric quantities) are used to specify the basic restrictions on electromagnetic fields:

— between 0 and 1 Hz basic restrictions are provided for magnetic flux density for static magnetic fields (0 Hz) and current density for time-varying fields up to 1 Hz, in order to prevent effects on the cardiovascular and central nervous system,

— between 1 Hz and 10 MHz basic restrictions are provided for current density to prevent effects on nervous system functions,

— between 100 kHz and 10 GHz basic restrictions on SAR are provided to prevent whole-body heat stress and excessive localised heating of tissues. In the range 100 kHz to 10 MHz, restrictions on both current density and SAR are provided,

— between 10 GHz and 300 GHz basic restrictions on power density are provided to prevent heating in tissue at or near the body surface.

The basic restrictions, given in Table 1, are set so as to account for uncertainties related to individual sensitivities, environmental conditions, and for the fact that the age and health status of members of the public vary.

Table 1

Basic restrictions for electric, magnetic and electromagnetic fields (0 Hz to 300 GHz)

Frequency range	Magnetic flux density (mT)	Current density (mA/m^2) (rms)	Whole body average SAR (W/kg)	Localised SAR (head and trunk) (W/kg)	Localised SAR (limbs) (W/kg)	Power density, S (W/m^2)
0 Hz	40	—	—	—	—	—
>0-1 Hz	—	8	—	—	—	—
1-4 Hz	—	8/f	—	—	—	—
4-1 000 Hz	—	2	—	—	—	—
1 000 Hz-100 kHz	—	f/500	—	—	—	—
100 kHz-10 MHz	—	f/500	0,08	2	4	—
10 MHz-10 GHz	—	—	0,08	2	4	—
10-300 GHz	—	—	—	—	—	10

Notes:

1. *f* is the frequency in Hz.

2. The basic restriction on the current density is intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body and includes a safety factor. The basic restrictions for ELF fields are based on established adverse effects on the central nervous system. Such acute effects are essentially instantaneous and there is no scientific justification to modify the basic restrictions for exposure of short duration. However, since the basic restriction refers to adverse effects on the central nervous system, this basic restriction may permit higher current densities in body tissues other than the central nervous system under the same exposure conditions.

3. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross section of 1 cm^2 perpendicular to the current direction.

4. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by √2 (~1,414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.

5. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.

6. All SAR values are to be averaged over any six-minute period.

7. Localised SAR averaging mass is any 10g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure. These 10g of tissue are intended to be a mass of contiguous tissue with nearly homogeneous electrical properties. In specifying a contiguous mass of tissue, it is recognised that this concept can be used in computational dosimetry but may present difficulties for direct physical measurements. A simple geometry such as cubic tissue mass can be used provided that the calculated dosimetric quantities have conservative values relative to the exposure guidelines.

8. For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. Additionally, for pulsed exposures, in the frequency range 0,3 to 10 GHz and for localised exposure of the head, in order to limit and avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 2mJ kg^{-1} averaged over 10 g of tissue.

ANNEX III

REFERENCE LEVELS

Reference levels of exposure are provided for the purpose of comparison with values of measured quantities. Respect of all recommended reference levels will ensure respect of basic restrictions.

If the quantities of measured values are greater than the reference levels, it does not necessarily follow that the basic restrictions have been exceeded. In this case, an assessment should be made as to whether exposure levels are below the basic restrictions.

The reference levels for limiting exposure are obtained from the basic restrictions for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. A summary of the reference levels is given in Tables 2 and 3. The reference levels are generally intended to be spatially averaged values over the dimension of the body of the exposed individual, but with the important proviso that the localised basic restrictions on exposure are not exceeded.

In certain situations where the exposure is highly localised, such as with hand-held telephones and the human head, the use of reference levels is not appropriate. In such cases respect of the localised basic restriction should be assessed directly.

Field levels

Table 2

Reference levels for electric, magnetic and electromagnetic fields
(0 Hz to 300 GHz, unperturbed rms values)

Frequency range	E-field strength (V/m)	H-field strength (A/m)	B-field (μT)	Equivalent plane wave power density S_{eq} (W/m^2)
0-1 Hz	—	$3{,}2 \times 10^4$	4×10^4	—
1-8 Hz	10 000	$3{,}2 \times 10^4/f^2$	$4 \times 10^4/f^2$	—
8-25 Hz	10 000	4 000/f	5 000/f	—
0,025-0,8 kHz	250/f	4/f	5/f	—
0,8-3 kHz	250/f	5	6,25	—
3-150 kHz	87	5	6,25	—
0,15-1 MHz	87	0,73/f	0,92/f	—
1-10 MHz	$87/f^{1/2}$	0,73/f	0,92/f	—
10-400 MHz	28	0,073	0,092	2
400-2 000 MHz	$1{,}375\ f^{1/2}$	$0{,}0037\ f^{1/2}$	$0{,}0046\ f^{1/2}$	f/200
2-300 GHz	61	0,16	0,20	10

Notes:

1. *f* as indicated in the frequency range column.
2. For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any six-minute period.
3. For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any $68/f^{1.05}$ -minute period (*f* in GHz).
4. No E-field value is provided for frequencies < 1 Hz, which are effectively static electric fields. For most people the annoying perception of surface electric charges will not occur at field strengths less than 25 kV/m. Spark discharges causing stress or annoyance should be avoided.

Note:

No higher reference levels on exposure to ELF fields are provided when exposures are of short duration (see Note 2 of Table 1). In many cases, where the measured values exceed the reference level, it does not necessarily follow that the basic restriction will be exceeded. Provided that adverse health impacts of indirect effects of exposure (such as microshocks) can be avoided, it is recognised that the general-public reference levels can be exceeded provided that the basic restriction on the current density is not surpassed. In many practical exposure situations external ELF fields at the reference levels will induce current densities in central nervous-system tissues that are below the basic restrictions. Also it is recognised that a number of common devices emit localised fields in excess of the reference levels. However, this generally occurs under conditions of exposure where the basic restrictions are not exceeded because of weak coupling between the field and the body.

For peak values, the following reference levels apply to the E-field strength (V/m), H-field strength (A/m) and the B-field (μT):

— for frequencies up to 100 kHz, peak reference values are obtained by multiplying the corresponding rms values by $\sqrt{2}$ (~1,414). For pulses of duration t_p the equivalent frequency to apply should be calculated as $f = 1\ /(2t_p)$,

— for frequencies between 100 kHz and 10 MHz peak reference values are obtained by multiplying the corresponding rms values by $1O^{\alpha}$, where $\alpha = (O{,}665\ \log(f/10^5) + O{,}176)$, f in Hz,

— for frequencies between 10 MHz and 300 GHz peak reference values are obtained by multiplying the corresponding rms values by 32.

Note:

Generally, with regard to pulsed and/or transient fields at low frequencies, there are frequency-dependent basic restrictions and reference levels from which a hazard assessment and exposure guidelines on pulsed and/or transient sources can be derived. A conservative approach involves representing a pulsed or transient EMF signal as a Fourier spectrum of its components in each frequency range, which can then be compared with the reference levels for those frequencies. The summation formulae for simultaneous exposure to multiple frequency fields can also be applied for the purposes of determining compliance with the basic restrictions.

Although little information is available on the relation between biological effects and peak values of pulsed fields, it is suggested that, for frequencies exceeding 10 MHz, S_{eq} as averaged over the pulse width should not exceed 1 000 times the reference levels or that field strengths should not exceed 32 times the fields strength reference levels. For frequencies between about 0,3 GHz and several GHz and for localised exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, the specific absorption from pulses must be limited. In this frequency range, the threshold SA of 4-16 mJ kg^{-1} for producing this effect corresponds, for 30–μ.s pulses, to peak SAR values of 130-520 W kg^{-1} in the brain. Between 100 kHz and 10 MHz, peak values for the fields strengths are obtained by interpolation from the 1,5-fold peak at 100 kHz to the 32-fold peak at 10 MHz.

Contact currents and limb currents

For frequencies up to 110 MHz additional reference levels are recommended in order to avoid hazards due to contact currents. The contact current reference levels are presented in Table 3. The reference levels on contact current were set to account for the fact that the threshold contact currents that elicit biological responses in adult women and children are approximately two-thirds and one-half, respectively, of those for adult men.

Table 3

Reference levels for contact currents from conductive objects
(f in kHz)

Frequency range	Maximum contact current (mA)
0 Hz-2,5 kHz	0,5
2,5 kHz-100 kHz	0,2 f
100 kHz-110 MHz	20

For the frequency range 10 MHz to 110 MHz, a reference level of 45 mA in terms of current through any limb is recommended. This is intended to limit the localised SAR over any six-minute period.

ANNEX IV

EXPOSURE FROM SOURCES WITH MULTIPLE FREQUENCES

In situations where simultaneous exposure to fields of different frequencies occurs, the possibility that these exposures will be additive in their effects must be considered. Calculations based on such additivity should be performed separately for each effect; thus separate evaluations shoud be made for thermal and electrical stimulation effects on the body.

Basic restrictions

In the case of simultaneous exposure to fields of different frequencies, the following criteria should be satisfied in terms of the basic restrictions.

For electric stimulation, relevant for frequencies from 1 Hz up to 10 MHz, the induced current densities should be added according to:

$$\sum_{i=1\ \mathrm{Hz}}^{10\ \mathrm{MHz}} \frac{J_i}{J_{L,i}} \leq 1$$

For thermal effects, relevant from 100 kHz, specific energy absorption rates and power densities should be added according to:

$$\sum_{i=100\ \mathrm{kHz}}^{10\ \mathrm{GHz}} \frac{SAR_i}{SAR_L} + \sum_{i>10\ \mathrm{GHz}}^{300\ \mathrm{GHz}} \frac{S_i}{S_L} \leq 1$$

where

J_i is the current density at frequency i;

$J_{L,\ i}$ is the current density basic restriction at frequency i as given in Table 1;

SAR_i is the SAR caused by exposure at frequency i;

SAR_L is the SAR basic restriction given in Table 1;

S_i is the power density at frequency i;

S_L is the power density basic restriction given in Table 1.

Reference levels

For application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied.

For induced current densities and electrical stimulation effects, relevant up to 10 MHz, the following two requirements should be applied to the field levels:

$$\sum_{i=1\ \mathrm{Hz}}^{1\ \mathrm{MHz}} \frac{E_i}{E_{L,i}} + \sum_{i>1\ \mathrm{MHz}}^{10\ \mathrm{MHz}} \frac{E_i}{a} \leq 1$$

and

$$\sum_{j=1\ \text{Hz}}^{150\ \text{kHz}} \frac{H_j}{H_{L,j}} + \sum_{j>150\ \text{kHz}}^{10\ \text{MHz}} \frac{H_j}{b} \leq 1$$

where

E_i is the electric field strength at frequency i;

$E_{L,\ i}$ is the electric field strength reference level from Table 2;

H_j is the magnetic field strength at frequency j;

$H_{L,\ j}$ is the magnetic field strength reference level from Table 2;

a is 87 V/m and b is 5 A/m (6,25 µT).

Compared to the ICNIRP guidelines (1) which deal with both occupational and general public exposure, cut off points in the summations correspond to exposure conditions for members of the public.

The use of the constant values (a and b) above 1 MHz for the electric field and above 150 kHz for the magnetic field is due to the fact that the summation is based on induced current densities, and should not be mixed with thermal effect circumstances. The latter forms the basic for $E_{L,\ i}$ and $H_{L,\ j}$ above 1 MHz and 150 kHz respectively, found in Table 2.

For thermal effect circumstances, relevant from 100 kHz, the following two requirements should be applied to the field levels:

$$\sum_{i=100\ \text{kHz}}^{1\ \text{MHz}} \left(\frac{E_i}{c}\right)^2 + \sum_{i>1\ \text{MHz}}^{300\ \text{GHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1$$

$$\sum_{j=100\ \text{kHz}}^{150\ \text{kHz}} \left(\frac{H_j}{d}\right)^2 + \sum_{j>150\ \text{kHz}}^{300\ \text{GHz}} \left(\frac{H_j}{H_{L,j}}\right)^2 \leq 1$$

and where

E_i is the electric field strengthen at frequency i;

$E_{L,\ i}$ is the electric field reference level from Table 2;

H_j is the magnetic field strength at frequency j;

$H_{L,\ j}$ is the magnetic field reference level derived from Table 2;

c is $87/f^{1/2}$ V/m and d 0,73/f A/m.

Again, compared to the ICNIRP guidelines some cut-off points have been adjusted for public exposure only.

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(1) International Commission on Non-Ionising Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Physics 74(4): 494-522(1998). Response to questions and comments on ICNIRP. Health Physics 75(4): 438-439 (1998).

For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{k = 10\ \text{MHz}}^{110\ \text{MHz}} \left(\frac{I_k}{I_{L,k}}\right)^2 \leq 1 \qquad \sum_{n > 1\ \text{Hz}}^{110\ \text{MHz}} \left(\frac{I_n}{I_{C,n}}\right)^2 \leq 1$$

where

l_k is the limb current component at frequency k;

$I_{L,\ k}$ is the reference level for limb current, 45 mA;

l_n is the contact current component at frequency n;

$I_{C,n}$ is the reference level for contact current at frequency (see Table 3).

The above summation formulae assume worst-case phase conditions among the fields from the multiple sources. As a result, typical exposure situations may in practice result in less restrictive exposure levels than indicated by the above formulae for the reference levels.

11.6 Direktiva 2004/40/EC

Originalen naslov:

Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields). 2004. Official Journal of the European Union L 184,

Slovenski prevod:

Direktiva o minimalnih zdravstvenih in varnostnih zahtevah v zvezi z izpostavljenostjo delavcev tveganjem, ki nastajajo zaradi fizikalnih dejavnikov (elektromagnetnih sevanj)

Uporabljan izraz v tem dokumentu:

Direktiva 2004/40EC

CORRIGENDA

Corrigendum to Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)

(Official Journal of the European Union L 159 of 30 April 2004)

Directive 2004/40/EC should read as follows:

DIRECTIVE 2004/40/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 29 April 2004

on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 137(2) thereof,

Having regard to the proposal from the Commission (1), presented after consultation with the Advisory Committee on Safety, Hygiene and Health Protection at Work,

Having regard to the Opinion of the European Economic and Social Committee (2),

Following consultation of the Committee of the Regions,

Acting in accordance with the procedure laid down in Article 251 of the Treaty (3),

Whereas:

(1) Under the Treaty the Council may, by means of directives, adopt minimum requirements for encouraging improvements, especially in the working environment, to guarantee a better level of protection of the health and safety of workers. Such directives are to avoid imposing administrative, financial and legal constraints in a way which would hold back the creation and development of small and medium-sized undertakings.

(2) The communication from the Commission concerning its action programme relating to the implementation of the Community Charter of the Fundamental Social Rights of Workers provides for the introduction of minimum health and safety requirements regarding the exposure of workers to the risks caused by physical agents. In September 1990 the European Parliament adopted a resolution concerning this action programme (4), inviting the Commission in particular to draw up a specific directive on the risks caused by noise and vibration and by any other physical agents at the workplace.

(3) As a first step, the European Parliament and the Council adopted Directive 2002/44/EC of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (16th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) (5). Next, on 6 February 2003, the European Parliament and the Council adopted Directive 2003/10/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) (17th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) (6).

(4) It is now considered necessary to introduce measures protecting workers from the risks associated with electromagnetic fields, owing to their effects on the health and safety of workers. However, the long-term effects, including possible carcinogenic effects due to exposure to time-varying electric, magnetic and electromagnetic fields for which there is no conclusive scientific evidence establishing a causal relationship, are not addressed in this Directive. These measures are intended not only to ensure the health and safety of each worker on an individual basis, but also to create a minimum basis of protection for all Community workers, in order to avoid possible distortions of competition.

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(1) OJ C 77, 18.3.1993, p. 12 and OJ C 230, 19.8.1994, p. 3.

(2) OJ C 249, 13.9.1993, p. 28.

(3) Opinion of the European Parliament of 20 April 1994 (OJ C 128, 9.5.1994, p. 146) confirmed on 16 September 1999 (OJ C 54, 25.2.2000, p. 75), Council Common Position of 18 December 2003 (OJ C E 66, 16.3.2004, p. 1), Position of the European Parliament of 30 March 2004 (not yet published in the Official Journal) and Council Decision of 7 April 2004.

(4) OJ C 260, 15.10.1990, p.167.

(5) OJ L 177, 6.7.2002, p. 13.

(6) OJ L 42, 15.2.2003, p. 38.

(5) This Directive lays down minimum requirements, thus giving Member States the option of maintaining or adopting more favourable provisions for the protection of workers, in particular the fixing of lower values for the action values or the exposure limit values for electromagnetic fields. The implementation of this Directive should not serve to justify any regression in relation to the situation which already prevails in each Member State.

(6) A system of protection against electromagnetic fields should limit itself to a definition, free of excessive detail, of the objectives to be attained, the principles to be observed and the fundamental values to be applied, in order to enable Member States to apply the minimum requirements in an equivalent manner.

(7) The level of exposure to electromagnetic fields can be more effectively reduced by incorporating preventive measures into the design of workstations and by selecting work equipment, procedures and methods so as to give priority to reducing the risks at source. Provisions relating to work equipment and methods thus contribute to the protection of the workers involved.

(8) Employers should make adjustments in the light of technical progress and scientific knowledge regarding risks related to exposure to electromagnetic fields, with a view to improving the safety and health protection of workers.

(9) Since this Directive is an individual Directive within the meaning of Article 16(1) of Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work (7), that Directive therefore applies to the exposure of workers to electromagnetic fields, without prejudice to more stringent and/or specific provisions contained in this Directive.

(10) This Directive constitutes a practical step towards creating the social dimension of the internal market.

(11) The measures necessary for the implementation of this Directive should be adopted in accordance with Council Decision 1999/468/EC of 28 June 1999 laying down the procedures for the exercise of implementing powers conferred on the Commission (8).

(12) Adherence to the exposure limit and action values should provide a high level of protection as regards the established health effects that may result from exposure to electromagnetic fields but such adherence may not necessarily avoid interference problems with, or effects on the functioning of, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, cochlear implants and other implants; interference problems especially with pacemakers may occur at levels below the action values and should therefore be the object of appropriate precautions and protective measures,

HAVE ADOPTED THIS DIRECTIVE:

SECTION I

GENERAL PROVISIONS

Article 1

Aim and scope

1. This Directive, which is the 18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC, lays down minimum requirements for the protection of workers from risks to their health and safety arising or likely to arise from exposure to electromagnetic fields (0 Hz to 300 GHz) during their work.

2. This Directive refers to the risk to the health and safety of workers due to known short-term adverse effects in the human body caused by the circulation of induced currents and by energy absorption as well as by contact currents.

3. This Directive does not address suggested long-term effects.

4. This Directive does not address the risks resulting from contact with live conductors.

5. Directive 89/391/EEC shall apply fully to the whole area referred to in paragraph 1, without prejudice to more stringent and/or more specific provisions contained in this Directive.

Article 2

Definitions

For the purposes of this Directive, the following definitions shall apply:

(a) ‘electromagnetic fields’: static magnetic and time-varying electric, magnetic and electromagnetic fields with frequencies up to 300 GHz;

(b) ‘exposure limit values’: limits on exposure to electromagnetic fields which are based directly on established health effects and biological considerations. Compliance with these limits will ensure that workers exposed to electromagnetic fields are protected against all known adverse health effects;

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(7) OJ L 183, 29.6.1989, p. 1. Directive as amended by Regulation (EC) No 1882/2003 of the European Parliament and of the Council (OJ L 284, 31.10.2003, p. 1).

(8) OJ L 184, 17.7.1999, p. 23.

(c) 'action values': the magnitude of directly measurable parameters, provided in terms of electric field strength (E), magnetic field strength (H), magnetic flux density (B) and power density (S), at which one or more of the specified measures in this Directive must be undertaken. Compliance with these values will ensure compliance with the relevant exposure limit values.

Article 3

Exposure limit values and action values

1. The exposure limit values are as set out in the Annex, Table 1.

2. The action values are as set out in the Annex, Table 2.

3. For the assessment, measurement and/or calculation of workers' exposure to electromagnetic fields, until harmonised European standards from the European Committee for Electrotechnical Standardisation (Cenelec) cover all relevant assessment, measurement and calculation situations, Member States may employ other scientifically-based standards or guidelines.

SECTION II

OBLIGATIONS OF EMPLOYERS

Article 4

Determination of exposure and assessment of risks

1. In carrying out the obligations laid down in Articles 6(3) and 9(1) of Directive 89/391/EEC, the employer shall assess and, if necessary, measure and/or calculate the levels of electromagnetic fields to which workers are exposed. Assessment, measurement and calculation may, until harmonised European standards from Cenelec cover all relevant assessment, measurement and calculation situations, be carried out in accordance with the scientifically-based standards and guidelines referred to in Article 3 and, when relevant, by taking into account the emission levels provided by the manufacturers of the equipment when it is covered by the relevant Community Directives.

2. On the basis of the assessment of the levels of electromagnetic fields undertaken in accordance with paragraph 1, if the action values referred to in Article 3 are exceeded, the employer shall assess and, if necessary, calculate whether the exposure limit values are exceeded.

3. The assessment, measurement and/or calculations referred to in paragraphs 1 and 2 need not be carried out in workplaces open to the public provided that an evaluation has already been undertaken in accordance with the provisions of Council Recommendation 1999/519/EC of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (O Hz to 300 GHz) (9), and the restrictions as specified therein are respected for workers and safety risks are excluded.

4. The assessment, measurement and/or calculations referred to in paragraphs 1 and 2 shall be planned and carried out by competent services or persons at suitable intervals, taking particular account of the provisions of Articles 7 and 11 of Directive 89/391/EEC concerning the necessary competent services or persons and the consultation and participation of workers. The data obtained from the assessment, measurement and/or calculation of the level of exposure shall be preserved in a suitable form so as to permit consultation at a later stage.

5. Pursuant to Article 6(3) of Directive 89/391/EEC, the employer shall give particular attention, when carrying out the risk assessment, to the following:

(a) the level, frequency spectrum, duration and type of exposure;

(b) the exposure limit values and action values referred to in Article 3 of this Directive;

(c) any effects concerning the health and safety of workers at particular risk;

(d) any indirect effects, such as:

  (i) interference with medical electronic equipment and devices (including cardiac pacemakers and other implanted devices);

  (ii) the projectile risk from ferromagnetic objects in static magnetic fields with a magnetic flux density greater than 3 mT;

  (iii) initiation of electro-explosive devices (detonators);

  (iv) fires and explosions resulting from ignition of flammable materials by sparks caused by induced fields, contact currents or spark discharges;

(e) the existence of replacement equipment designed to reduce the levels of exposure to electromagnetic fields;

(f) appropriate information obtained from health surveillance, including published information, as far as possible;

(g) multiple sources of exposure;

(h) simultaneous exposure to multiple frequency fields.

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(9) OJ L 199, 30.7.1999, p. 59.

6. The employer shall be in possession of an assessment of the risk in accordance with Article 9(1)(a) of Directive 89/391/EEC and shall identify which measures must be taken in accordance with Articles 5 and 6 of this Directive. The risk assessment shall be recorded on a suitable medium, according to national law and practice; it may include a justification by the employer that the nature and extent of the risks related to electromagnetic fields make a further detailed risk assessment unnecessary. The risk assessment shall be updated on a regular basis, particularly if there have been significant changes which could render it out of date, or when the results of health surveillance show it to be necessary.

Article 5

Provisions aimed at avoiding or reducing risks

1. Taking account of technical progress and of the availability of measures to control the risk at source, the risks arising from exposure to electromagnetic fields shall be eliminated or reduced to a minimum.

The reduction of risks arising from exposure to electromagnetic fields shall be based on the general principles of prevention set out in Directive 89/391/EEC.

2. On the basis of the risk assessment referred to in Article 4, once the action values referred to in Article 3 are exceeded, the employer, unless the assessment carried out in accordance with Article 4(2) demonstrates that the exposure limit values are not exceeded and that safety risks can be excluded, shall devise and implement an action plan comprising technical and/or organisational measures intended to prevent exposure exceeding the exposure limit values, taking into account in particular:

(a) other working methods that entail less exposure to electromagnetic fields;

(b) the choice of equipment emitting less electromagnetic fields, taking account of the work to be done;

(c) technical measures to reduce the emission of electromagnetic fields including, where necessary, the use of interlocks, shielding or similar health protection mechanisms;

(d) appropriate maintenance programmes for work equipment, workplaces and workstation systems;

(e) the design and layout of workplaces and workstations;

(f) limitation of the duration and intensity of the exposure;

(g) the availability of adequate personal protection equipment.

3. On the basis of the risk assessment referred to in Article 4, workplaces where workers could be exposed to electromagnetic fields exceeding the action values shall be indicated by appropriate signs in accordance with Council Directive 92/58/EEC of 24 June 1992 on the minimum requirements for the provision of safety and/or health signs at work (ninth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC ([10]), unless the assessment carried out in accordance with Article 4(2) demonstrates that the exposure limit values are not exceeded and that safety risks can be excluded. The areas in question shall be identified, and access to them limited where this is technically possible and where there is a risk that the exposure limit values could be exceeded.

4. In any event, workers shall not be exposed above the exposure limit values.

If, despite the measures taken by the employer to comply with this Directive, the exposure limit values are exceeded, the employer shall take immediate action to reduce exposure below the exposure limit values. He shall identify the reasons why the exposure limit values have been exceeded, and shall amend the protection and prevention measures accordingly in order to prevent them being exceeded again.

5. Pursuant to Article 15 of Directive 89/391/EEC, the employer shall adapt the measures referred to in this Article to the requirements of workers at particular risk.

Article 6

Worker information and training

Without prejudice to Articles 10 and 12 of Directive 89/391/EEC, the employer shall ensure that workers who are exposed to risks from electromagnetic fields at work and/or their representatives receive any necessary information and training relating to the outcome of the risk assessment provided for in Article 4(1) of this Directive, concerning in particular:

(a) measures taken to implement this Directive;

(b) the values and concepts of the exposure limit values and action values and the associated potential risks;

(c) the results of the assessment, measurement and/or calculations of the levels of exposure to electromagnetic fields carried out in accordance with Article 4 of this Directive;

(d) how to detect adverse health effects of exposure and how to report them;

(e) the circumstances in which workers are entitled to health surveillance;

(f) safe working practices to minimise risks from exposure.

([10]) OJ L 245, 26.8.1992, p. 23.

Article 7

Consultation and participation of workers

Consultation and participation of workers and/or of their representatives shall take place in accordance with Article 11 of Directive 89/391/EEC on the matters covered by this Directive.

SECTION III

MISCELLANEOUS PROVISIONS

Article 8

Health surveillance

1. With the objective of prevention and early diagnosis of any adverse health effects due to exposure to electromagnetic fields, appropriate health surveillance shall be carried out in accordance with Article 14 of Directive 89/391/EEC.

In any event, where exposure above the limit values is detected, a medical examination shall be made available to the worker(s) concerned in accordance with national law and practice. If health damage resulting from such exposure is detected, a reassessment of the risks shall be carried out by the employer in accordance with Article 4.

2. The employer shall take appropriate measures to ensure that the doctor and/or the medical authority responsible for the health surveillance has access to the results of the risk assessment referred to in Article 4.

3. The results of health surveillance shall be preserved in a suitable form so as to permit consultation at later date, taking account of confidentiality requirements. Individual workers shall, at their request, have access to their own personal health records.

Article 9

Sanctions

Member States shall provide for adequate sanctions to be applicable in the event of infringement of national legislation adopted pursuant to this Directive. These sanctions must be effective, proportionate and dissuasive.

Article 10

Technical amendments

1. Modifications of the exposure limit values and action values set out in the Annex shall be adopted by the European Parliament and the Council in accordance with the procedure laid down in Article 137(2) of the Treaty.

2. Amendments to the Annex of a strictly technical nature in line with:

(a) the adoption of Directives in the field of technical harmonisation and standardisation with regard to the design, building, manufacture or construction of work equipment and/or workplaces;

(b) technical progress, changes in the most relevant harmonised European standards or specifications, and new scientific findings concerning electromagnetic fields

shall be adopted in accordance with the regulatory procedure referred to in Article 11(2).

Article 11

Committee

1. The Commission shall be assisted by the Committee referred to in Article 17 of Directive 89/391/EEC.

2. Where reference is made to this paragraph, Articles 5 and 7 of Decision 1999/468/EC shall apply, having regard to the provisions of Article 8 thereof.

The period referred to in Article 5(6) of Decision 1999/468/EC shall be set at three months.

3. The Committee shall adopt its rules of procedure.

SECTION IV

FINAL PROVISIONS

Article 12

Reports

Every five years Member States shall provide a report to the Commission on the practical implementation of this Directive, indicating the points of view of the social partners.

Every five years the Commission shall inform the European Parliament, the Council, the European Economic and Social Committee and the Advisory Committee on Safety and Health Protection at Work of the content of these reports, of its assessment of developments in the field in question and of anyinitiative, in particular as regards exposure to static magnetic fields, that may be warranted in the light of new scientific knowledge.

Article 13

Transposition

1. The Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive no later than 30 April 2008. They shall forthwith inform the Commission thereof.

When Member States adopt these measures, they shall contain a reference to this Directive or shall be accompanied by such reference on the occasion of their official publication. The methods of making such reference shall be laid down by Member States.

2. Member States shall communicate to the Commission the provisions of national law which they adopt or have already adopted in the field covered by this Directive.

Article 14

Entry into force

This Directive shall enter into force on the day of its publication in the *Official Journal of the European Union*.

Article 15

Addressees

This Directive is addressed to the Member States.

Done at Strasbourg, 29 April 2004.

For the European Parliament	*For the Council*
The President	*The President*
P. COX	M. McDOWELL

ANNEX

EXPOSURE LIMIT AND ACTION VALUES FOR ELECTROMAGNETIC FIELDS

The following physical quantities shall be used to describe the exposure to electromagnetic fields:

Contact current (I_C) between a person and an object is expressed in amperes (A). A conductive object in an electric field can be charged by the field.

Current density (J) is defined as the current flowing through a unit cross section perpendicular to its direction in a volume conductor such as the human body or part of it, expressed in amperes per square metre (A/m^2).

Electric field strength is a vector quantity (E) that corresponds to the force exerted on a charged particle regardless of its motion in space. It is expressed in volts per metre (V/m).

Magnetic field strength is a vector quantity (H), which, together with the magnetic flux density, specifies a magnetic field at any point in space. It is expressed in amperes per metre (A/m).

Magnetic flux density is a vector quantity (B), resulting in a force that acts on moving charges, expressed in teslas (T). In free space and in biological materials, magnetic flux density and magnetic field strength can be interchanged using the equivalence $1 \text{ A/m} = 4\pi\ 10^{-7}$ T.

Power density(S) is the appropriate quantity used for very high frequencies, where the depth of penetration in the body is low. It is the radiant power incident perpendicular to a surface, divided by the area of the surface and is expressed in watts per square metre (W/m^2).

Specific energy absorption (SA) is defined as the energy absorbed per unit mass of biological tissue, expressed in joules per kilogram (J/kg). In this Directive it is used for limiting non-thermal effects from pulsed microwave radiation.

Specific energy absorption rate (SAR) averaged over the whole body or over parts of the body, is defined as the rate at which energy is absorbed per unit mass of body tissue and is expressed in watts per kilogram (W/kg). Whole body SAR is a widely accepted measure for relating adverse thermal effects to radio frequency (RF) exposure. Besides the whole body average SAR, local SAR values are necessary to evaluate and limit excessive energy deposition in small parts of the body resulting from special exposure conditions. Examples of such conditions are: a grounded individual exposed to RF in the low MHz range and individuals exposed in the near field of an antenna.

Of these quantities, magnetic flux density, contact current, electric and magnetic field strengths and power density can be measured directly.

A. EXPOSURE LIMIT VALUES

Depending on frequency, the following physical quantities are used to specify the exposure limit values of electromagnetic fields:

— exposure limit values are provided for current density for time-varying fields up to 1 Hz, to prevent effects on the cardiovascular and central nervous system,

— between 1 Hz and 10 MHz exposure limit values are provided on current density to prevent effects on central nervous system functions,

— between 100 kHz and 10 GHz exposure limit values on SAR are provided to prevent whole-body heat stress and excessive localised heating of tissues. In the range 100 kHz to 10 MHz, exposure limit values on both current density and SAR are provided,

— between 10 GHz and 300 GHz an exposure limit value on power density is provided to prevent excessive tissue heating at or near the body surface.

Table 1

Exposure limit values (Article 3(1)). All conditions to be satisfied

Frequency range	Current density for head and trunk J (mA/m^2) (rms)	Whole body average SAR (W/kg)	Localised SAR (head and trunk) (W/kg)	Localised SAR (limbs) (W/kg)	Power density S (W/m^2)
Up to 1 Hz	40	—	—	—	—
1 — 4 Hz	40/f	—	—	—	—
4 — 1 000 Hz	10	—	—	—	—
1 000 Hz — 100 kHz	f/100	—	—	—	—
100 kHz — 10 MHz	f/100	0,4	10	20	—
10 MHz — 10 GHz	—	0,4	10	20	—
10 — 300 GHz	—	—	—	—	50

Notes:

1. f is the frequency in Hertz.

2. The exposure limit values on the current density are intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body. The exposure limit values in the frequency range 1 Hz to 10 MHz are based on established adverse effects on the central nervous system. Such acute effects are essentially instantaneous and there is no scientific justification to modify the exposure limit values for exposure of short duration. However, since the exposure limit values refer to adverse effects on the central nervous system, these exposure limit values may permit higher current densities in body tissues other than the central nervous system under the same exposure conditions.

3. Because of the electrical inhomogeneity of the body, current densities should be calculated as averages over a cross-section of 1 cm^2 perpendicular to the current direction.

4. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $(2)^{½}$.

5. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate exposure limit value. For pulses of duration t_p, the equivalent frequency to apply for the exposure limit values should be calculated as $f = 1/(2t_p)$.

6. All SAR values are to be averaged over any six-minute period.

7. Localised SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for estimating exposure. These 10 g of tissue are intended to be a mass of contiguous tissue with nearly homogeneous electrical properties. In specifying a contiguous mass of tissue, it is recognised that this concept can be used in computational dosimetry but may present difficulties for direct physical measurements. A simple geometry such as cubic tissue mass can be used provided that the calculated dosimetric quantities have conservative values relative to the exposure guidelines.

8. For pulsed exposures in the frequency range 0,3 to 10 GHz and for localised exposure of the head, in order to limit and avoid auditory effects caused by thermoelastic expansion, an additional exposure limit value is recommended. This is that the SA should not exceed 10 mJ/kg averaged over 10 g of tissue.

9. Power densities are to be averaged over any 20 cm^2 of exposed area and any $68/f^{1,05}$-minute period (where f is in GHz) to compensate for progressively shorter penetration depth as the frequency increases. Spatial maximum power densities averaged over 1 cm^2 should not exceed 20 times the value of 50 W/m^2.

10. With regard to pulsed or transient electromagnetic fields, or generally with regard to simultaneous exposure to multiple frequency fields, appropriate methods of assessment, measurement and/or calculation capable of analysing the characteristics of the waveforms and nature of biological interactions have to be applied, taking account of European harmonised standards developed by Cenelec.

B. ACTION VALUES

The action values referred to in Table 2 are obtained from the exposure limit values according to the rationale used by the International Commission on Non-ionising Radiation Protection (ICNIRP) in its guidelines on limiting exposure to non-ionising radiation (ICNIRP 7/99).

Table 2

Action values (Article 3(2)) (unperturbed rms values)

Frequency range	Electric field strength, E (V/m)	Magnetic field strength, H (A/m)	Magnetic flux density, B (μT)	Equivalent plane wave power density, S_{eq} (W/m^2)	Contact current, I_C(mA)	Limb induced current, I_L(mA)
0 — 1Hz	—	$1,63x10^5$	$2x10^5$	—	1,0	—
1 — 8 Hz	20 000	$1,63x10^5/f^2$	$2x10^5/f^2$	—	1,0	—
8 — 25 Hz	20 000	$2x10^4/f$	$2,5x10^4/f$	—	1,0	—
0,025 — 0,82kHz	500/f	20/f	25/f	—	1,0	—
0,82 — 2,5 kHz	610	24,4	30,7	—	1,0	—
2,5 — 65 kHz	610	24,4	30,7	—	0,4 f	—
65 — 100 kHz	610	1 600/f	2 000/f	—	0,4 f	—
0,1 — 1 MHz	610	1,6/f	2/f	—	40	—
1 — 10 MHz	610/f	1,6/f	2/f	—	40	—
10 — 110 MHz	61	0,16	0,2	10	40	100
110 — 400 MHz	61	0,16	0,2	10	—	—
400 — 2 000 MHz	$3f^{½}$	$0,008f^{½}$	$0,01f^{½}$	f/40	—	—
2 — 300 GHz	137	0,36	0,45	50	—	—

Notes:

1. f is the frequency in the units indicated in the frequency range column.
2. For frequencies between 100 kHz and 10 GHz, S_{eq}, E, H, Band $I_L$are to be averaged over any six-minute period.
3. For frequencies exceeding 10 GHz, S_{eq}, E, Hand Bare to be averaged over any $68/f^{1.05}$-minute period (f in GHz).
4. For frequencies up to 100 kHz, peak action values for the field strengths can be obtained by multiplying the rms value by $(2)^{½}$. For pulses of duration t_p, the equivalent frequency to apply for the action values should be calculated as $f = 1/(2t_p)$.

   For frequencies between 100 kHz and 10 MHz, peak action values for the field strengths are calculated by multiplying the relevant rms values by 10 , where a = (0,665 log (f/10) + 0,176), f in Hz.

   For frequencies between 10 MHz and 300 GHz, peak action values are calculated by multiplying the corresponding rms values by 32 for the field strengths and by 1 000 for the equivalent plane wave power density.
5. With regard to pulsed or transient electromagnetic fields, or generally with regard to simultaneous exposure to multiple frequency fields, appropriate methods of assessment, measurement and/or calculation capable of analysing the characteristics of the waveforms and nature of biological interactions have to be applied, taking account of harmonised European standards developed by Cenelec.
6. For peak values of pulsed modulated electromagnetic fields, it is also suggested that, for carrier frequencies exceeding 10 MHz, S_{eq} as averaged over the pulse width should not exceed 1 000 times the S_{eq} action values or that the field strength should not exceed 32 times the field strength action values for the carrier frequency.

Izjava

Izjavljam, da sem doktorsko disertacijo izdelal samostojno pod vodstvom mentorja prof. dr. Damijana Miklavčiča, dipl. ing. Izkazano pomoč drugih sodelavcev sem v celoti navedel v zahvali. Že objavljeni dosežki drugih avtorjev so navedeni v literaturi.

Blaž Valič