Abstract

This chapter of the EMF Dosimetry Handbook provides guidance on assessing whether persons bearing metallic implants inside their bodies should be restricted from exposure to the upper tier limits of the radiofrequency (RF) safety guidelines (1998) published by the International Commission for Non-ionising Radiation Protection (ICNIRP) and the C95.1 (2005) standard of the Institute of Electrical and Electronic Engineers (IEEE). The recommendations presented here are based on original research by the authors, investigations of specific implant cases by the Telstra Research Laboratories in Melbourne, Australia and various publications in the scientific literature. Wherever possible, rules-of-thumb have been developed to provide simple and practical ways for assessing implants and for some external body worn metallic objects. Nonetheless, there remain some assessment scenarios that will still require detailed analysis.
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1 Background

1.1 Types of metal implants in the body
Many people carry pieces of metal implanted within their bodies, which vary in their origin. These metal implants can for example be unwanted remnants of shrapnel, or more commonly, screws, rods, wires, pins or plates that are implanted by orthopaedic surgeons to repair broken bones and worn joints. Other metallic implant types include arterial stents and implanted electronic devices such as cardiac pacemakers and cochlear implants. External body-worn metallic objects, such as spectacles, jewellery, and the outer components of the cochlear implant system, are also considered in this chapter.

1.2 RF heating and human exposure limits
Tissue heating is a well established effect of exposure to electromagnetic radiofrequency (RF) fields due to the absorption of RF power from fields induced inside the body. The common metric for RF heating is the Specific energy Absorption Rate, or SAR in W/kg, which is simply related to the internal RF electric field at any point by:

$$SAR = \frac{\sigma |E_{int}|^2}{\rho}$$

where $E_{int}$ is the magnitude of the internal electric field (V/m), $\sigma$ is the electrical conductivity of the tissue (S/m), and $\rho$ is the mass density of the tissue (kg/m³).

Metallic implants can sometimes concentrate the RF heating effect around them by the way they scatter the incident RF field. This possibility has been recognised in various RF safety guidelines and standards (ICNIRP, 1998, IEEE, 2005, ARPANSA, 2002) which caution that the potential for exceeding allowable exposure limits for localised SAR around metal implants should be assessed for persons exposed up to upper tier limits, i.e. the occupational limits in the ICNIRP Guidelines for electromagnetic exposures (1998) and the controlled environment limits in the IEEE C95.1 RF safety Standard (2006). The lower tier limits prescribed for general public exposures in these documents incorporate substantial additional safety margins that are generally regarded as providing sufficient protection for implant RF field enhancements.

The localised SAR limits in the ICNIRP Guidelines (1998) and the IEEE C95.1 standard (2006) are assessed by averaging the point SAR over a mass of 10 g, usually in the shape of a cube, in recognition of the thermal diffusion properties of tissues. Different upper tier limits apply to different parts of the body as indicated in Table 1 below:

Table 1 Upper tier limits for localised SAR in the ICNIRP Guidelines (1998) and the IEEE C95.1 (2006) standard for human exposure to RF fields.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Head and torso</td>
<td>Head (except pinna), torso, upper arms, elbows, thighs and knees</td>
</tr>
<tr>
<td>Arms and legs</td>
<td>The pinna and limbs distal to the elbows and knees</td>
</tr>
</tbody>
</table>

The upper tier RF limits for exposure to ambient electric (E) and magnetic (H) fields in both the ICNIRP Guidelines (1998) and the IEEE C95.1 Standard (2006) have been primarily formulated to restrict whole body average (WBA) SAR absorption to less than 0.4 W/kg for standing children and adults exposed to uniform plane wave fields. There is a general presumption that these $E$ and $H$-field limits will also ensure that the localised 10/20 W/kg SAR limits are not exceeded for all circumstances.
1.3 Safety targets for RF tissue temperature increases

Tissue temperature rise is a more fundamental indicator of RF heating hazard than localised SAR as it includes the effect of the body's capacity to dissipate RF heating. A conservative safety target is to restrict RF tissue heating to no more than 1°C in the head and torso (ICNIRP 1998). For other parts of the body that are more tolerant of temperature increases and have less critical functions (i.e., where the higher 20 W/kg SAR limit of the ICNIRP Guidelines or the IEEE C95.1 standard is applied), then a target temperature rise of 2°C would seem appropriate.

1.4 RF safety assessments of metal implants

Detailed assessments of SAR concentrations and temperature rises around metal implants generally require complex analyses and specialised skills that are beyond the reasonable capabilities and resources of the great majority of affected persons and organisations. Furthermore, due to enormous diversity in the size, shape and location of metal implants, as well as the many different possible scenarios for RF exposure, it has been difficult to make generalizations from one particular implant assessment to another.

As a result, and despite warnings from RF safety standards and guidelines, most persons bearing personal metal objects and working in high RF fields have not been assessed for the potentially adverse RF heating of those metal objects. To address this lack, this chapter offers practical and accessible guidelines, or rules-of-thumb, for making such assessments for as many implant scenarios as possible.

In devising these rules-of-thumb, the authors have drawn upon many sources including their own research, previous assessments conducted by the Telstra Research Laboratories in Melbourne, Australia, as well as published scientific papers on this topic. In general it is assumed that:

- The rules-of-thumb only apply to persons who are not exposed above the upper tier limits of the ICNIRP Guidelines (1998) or the IEEE C95.1 standard (2006).
- A metallic implant in the head or torso can be considered safe if the localised SAR (averaged over a 10 g cube) in tissue around the metal object does not exceed 10 W/kg or if the RF induced temperature rise in tissue around the metal object does not exceed 1°C.
- A metallic implant in the limbs and pinna can be considered safe if the localised SAR (averaged over a 10 g cube) in tissue around the metal object does not exceed 20 W/kg or if the RF induced temperature rise in tissue around the metal object does not exceed 2°C.
- The rules should hold for all orientations of the metal objects with respect to the incident field since an individual will generally move about in the field.
- There is no RF heating of the implant itself, i.e. the implant is assumed to be a perfect electrical conductor and the only RF heating occurs in the tissue around the implant.

As this topic is still in a relatively early stage of development, it should be expected that at least some of the rules-of-thumb offered in this chapter will require further amendment as more research is accumulated. Nonetheless, it is hoped that the publication of formulative rules-of-thumb will at least be a useful starting point and impetus for the development of better guidelines, and preferable to making no assessments at all.
2 RF and thermal factors affecting implant assessments

2.1 RF factors

2.1.1 RF absorption in the body

The factors influencing the electromagnetic interaction between metal implants and the RF exposure field external to the body are varied and complex. Firstly, one must consider the general interaction of the body with the RF exposure field, as this affects the local incident field exposure around the implant. The main factors that affect the efficiency and distribution of RF absorption in the body are:

1. The frequency of the RF source
2. The polarisation of the incident RF field with respect to the body and its parts
3. The position of the RF source to the body which may lead to partial body exposures and near field coupling effects
4. The size, shape and grounding of the body
5. The dielectric properties (permittivity and conductivity) of body tissues

The dependence of SAR distribution on the RF exposure frequency offers a number of avenues for developing rules-of-thumb. For certain frequency ranges, the internal SAR may be too low to exceed peak allowable limits in particular parts of the body, even with significant RF field concentrations around the implants. Thus, it would be useful to identify those frequency ranges where metallic implant assessments are not necessary in all or parts of the body. Conversely, in certain frequency ranges, there may be parts of the body where localised SAR levels are relatively high, and where the additional SAR enhancement effect of the implant is more critical. Frequency ranges that are particularly worth noting include:

1. **Frequencies above 4-6 GHz**
   At frequencies above this range the small skin depth of absorption, \( \delta \), can provide effective RF shielding of implants buried in the body. At one skin depth, the point SAR will diminish by a factor of 0.14 relative to point SAR at the surface.

2. **Frequencies up to the MF band (300 kHz – 3 MHz)**
   In this range RF coupling to the body is weak, and \( E \)-field limits in the ICNIRP Guidelines (1998) and the IEEE C95.1 Standard (2006) are predicated on the more stringent requirements of protecting against external shock and burns arising from contact with passively charged conductors.

3. **Frequencies in the HF (3–30 MHz) and VHF (30–300 MHz) bands**
   In this range, whole and partial body resonances occur. Induced RF currents in the ankle and neck are of particular interest due to the concentration of RF current flows in these narrowed conduction areas.

**2.1.2 RF absorption around the metal implant**

Having established a base level of RF exposure in the body, the next step is to determine how the metal object perturbs and possibly concentrates the SAR around it. This should include a consideration of the following factors:

1. The size of the metal object
2. The shape of the metal object
3. Any gaps in the metal object
4. Location of the metal object within the body
5. Dielectric values of tissues around implanted metal objects
6. Whether the implant traverses local tissue boundaries
7. Orientation of the implant with respect to the local induced in vivo fields.
8. Distribution of the in vivo field around the implant (more important for large implants)

It should be noted that passive metal objects cannot of themselves generate any additional RF energy in accordance with the thermodynamic law for conservation of energy. However, due to RF field scattering, they can redistribute the incident RF energy around them, leading to SAR concentrations at some points and corresponding SAR reductions in other areas.
There are at least four basic mechanisms of SAR enhancement around implants as displayed in Figure 1:

1. SAR enhancement at the ends of implants, particularly when the long axis is parallel to the in situ electric field.
2. SAR enhancement in gaps of linear implants.
3. SAR enhancement in the gaps of broken loops that are cut by changing magnetic flux density (B).
4. Constructive interference in surface layers with underlying metallic plates.

**Figure 1** Four basic mechanisms of SAR enhancement around metallic implants

### 2.2 Thermal factors

Thermal factors that can influence the local temperature rise around RF exposed implants include:

1. The thermal conductivity and physical structure of the implant which influences the ability of the implant to redistribute temperature variations around it through internal heat transfer.
2. The size and specific heat capacity of the implant which alters the thermal mass of the implant, and affects the transient response to heating.
3. The heat transfer environment around the implant including: the thermal conductivity of surrounding tissues; the micro blood perfusion of surrounding tissues, and; the proximity of implant to large blood vessels.
4. The proximity of the implant to the body surface, where heat transfer from the skin to the ambient environment becomes important.

To a good first approximation, heat transfer inside the body can be numerically modelled using the classic bioheat equation (Pennes, 1948):
\[ \rho c \frac{dT}{dt} = K \nabla^2 T + \rho SAR + A_0 - b(T - T_b) \]

where \( T \) is the tissue temperature (°C), \( c \) is the specific heat capacity (J/kg°C), \( K \) is the thermal conductivity (W/m°C), \( A_0 \) is the metabolic heat production (W/m³), \( b \) is the heat-sink strength from each tissue volume by blood perfusion (W/m³ °C), and \( T_b \) is the temperature of the perfusing blood. The desired solution for \( T \) is obtained when the system reaches steady-state thermal equilibrium.

Heat transfer at the surface of the body can be modelled as a convective boundary:

\[ K \frac{dT}{dn} = -h(T - T_a) + q_e \]

where \( h \) is the convection coefficient (W/m²°C), \( T_a \) is the ambient temperature (°C), \( q_e \) is the evaporative heat loss (W/m²) and \( n \) is the direction of the unit normal to the surface. The convection coefficient may include a linearised component for heat radiation.

A favoured method for computational analysis of the bioheat equation in human bodies is the finite difference (FD) technique whereby complex heterogeneous models of the human body and implants can be represented by voxels in a regular rectangular mesh. A particular advantage of this approach is that the finite difference mesh can be made to coincide with the voxel mesh of an RF model based on the Finite Difference Time Domain (FDTD) technique, thereby allowing easy transfer of the calculated RF SAR data to the FD thermal analysis. For a detailed example of this approach see, for example, McIntosh et al. (2005).
3 Canonical studies of implant rods and infinite plates

3.1 Introduction

This chapter section is drawn from a project report by the authors (Anderson and McIntosh, 2004 2008) for a study on metallic implants that was sponsored by the Asian Office for Aerospace Research and Development (AOARD) of the United States Air Force Office of Scientific Research (AFOSR). It also includes observations gathered from earlier implant modelling for specific assessments that were conducted at the Telstra Research Laboratories in Melbourne, Australia.

Results and conclusions about implants are provided from canonical studies of the following areas:

- Calculations of SAR attenuation in planar multilayer skin/muscle/bone/metal models exposed to a plane wave; and;
- A canonical assessment of rod implants exposed to a plane wave in infinite medium that investigated the influence of size, tip shape, rod orientation and the dielectric properties of the surrounding tissue medium.

3.2 Canonical modelling of plane waves travelling through layered tissues

Radios waves are attenuated as they travel through lossy materials such as human tissues. At high frequencies, above 4-6 GHz, the rate of attenuation with depth is so pronounced for human exposures that most of the RF power is absorbed at the body surface. At these frequencies, metallic objects located deeper in the body may be effectively shielded from RF exposures.

The extent of this shielding can be gauged by examining a simple canonical model of a plane wave travelling through multiple planar layers representing skin, muscle and bone, as represented in Figure 2 below. This scenario has been modelled in a commercial RF analysis package, FEKO v4.1 (EMSS, 2003), using Greens functions for planar multilayered substrates. The final bone layer extends infinitely in the z direction.

![Figure 2 Model setup for examination of a plane wave incident on infinite multilayers of skin, muscle and bone.](image)

Skin and muscle thickness over bone varies in different locations of the body. In some places, there is effectively no muscle layer at all, e.g. on the forehead and shins. To cover these different scenarios, the following scenarios were analysed:

- 3 mm skin layer, infinite bone
- 5 mm skin layer, infinite bone
- 7 mm skin layer, infinite bone
- 5 mm skin layer, 10 mm muscle layer, infinite bone
- 5 mm skin layer, 30 mm muscle layer, infinite bone
The models were examined in the frequency range of 1-10 GHz using dielectric values for dry skin, skeletal muscle and cortical bone from Gabriel (1996) as shown in Table 3.

Table 2  Tissue dielectric values for multilayer models

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Dry skin</th>
<th>Skeletal muscle</th>
<th>Cortical bone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\varepsilon_r)</td>
<td>(\sigma) (S/m)</td>
<td>(\varepsilon_r)</td>
</tr>
<tr>
<td>1</td>
<td>40.9</td>
<td>0.900</td>
<td>54.8</td>
</tr>
<tr>
<td>2</td>
<td>38.6</td>
<td>1.265</td>
<td>53.3</td>
</tr>
<tr>
<td>4</td>
<td>36.6</td>
<td>2.340</td>
<td>50.8</td>
</tr>
<tr>
<td>6</td>
<td>34.9</td>
<td>3.891</td>
<td>48.2</td>
</tr>
<tr>
<td>8</td>
<td>33.2</td>
<td>5.824</td>
<td>45.5</td>
</tr>
<tr>
<td>10</td>
<td>31.3</td>
<td>8.014</td>
<td>42.8</td>
</tr>
</tbody>
</table>

Results of the multi tissue layer model analyses are shown in Figures 3 to 7. The curves for each frequency have been normalised so that the point SAR = 1 at the air skin surface.

Figure 3  Normalised point SAR in a multilayer tissue model (3 mm skin, infinite bone) exposed to a plane wave over the frequency range 1-10 GHz.
Figure 4 Normalised point SAR in a multilayer tissue model (5 mm skin, infinite bone) exposed to a plane wave over the frequency range 1-10 GHz.

Figure 5 Normalised point SAR in a multilayer tissue model (7 mm skin, infinite bone) exposed to a plane wave over the frequency range 1-10 GHz.
Figure 6  Normalised point SAR in a multilayer tissue model (5 mm skin, 10 mm muscle, infinite bone) exposed to a plane wave over the frequency range 1-10 GHz.

Figure 7  Normalised point SAR in a multilayer tissue model (5 mm skin, 30 mm muscle, infinite bone) exposed to a plane wave over the frequency range 1-10 GHz.
A number of general trends are evident from these results:

1. SAR decays more rapidly with depth as the frequency of exposure increases. For all cases studied, the point SAR at a depth of 10 mm had diminished by at least a factor of 10 for exposures above 6 GHz. This observation lends support to the treatment of RF exposures above 6 GHz as a surface heating phenomenon.

2. The large disparity in dielectric values between bone and skin or muscle causes a reflected wave from the bone interface. This can lead to a significant standing wave pattern in the skin and/or muscle exhibiting constructive or destructive interference depending on the layer thickness and the exposure wavelength, $\lambda$, which is dependent on frequency. A constructive interference pattern occurs when the skin/muscle layer is approximately a quarter wavelength thick, resulting in enhanced SAR. This phenomenon was most pronounced at 1-2 GHz for the models studied.

3. At the depth of the bone layer, the point SAR is substantially diminished compared to SAR at the surface in all of the studied cases.

### 3.3 Canonical modelling of plane waves reflected off metallic planar boundaries

An obvious thread to follow up from the observation of standing waves described in the preceding section is the constructive interference patterns that can result from RF waves reflected off a planar metal surface underneath the skin. Classical transmission line theory indicates that the maximal constructive interference occurs when the thickness of the skin between the air and plate is a quarter of the RF wavelength, $\lambda$, in the skin. Using a FEKO model as indicated in Figure 8, the calculated field pattern in a 3 mm layer of skin in front of a metal boundary is shown in Figure 9. It shows the maximal SAR levels occur at 4 GHz where the wavelength in skin is approximately 12 mm, in accordance with the $\lambda/4$ expectation.

![Figure 8 Model setup for examination of a plane wave incident on an infinite layers of skin overlaying a perfect electrical conducting (PEC) plane. The averaging cube for calculating 1 g or 10 g SAR is positioned against the air/skin surface and extends behind the metal plane where SAR equals zero.](image-url)
Figure 9  Point SAR distribution for a 1 mW/cm² plane wave normally incident on a 3 mm thick layer of skin overlaying a metallic plane. Results were calculated in a similar FEKO model as described in the previous section.

For other skin thicknesses, the frequency at which maximal quarter wave enhancement occurs is indicated in Table 3 as gauged by the 10 g average SAR over the shape of a cube at the surface. The point SAR in the skin layer for exposures at these frequencies at the upper tier ambient $E$-field limit in the ICNIRP Guidelines (1998) is shown in Figure 9.

Table 3  10 g average SAR (in the shape of a cube) in a skin layer overlaying a metal plane exposed to a normally incident plane wave at the upper tier limit for ambient $E$-field exposure ICNIRP Guidelines (1998), as shown in Figure 10.

<table>
<thead>
<tr>
<th>skin thickness</th>
<th>3 mm</th>
<th>4 mm</th>
<th>5 mm</th>
<th>6 mm</th>
<th>7 mm</th>
<th>8 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{\text{tissue}} = 4 \times \text{skin thickness}$</td>
<td>12 mm</td>
<td>16 mm</td>
<td>20 mm</td>
<td>24 mm</td>
<td>28 mm</td>
<td>32 mm</td>
</tr>
<tr>
<td>Freq (GHz)</td>
<td>4.10</td>
<td>3.04</td>
<td>2.41</td>
<td>1.99</td>
<td>1.70</td>
<td>1.47</td>
</tr>
<tr>
<td>ICNIRP $E$-field limit (W/m²)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>42.5</td>
<td>36.8</td>
</tr>
<tr>
<td>Max 10 g avg SAR (W/kg) at ICNIRP $E$-field limit</td>
<td>1.126</td>
<td>1.130</td>
<td>1.126</td>
<td>1.116</td>
<td>0.944</td>
<td>0.804</td>
</tr>
</tbody>
</table>
Table 3 indicates that the ICNIRP 10 g localized SAR limits (10 W/kg for head and torso, 20 W/kg for the limbs) are not exceeded for ambient exposures at the occupational field limits. The quarter wave enhancement effect appears to monotonically decrease for increasing skin thickness greater than 4 mm (see figure 10).

3.4 Canonical modelling of rod implants in infinite medium

3.4.1 General approach

As depicted in Figure 1, SAR can be enhanced at the tips of linear metal structures, particularly when the $E$-field is oriented parallel to the longest dimension of the implant. This phenomenon has been investigated by the authors in a series of canonical models for rods exposed to a plane wave in an infinite dielectric medium, and with particular regard to the following factors:

1. The length of the rod
2. The shape of the rod tip
3. The orientation of the rod with respect to the incident $E$-field exposure
4. The dielectric medium around the rod

3.4.2 Use of VAR instead of SAR

Rather than calculate mass averaged SAR around the rod, it was decided that the Volumetric Absorption Rate (VAR) in W/m³ averaged over a fixed sized cube was a more appropriate metric for comparing the relative RF field enhancements. The VAR at any point is calculated as $VAR = \sigma |E|^2$, c.f. $SAR = \sigma |E|^2/\rho$. The RF power calculated by integrating point VAR over a 10 cm³ cube is equivalent to the RF power obtained by integrating SAR over a cube of 10 g mass if the density of the medium is 1000 kg/m³, as is commonly assumed for most tissue types.

The decision to choose volume averaged VAR as the comparison metric was based on its greater ease of calculation and because it is more directly related to tissue temperature rise. On the first point, the density of metals (steel ~ 8000 kg/m³) is much higher that the density of tissues (~ 1000 kg/m³) which can substantially affect the size of a constant mass averaging cube when it intersects a metal implant and hence greatly complicates the calculation of mass averaged SAR compared to a constant size VAR averaging cube.
Moreover, this variability in the size of a SAR averaging mass also introduces an arbitrary variation in the level of RF power deposited in the cube which makes mass averaged SAR less directly related to temperature rise than volume averaged VAR. The more direct coupling between VAR and tissue temperature can be plainly seen in the bioheat equation for steady state RF heating shown below:

\[ K \nabla^2 T + \rho \text{SAR} + A_0 - b(T - T_b) = K \nabla^2 T + \text{VAR} + A_0 - b(T - T_b) = 0 \]

### 3.4.3 Model setup

The analyses were performed using Method of Moment (MoM) analysis in the FEKO v4.1 software (EMMS, 2003). The 10 cm³ volume averaged VAR was calculated by averaging point VAR in a 24 x 24 x 24 cubic array as depicted in Figure 13. The rod models consisted of a perfect electrically conducting (PEC) round rod exposed to a plane wave in an infinite tissue medium. The volume averaged VAR over a 10 cm³ cube was calculated along the length of the rod as shown in Figure 14.

![Figure 11](image_url)

**Figure 11** The 10 cm³ averaging cube for VAR was subdivided into a cubic array of 24 x 24 x 24 cuboids. The 10 cm³ VAR was obtained by averaging the point VAR at the centre of each of the 13,824 cuboids.
Figure 12 FEKO model of a PEC rod implant exposed to a plane wave in an infinite tissue medium. The 10 cm³ VAR was evaluated along the length of the rod.

In these canonical analyses, the rod was immersed in an infinite tissue medium of either bone or muscle. The analyses were conducted over a frequency range of 0.1 MHz to 10 GHz with uniform logarithmic spacing of 5 points per decade (1, 1.6, 2.5, 4, 6.3, 10). The tissue dielectric values were obtained from Gabriel et al. (1996) as shown in Table 4.
### Table 4 Relative permittivity, $\varepsilon_r$, and conductivity, $\sigma$, of cortical bone and skeletal muscle used in the canonical analyses of a rod exposed to a plane wave in infinite tissue medium. The plane wave wavelength, $\lambda$, and the skin depth, $\delta$, in the tissues are also shown.

| freq (MHz) | Cortical bone | | | | Muscle | | | | |
|-----------|---------------|----------|---------|---------|----------|----------|---------|
|           | $\varepsilon_r$ | $\sigma$ (S/m) | $\lambda$(mm) | $\delta$(mm) | $\varepsilon_r$ | $\sigma$ (S/m) | $\lambda$(mm) | $\delta$(mm) |
| 0.1       | 2.28 E+2      | 2.08 E-2 | 67274  | 11379  | 8.09 E+3  | 3.62 E-1  | 15624.2 | 2815.1 |
| 0.16      | 2.11 E+2      | 2.10 E-2 | 9088   | 11893.4 | 6.95 E+3  | 3.75 E-1  | 2230.8 |
| 0.25      | 1.97 E+2      | 2.12 E-2 | 40694  | 7366   | 5.76 E+3  | 3.96 E-1  | 9092.6  | 1769.7 |
| 0.3       | 1.91 E+2      | 2.14 E-2 | 36633  | 6765   | 5.23 E+3  | 4.07 E-1  | 8137.3  | 1602.1 |
| 0.4       | 1.82 E+2      | 2.18 E-2 | 30889  | 5917   | 4.34 E+3  | 4.28 E-1  | 6835.0  | 1360.7 |
| 0.63      | 1.66 E+2      | 2.27 E-2 | 23298  | 4775   | 2.97 E+3  | 4.65 E-1  | 5227.7  | 1038.4 |
| 1         | 1.45 E+2      | 2.44 E-2 | 17230  | 3793   | 1.84 E+3  | 5.03 E-1  | 4032.0  | 785.2  |
| 1.6       | 1.19 E+2      | 2.70 E-2 | 12571  | 2935   | 1.07 E+3  | 5.35 E-1  | 3128.8  | 594.6  |
| 2.5       | 9.33 E+1      | 3.03 E-2 | 9331   | 2251   | 6.40 E+2  | 5.59 E-1  | 2470.6  | 460.7  |
| 3         | 8.32 E+1      | 3.19 E-2 | 8278   | 2012   | 5.22 E+2  | 5.68 E-1  | 2244.2  | 416.2  |
| 4         | 6.87 E+1      | 3.44 E-2 | 6870   | 1682   | 3.85 E+2  | 5.81 E-1  | 1927.7  | 355.4  |
| 6.3       | 5.01 E+1      | 3.86 E-2 | 5144   | 1272   | 2.49 E+2  | 5.99 E-1  | 1513.7  | 278.5  |
| 10        | 3.68 E+1      | 4.28 E-2 | 3837   | 969    | 1.71 E+2  | 6.17 E-1  | 1179.3  | 218.8  |
| 16        | 2.79 E+1      | 4.70 E-2 | 2831   | 748    | 1.25 E+2  | 6.34 E-1  | 909.6   | 172.4  |
| 25        | 2.25 E+1      | 5.09 E-2 | 2096   | 597    | 9.93 E+1  | 6.51 E-1  | 705.5   | 138.6  |
| 30        | 2.09 E+1      | 5.25 E-2 | 1844   | 548    | 9.18 E+1  | 6.58 E-1  | 634.2   | 127.1  |
| 40        | 1.89 E+1      | 5.51 E-2 | 1497   | 483    | 8.26 E+1  | 6.69 E-1  | 533.7   | 111.4  |
| 63        | 1.67 E+1      | 5.94 E-2 | 1057   | 403    | 7.25 E+1  | 6.88 E-1  | 401.0   | 91.6   |
| 100       | 1.53 E+1      | 6.43 E-2 | 722    | 343    | 6.60 E+1  | 7.08 E-1  | 293.1   | 76.7   |
| 160       | 1.43 E+1      | 7.05 E-2 | 479    | 295    | 6.17 E+1  | 7.31 E-1  | 206.7   | 65.9   |
| 250       | 1.37 E+1      | 7.84 E-2 | 318    | 255    | 5.90 E+1  | 7.57 E-1  | 143.7   | 58.5   |
| 300       | 1.34 E+1      | 8.27 E-2 | 268    | 239    | 5.82 E+1  | 7.71 E-1  | 122.8   | 56.1   |
| 400       | 1.31 E+1      | 9.13 E-2 | 204    | 213    | 5.71 E+1  | 7.96 E-1  | 95.0    | 52.6   |
| 630       | 1.28 E+1      | 1.13 E-1 | 132    | 169    | 5.58 E+1  | 8.58 E-1  | 62.3    | 47.3   |
| 1000      | 1.24 E+1      | 1.56 E-1 | 84.7   | 121    | 5.48 E+1  | 9.78 E-1  | 40.0    | 40.7   |
| 1600      | 1.19 E+1      | 2.42 E-1 | 53.9   | 76.2   | 5.38 E+1  | 1.24 E+0  | 25.3    | 31.7   |
| 2500      | 1.14 E+1      | 4.04 E-1 | 35.3   | 44.6   | 5.27 E+1  | 1.77 E+0  | 16.4    | 21.9   |
| 3000      | 1.11 E+1      | 5.06 E-1 | 29.8   | 35.2   | 5.21 E+1  | 2.14 E+0  | 13.7    | 18.0   |
| 4000      | 1.05 E+1      | 7.27 E-1 | 22.8   | 24.0   | 5.08 E+1  | 3.02 E+0  | 10.4    | 12.7   |
| 6300      | 9.46 E+0      | 1.27 E+0 | 15.2   | 13.03  | 4.78 E+1  | 5.57 E+0  | 6.79    | 6.68   |
| 10000     | 8.12 E+0      | 2.14 E+0 | 10.3   | 7.27   | 4.28 E+1  | 1.06 E+1  | 4.48    | 3.34   |

#### 3.4.4 Peak VAR vs. frequency for E polarization exposure of a 40 mm rod in infinite bone

In an initial exploration of linear resonance mechanisms, a model of a round rod (40 mm long, 4 mm diameter) was exposed to a plane wave in an infinite bone medium. The incident $E$-field was set to 1 V/m at the centre of the rod, with $E$ parallel to the rod’s axis as depicted in Figure 12. The 10 cm$^3$ VAR along the length of the rod was normalized with respect to the unperturbed 10 cm$^3$ VAR at the same location when the rod is not present. The peak relative VAR enhancement along the rod is plotted in Figure 13 over the frequency range 0.1 MHz to 10 GHz.
Figure 13  Peak relative VAR enhancement caused by the presence of a 40 cm long rod exposed to an $E$ polarised plane wave in infinite bone medium.

The graph depicted in Figure 13 displays some interesting features. Firstly, a resonant response is clearly evident at around 630 MHz with a peak VAR enhancement of around 4.2. Below this frequency, there is a lower and constant enhancement of 2.1. Above the resonance, the VAR enhancement drops to unity, i.e., there is no enhancement of 10 cm³ average VAR.

Figure 14 displays field plots of point VAR at frequencies in each of the three frequency regions just described. At resonance (630 MHz), the peak VAR enhancement is clearly seen at the tips of the rods. A relative reduction in VAR can also be observed around the middle of the implant, illustrating the important general principle of power conservation. In other words, the rod cannot create additional VAR, but simply redistributes the available RF power around it provided by the incident exposure. At sub-resonance, (1 MHz in Figure 16), a similar pattern of field enhancement/reduction around the rod occurs as at resonance. This similarity was evident for all frequencies below resonance. However, above resonance, there is a clear shift in the pattern of VAR distribution. At 6.3 GHz, where $\lambda$ is 15.2 mm and small compared to the rod length, the rod acts as an electrically large scatterer, producing a pattern of standing waves immediately in front of it (note also the attenuation of the $E$-field to the left of the picture as the field propagates towards the implant). Over the 21.5 mm side length of the 10 cm³ averaging cube (which is large relative to $\lambda/4$), the constructive and destructive peaks of these standing waves average out to unity. The logarithmic attenuation of the plane wave as it travels through the medium is also quite evident at these high frequencies.
3.4.5 Peak VAR variation with rod length

The influence of rod length on 10 cm³ VAR enhancement was studied by analysing 4 mm diameter round rods of varying lengths (20, 30, 40, 80, 160 and 320 mm long) exposed to a plane wave in an infinite bone medium with $E$ parallel to the rod axis. The relative enhancement of 10 cm³ VAR is shown in Figure 15. The plots for each rod length display the same general resonant features as described previously, though with some interesting differences.

Firstly, the frequency of the resonant peak changes with rod length. In particular, the resonant peak appears to occur when the rod length is around one third of the exposure wavelength, as previously reported by Fleming et al. (1999). This topic is explored further in section 3.4.9.

Secondly, rod length influences the magnitude of the relative 10 cm³ VAR enhancement at the resonant peak and at sub-resonance. Figure 16 shows the peak 10 cm³ VAR enhancement at resonance. Only a modest enhancement is seen for small rods ($\times 1.57$ for a 20 mm length), but the enhancement is quite substantial for larger rods ($\times 37.4$ for 160 mm length). The increase in 10 cm³ VAR enhancement appears to be fairly linear for rod lengths greater than 40 mm. Figure 17 shows 10 cm³ VAR enhancement in the plateau sub-resonance region, with similar trends as described for the resonant VAR enhancement. See section 3.4.10 for a further discussion of small implants.
Figure 15  Variation in the peak relative enhancement of 10 cm³ VAR for 4 mm diameter round rods of varying length exposed to an $E$ polarised plane wave in infinite bone medium.

Figure 16  Variation in the peak enhancement of 10 cm³ VAR with rod length at resonance in an infinite bone medium.
**Figure 17** Variation in the peak enhancement of 10 cm³ VAR with rod length for plane wave exposure at sub-resonance frequencies in an infinite bone medium.

### 3.4.6 Peak VAR variation with shape of rod tip

The influence of rod tip shape on the peak relative enhancement of 10 cm³ VAR is shown in Figure 18 for 80 mm long round rods (4 mm diameter) exposed to an E polarized plane wave in infinite bone medium with either flat or conical tips. They indicate that the flat tip rod exhibited a very similar 10 cm³ VAR enhancement response compared to the rod with conical tips, indicating that the rod tip shape is not a significant cause of variation.

**Figure 18** Variation in the peak enhancement of 10 cm³ VAR with frequency for flat and pointed end tips of an 80 cm round rod exposed to an E polarised plane wave in an infinite bone medium.
3.4.7 Peak VAR variation with field orientation
An important determinant of RF field enhancement around long linear structures is the orientation of the $E$-field with respect to the implant. Maximum coupling at frequencies around or below resonance occurs when the $E$-field is parallel to the long axis of the structure. This is clear in Figure 19 which illustrates the peak relative VAR enhancement around an 80 mm long round rod (4 mm diameter, flat ends) exposed to a plane wave in infinite bone medium. In contrast to the maximum enhancements when $E$ is parallel to the rod, virtually no enhancement is seen when $E$ is perpendicular to the rod. Halfway between these orientations at 45°, the peak sub-resonant enhancement is around 59% of the parallel enhancements, but the resonant response is much more subdued being only 32% of the parallel enhancement. A second smaller resonant peak is also evident.

![Graph showing peak relative VAR enhancement vs. frequency with different polarizations](image)

Figure 19  Variation in the peak enhancement of 10 cm³ VAR with frequency for different polarisations of a plane wave $E$-field incident on an 80 cm round rod in an infinite bone medium.

3.4.8 Peak VAR variation with dielectric value of medium
In the final series of canonical rod implant models, the influence of the tissue dielectric properties was examined. In these analyses, flat tip rods of various lengths were exposed to $E$ polarized plane waves in both infinite bone and infinite muscle medium. The results of these analyses are shown in Figure 20 with comparison to the results obtained in the bone medium.
Figure 20 Variation in the peak enhancement of 10 cm³ VAR with frequency for different rod lengths exposed to an E polarised plane wave in infinite bone and muscle medium.

These results reveal some very obvious and interesting trends that are consistent for all of the different length rods. Firstly, the 10 cm³ peak VAR enhancement in the sub-resonance frequency range is exactly the same for rods immersed in muscle as for rods in bone. Likewise, in the supra-resonance region, the 10 cm³ peak VAR enhancement trends to unity for rods in both mediums. However, in the resonant region there are clear differences wherein the enhanced resonant response seen in bone, is completely damped out when the rod is placed in muscle. It would seem reasonable to speculate that this damping effect is due to the increased RF power losses arising from the higher conductivity of muscle, noting that VAR (and SAR) is directly proportional to conductivity. Note also that the actual value of VAR and SAR may be higher in muscle than in bone, even though the relative enhancement as shown in Fig. 20 is less. For rods of all lengths immersed in muscle, the peak 10 cm³ VAR enhancement is negligible (i.e., <×1.4) for frequencies above 500 MHz.

3.4.9 Resonant length of implants
In this section we further investigate the observation from section 3.4.5 that the resonant response of linear objects in low loss tissues (like bone) occurs when its length is around one third of the wavelength (λ/3) in the surrounding medium. As seen in section 3.4.8, this resonant response is damped out in high loss media like muscle, but it is quite prominent in low loss media like bone.

The implants examined in this section were flat ended round rods of two different lengths (40 and 80 mm) and two different diameters (4 and 10 mm) giving four basic model types.: The implants were immersed in an infinite bone medium and exposed to a plane waves of various orientations, i.e. with the E vector oriented at 0° (parallel), 15°, 30°, 45°, 60°, 75° and 90° (perpendicular) to the rod. The E-field of the incident plane wave was set to 1 V/m peak at the centre of the rod. A broad range of frequencies were examined on either side of the resonant frequency for each rod (10 MH to 10 GHz). As in previous sections, the peak relative VAR enhancement was used as the metric for assessing the level of RF field enhancement around the implant. The dielectric properties of the bone medium were taken from Gabriel (1996).
Figure 21 Seven orientations, $\alpha$, of the incident plane wave exposure field for examination of the resonant length.

The peak relative VAR enhancement is shown in the following plots for the four model types.
Figure 22  Peak VAR Response vs Frequency, length= 40mm, diameter= 4mm

Figure 23  Peak VAR Response vs Length of Implant/Wavelength, length= 40mm, diameter= 4mm
Figure 24  Peak VAR Response vs Frequency, length= 40mm, diameter= 10mm

Figure 25  Peak VAR Response vs Length of Implant/Wavelength, length= 40mm, diameter= 10mm
Figure 26  Peak VAR Response vs Frequency, length= 80mm, diameter= 4mm

Figure 27  Peak VAR Response vs Length of Implant/Wavelength, length= 80mm, diameter= 4mm
Figure 28  Peak VAR Response vs Frequency, length= 80mm, diameter= 10mm

Figure 29  Peak VAR Response vs Length of Implant/Wavelength, length= 80mm, diameter= 10mm
The resonant peak is quite evident for orientation angles, $\alpha$, ranging from $0^\circ$ to $45^\circ$ in the curves provided in Figure 22 to Figure 29. The location of the resonant peaks is summarised in Table 5 and Figure 30. This data indicates a gradual reduction in resonant length ($L/\lambda$) with the increasing orientation angle ($\alpha$) between the E-field and the implant axis. For the average data of the four implants over an $\alpha$ range of $0^\circ$-$45^\circ$, this trend can be represented as the following linear equation with a high degree of correlation ($R^2 = 0.9995$):

$$L/\lambda = -0.000905\alpha + 0.3526$$

Figure 31 below shows that ratio of the rod diameter to its length ($d/L$) is a quite a good predictor for the resonant length. The resonant length ($L/\lambda$) can be predicted by the following logarithmic equations:

$$L/\lambda = -0.0562 \ln(d/L) + 0.2293 \quad \text{for } \alpha = 0^\circ, R^2=0.9899$$
$$L/\lambda = -0.0598 \ln(d/L) + 0.2050 \quad \text{for } \alpha = 0^\circ$-$45^\circ, R^2=0.9899$
Figure 31  Resonant length (L/\lambda) of implants vs the ratio of the rod diameter to its length (d/L).

3.4.10  Peak VAR for small implants (<2cm)
In section 3.4.5 it was observed that the peak VAR enhancement was quite small (<x2) for round rods of length less than 2cm. In order to confirm the generalisability of this observation the peak VAR enhancement was also examined for other small commonly encountered implants of different (screw, clip, thin wire and stent), each with a maximum dimension of 2cm.

Numerical calculation of RF field scattering around the examined implants was conducted by the Method of Moments as implemented in the EMSS FEKO v5.3 commercial software. The implants were modelled as perfect electrical conductors (PEC) using triangular surface elements. The field levels in the infinite medium surrounding the implants were calculated using Greens functions provided in FEKO. The dielectric properties for the infinite bone and muscle mediums were derived from Gabriel (1996).

Model diagrams for each of the examined small implants are shown in the following pages. In each case the length of the implant was 20mm. For the analyses, each small implant model was exposed to a plane wave travelling through the infinite medium surrounding the implant. The plane wave had an E-polarisation that was parallel to the long axis of each implant as this polarisation produces the highest peak SAR enhancements around the implant. Due to the finite conductivity of the muscle and bone mediums, the intensity of the plane wave exposure field attenuates in its direction of travel. For our analyses we placed the implants so that their centres were located where the field level was 1 V/m peak when the implant was not present.

The peak relative VAR enhancement was calculated for each of the small implant models across a frequency range that include the resonant frequency of the implant. The relative VAR enhancement is the ratio of the 10 cm³ VAR around the implant to the VAR at the same location when the implant is not present.
Figure 32  Screw in infinite bone medium. The maximum peak relative VAR enhancement occurs at 1200 MHz with a value 1.75
Figure 33  Screw in infinite muscle medium. The maximum peak relative VAR enhancement occurs at 500 MHz with a value 1.34
Figure 34  Thin wire in infinite bone medium. The maximum peak relative VAR enhancement occurs at 1500 MHz with a value 1.55
Figure 35  Clip in infinite muscle medium. The maximum peak relative VAR enhancement occurs at 700 MHz with a value 1.46
Figure 36  Stent in infinite muscle medium. The maximum peak relative VAR enhancement occurs at 400 MHz with a value 1.5
The relative VAR enhancements for all of the small 2 cm implants are grouped together on the plot below. It shows that the resonant frequency varies with the shape of the implant and the medium (bone or muscle) in which it is immersed. However it can be seen that in all circumstance the maximum peak relative VAR enhancement is always less than two, which may be deemed as insignificant.

Figure 37  Maximum peak relative VAR enhancement for small implants of various shapes.
4 Specific implant assessments

In this section we describe specific implant assessments that have been published in the literature as well as unpublished assessments conducted by the Telstra Research Laboratories for Telstra RF workers.

The majority of these studies employed numerical modelling (primarily FDTD and MoM), with metal objects placed in or near human body models or canonical models to perform the assessments. In some cases this was followed by the use of thermal modelling (primarily FD) to assess the resultant thermal changes.

For a separate review of the literature and for a general discussion on metallic implants see Virtanen et al. (2006).
### 4.1 Linear implants (e.g. pins, rods, and long narrow plates)

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin/rod</td>
<td>7 - 28 mm long and 0.5 - 8 mm diameter</td>
<td>Different orientations of pin/rod located on the skin or in muscle, fat or bone of a cylinder model of the body</td>
<td>250 mW, 900/1800 MHz mobile phone type exposure simulated by a monopole on metal handset box 10 mm from skin surface</td>
<td>Resonance found around $\lambda/3$ (14 mm for 900 MHz). Enhancement of average SAR found to be 2 to 3 times but study concludes that the “... enhancement is unlikely to be problematic.”</td>
<td>Virtanen et al. (2005)</td>
</tr>
<tr>
<td>Long narrow plate</td>
<td>220 mm long and ~ 20 mm thickness</td>
<td>Attached to humerus with six screws and surrounded by muscle in whole body</td>
<td>RF plane wave exposure</td>
<td>Resonance around 50–100 MHz. Peak 10 g SAR = 1.03 W/kg at bottom of rod for 10 W/m² input and hence complies with ICNIRP Guidelines (1998)</td>
<td>Telstra individual assessment (2005)</td>
</tr>
<tr>
<td>Intramedullary nail</td>
<td>440 mm long and 15 mm diameter</td>
<td>Inside femur (attached with screw 65 mm from top) in whole body</td>
<td>900 MHz plane wave exposure</td>
<td>Negligible effect</td>
<td>Telstra individual assessment (2001)</td>
</tr>
<tr>
<td>Pin</td>
<td>Wire 5 - 25 mm long (peak at $\sim \lambda/2 = 20$ mm). Diameter either 0 (filament) or 1 mm (pin).</td>
<td>In a spherical model of a head, parallel to dipole and 10 mm from surface</td>
<td>250 mW, 900 MHz dipole 15 mm from head (GSM900 mobile phone type exposure)</td>
<td>Peak 10 g SAR increases no more than 30% compared to tissue without implant. Peak 1 g SAR is around 3.9 W/kg for filament 20-25 mm in diameter</td>
<td>Cooper and Hombach (1996)</td>
</tr>
</tbody>
</table>

**Summary:** The assessments conducted at 900 MHz indicate that short (5-28 mm long) and long (440 mm) implants do not cause excessive SAR, which is in line with the results of the canonical modelling of rods (see figure 20). The assessment of the long narrow plate (220 mm) in the humerus (upper arm) provides some limited evidence that implant assessments in that location are not likely to be problematic at any frequency.
### 4.2 Screws

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screws</td>
<td>~ 15 mm long and ~ 4 mm wide</td>
<td>In elbow in whole body FDTD model</td>
<td>RF plane wave exposure</td>
<td>Resonance around 900 MHz but effect negligible</td>
<td>Telstra individual assessment (2003)</td>
</tr>
</tbody>
</table>

**Summary:** This assessment lends support to the notion that small implants do not cause excessive SAR concentration.

### 4.3 Arterial stents

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronary artery stent</td>
<td>34 mm long and 2 mm diameter</td>
<td>Top of the heart in the middle artery (modelled as cylinder) in whole body FDTD model</td>
<td>100-900 MHz plane wave exposure</td>
<td>At 100 MHz the peak 1 g SAR near the stent was 0.35 W/kg for 10 W/m² exposure.</td>
<td>Telstra individual assessment (2001)</td>
</tr>
<tr>
<td>Coronary artery stent</td>
<td>6 mm and 25 mm diameter stents</td>
<td>The stent is modelled as a cylinder in infinite muscle tissue with blood inside. Measurements were made in egg-white.</td>
<td>Heating furnaces - 6.25 and 92.6 kHz RF and MRI considered</td>
<td>Conclude that the ANSI/IEEE C95.1-1992 standard limits provide adequate protection. Paper also confirms convective cooling effects of blood vessel.</td>
<td>Foster, Goldberg and Bonsignore (1999)</td>
</tr>
</tbody>
</table>

**Summary:** Studies show no cause for concern. The potential for adverse heating around stents is substantially mitigated by the convective cooling from blood flow within the artery.
### 4.4 Wide plates

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular cranioplasty plate</td>
<td>50 mm diameter, curved around forehead, and 1.5 mm thick</td>
<td>Implanted on the front of the cranium around 5-6 mm under the surface of the forehead in whole body FDTD model</td>
<td>100 MHz-3 GHz plane-wave from the front to the back of the body</td>
<td>Resonant response occurred at around 200-300 MHz (peak 10 g SAR is around 0.8 W/kg for 10 W/m² input power at the occupational limit) and cumulative interference in the scalp at around 2100-2800 MHz (4.9 W/kg for 50 W/m²) (where the scalp thickness was λ/4). The resultant temperature increase is less than 1 °C.</td>
<td>McIntosh et al. (2005)</td>
</tr>
<tr>
<td>Circular Disk</td>
<td>15 - 22 mm diameter</td>
<td>In a spherical model of a head, 10 mm from the surface</td>
<td>250 mW, 900 MHz dipole (15 mm from head) mobile phone type exposure</td>
<td>Peak 1 g SAR is around 3.5 W/kg for disk around 18 mm in diameter</td>
<td>Cooper and Hombach (1996)</td>
</tr>
</tbody>
</table>

**Summary:** In comparison to the linear enhancements for rod tips, the peak linear SAR enhancement is generally more spread around the circumference of a plate which reduces the peak 10 g average SAR. The cumulative interference effect (with fields in the skin-plate interface giving rise to increased SAR in front of the plate) has been shown to not lead to SAR limits being exceeded (in line with the canonical modelling of section 3.3).

### 4.5 Pacemakers

**Summary:** There have been many studies in the area of the interaction between electromagnetic fields and pacemakers but the main topic of interest has been interference issues (see, for example, Hrabar et al. (2001)).
### 4.6 Loops

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loops</td>
<td>15 - 50 mm diameter</td>
<td>Different orientations of pin/rod located on the skin or in muscle, fat or bone of a cylinder model of the body</td>
<td>250 mW, 900/1800 MHz mobile phone type exposure (from monopole), 10 mm from surface</td>
<td>Resonance found when loop is λ/3 to λ/2 in diameter. Relative enhancement for 1 g SAR up to 2.7× at 900 MHz for 30 mm diameter ring, although at typical mobile phone power levels &quot;... enhancement is unlikely to be problematic.&quot; Averaged SAR highest when loop is in muscle.</td>
<td>Virtanen et al. (2005)</td>
</tr>
<tr>
<td>Wire loop</td>
<td>~ 20 - 25 mm diameter with ties around 7-12 mm long</td>
<td>Ties around the sternum. Heat transfer analysed in finite element (FE) model.</td>
<td>Plane wave exposure at 3, 9.5, 80, 1650-3000 MHz</td>
<td>Temperature rise estimated to be 1.3 °C for 50 W/m² at 80 MHz. The occupational limit at this frequency in ICNIRP (1988) is 10 W/m² so all max temperature increases &lt; 1 °C.</td>
<td>Hocking, Joyner and Fleming (1991)</td>
</tr>
</tbody>
</table>

**Summary:** Assessments here for a variety of dimensions and exposure conditions show no cause for concern. There are no published studies of SAR enhancement in the gaps of loops – further research is needed.
### 4.7 Cochlear implant systems and auditory brainstem implant (ABI) systems

<table>
<thead>
<tr>
<th>Type</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cochlear implant system</td>
<td>Models of cochlea (assessed using the Finite Integration Algorithm (FIT))</td>
<td>900 MHz mobile phone</td>
<td>Local increases about electrode arrays of SAR and temperature</td>
<td>Franzoni et al. (2006)</td>
</tr>
<tr>
<td>Cochlear implant system (with metal</td>
<td>Standard placement for internal and external components, in whole body</td>
<td>Mobile phone type exposure (from</td>
<td>At 900 MHz (1800 MHz) peak 10 g averaged SAR reached near the implant was calculated to be 1.31 W/kg (0.93 W/kg) and the peak temperature increase was 0.33 °C (0.16 °C).</td>
<td>McIntosh et al. (2006)</td>
</tr>
<tr>
<td>hook over the ear)</td>
<td>whole body FDTD model</td>
<td>dipole) at 900 MHz/250 mW and 1800 MHz/125 mW. Dipole placed 10 mm from ear. Different orientations considered.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cochlear implant system (no external</td>
<td>Standard placement for internal component, in whole body FDTD model</td>
<td>50 Hz, 50 kHz, 5 MHz and mobile</td>
<td>Satisfied ICNIRP exposure limits</td>
<td>Bahr and Boltz (2006)</td>
</tr>
<tr>
<td>component)</td>
<td></td>
<td>phone frequencies 900 MHz, 1750 MHz and 1950 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABI and cochlear implant system</td>
<td>Receiver-stimulator placed on outside of head and leads placed across</td>
<td>MRI imaging (RF component at 63.8 MHz)</td>
<td>No heating due to devices observed</td>
<td>Chou, McDougall and Chan (1995)</td>
</tr>
<tr>
<td>(no external components in either)</td>
<td>central slice of head in phantom</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Summary:** These studies are fairly comprehensive for cochlear implant systems covering a wide variety of exposure conditions and show no cause for concern.
### 4.8 Spectacles

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Several common frame shapes</td>
<td>About human head FDTD model</td>
<td>1.5 – 3 GHz plane wave at 50 W/m² and 1.8 GHz dipole</td>
<td>SAR averaged over eye increases by up to 160% (compared to when spectacles not present) and decreases up to 80% depending upon type of spectacles. Safety standards satisfied.</td>
<td>Edwards and Whittow (2005)</td>
</tr>
<tr>
<td>Frame 166 mm wide, lens aperture 68 x 40 mm</td>
<td>About human head FDTD model</td>
<td>450 MHz, 1 W monopole placed in front of face</td>
<td>Minor decrease in 10 g average SAR with spectacles (compared to when spectacles not present)</td>
<td>Troulis (2003)</td>
</tr>
<tr>
<td>About human head FDTD model</td>
<td>Mobile phones 915 MHz GSM and 1.9 GHz DECT</td>
<td>SAR levels comply with Austrian safety standard ÖNORM S1120 (4 W/kg for 1 g mass)</td>
<td></td>
<td>Yelkenci and Magerl (2000)</td>
</tr>
<tr>
<td>About a phantom</td>
<td>835 MHz, 600 mW, handset with pull-out antenna</td>
<td>Unaveraged SAR in eye increased up to 29% with spectacles present but still below RF safety standard limits</td>
<td></td>
<td>Anderson and Joyner (1995)</td>
</tr>
<tr>
<td>120 mm wide, lens circumference 150 mm, wings 150 mm long</td>
<td>About a phantom</td>
<td>2 – 4 GHz TEM waves</td>
<td>Spectacles give “… either a shielding or enhancement effect …” but “No serious human health effect is conclusively revealed …”.</td>
<td>Griffin (1983) and Griffin and Davias (1983)</td>
</tr>
</tbody>
</table>

**Summary:** The fairly thorough consideration here has been driven by the concern of possible enhancement of RF energy in the eyes by the spectacles. In particular, the study by Edwards and Whittow (2005) was quite exhaustive in the number of frames and exposure scenarios examined.

### 4.9 Jewellery

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earrings: 1. Band 86 mm long, 5 mm thick, and 10 mm wide 2. One 25 mm long and two around 10 mm diameter</td>
<td>1. Band along back side of pinna. 2. Studs along back side of pinna</td>
<td>900 MHz dipole simulating mobile phone</td>
<td>Increased point SAR values were observed but no significant differences were found when considering the 10 g volume averaged SAR.</td>
<td>Fayos-Fernández et al. (2006)</td>
<td></td>
</tr>
</tbody>
</table>

**Summary:** The study presented raises no concerns, even with the jewellery in close proximity to the RF source, and one item of significant size (86 mm long). Even though jewellery can be worn on the body surface the dimensions of jewellery is usually small (< 20 mm).
4.10 Tooth fillings, caps, and orthodontic braces and plates

<table>
<thead>
<tr>
<th>Type</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teeth caps</td>
<td>In human head</td>
<td>Mobile phones 915 MHz GSM and 1.9 GHz DECT at maximum levels</td>
<td>SAR levels comply with Austrian safety standard ÖNORM S1120 (4 W/kg for 1 g mass)</td>
<td>Yelkenci and Magerl (2000)</td>
</tr>
</tbody>
</table>

Summary: The Yelkenci et al. (2000) study raises no concerns, as could be expected for very small metal implants. Moreover, given that the oral cavity is routinely subjected and adapted to substantial heat loads (e.g., from a hot cup of coffee), then RF heating at upper tier limits would seem to be comparatively trivial.

4.11 Implanted retinal stimulators

<table>
<thead>
<tr>
<th>Type</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implanted</td>
<td>In eye, adjacent</td>
<td>46 mW, 2 MHz extraocular transmitting multiturn coil around 20 mm from eye</td>
<td>Peak temperature rise of 0.6 °C, without blood flow, and 0.4 °C, with blood flow assumed</td>
<td>DeMarco et al. (2003), Lazzi et al. (2003)</td>
</tr>
<tr>
<td>Implanted</td>
<td>In eye, adjacent</td>
<td>50 mW, 1.45 and 2.44 MHz extraocular transmitting multiturn coil</td>
<td>Peak 1 g SAR is 1.59 W/kg at 2.44 GHz and 0.83 W/kg at 1.45 GHz</td>
<td>Gosalia K and Lazzi G (2003)</td>
</tr>
</tbody>
</table>

Summary: These studies raise little concern. Would need to consider each case with improvements and changes in the technology.

4.12 Implanted radiators

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implanted</td>
<td>Loop 5 mm x 10 mm</td>
<td>Normal to chest wall with hip-mounted monitor, in human body FDTD model</td>
<td>403 MHz, 25 µW radiated power</td>
<td>Peak 10 g SAR is 1.79 W/kg</td>
<td>Scanlon (2004)</td>
</tr>
</tbody>
</table>

Summary: Particular study gives example that satisfies safety standards. Such devices can be expected to become more prevalent in society with the increase in medical monitoring systems and would need to be reviewed for each new technology.
### 4.13 Spinal fusion systems and cervical fixation devices in MRI

<table>
<thead>
<tr>
<th>Type</th>
<th>Dimensions</th>
<th>Placement</th>
<th>Exposure</th>
<th>Comments</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical fixation devices</td>
<td></td>
<td>In standard position in phantom</td>
<td>MRI imaging (RF component at 63.8 MHz)</td>
<td>Study confirmed pain to patient caused by significant heating</td>
<td>Chou, Hover, McDougall and Ren (2004)</td>
</tr>
<tr>
<td>Spinal fusion stimulator</td>
<td>Not stated</td>
<td>In standard position in phantom</td>
<td>MRI imaging (RF component at 63.8 MHz)</td>
<td>Temperature increase less than 2 °C unless broken electrode present which gave rise to 14 °C increase</td>
<td>Chou, McDougall and Chan (1997)</td>
</tr>
<tr>
<td>(two wire leads and flat metal case) around the lumbar vertebrae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinal fusion implant (two wires and a flat metal case)</td>
<td>Wires 11.8 cm long. Case 3.67 cm by 2.3 cm.</td>
<td>In central position in box shaped torso</td>
<td>MRI switched-gradient magnetic fields. Exposure 600 Hz magnetic field</td>
<td>Highly localised increase in the E-field up to 197 times compared to when implant not present</td>
<td>Buechler, Durney and Christensen (1997)</td>
</tr>
</tbody>
</table>

**Summary:** Studies show situations of significant concern for MRI patients, but are difficult to generalise to assessments of persons exposed to the upper tier limits.
5 General rules-of-thumb and observations for implant assessments

Listed below are rules of thumb and general observations which may be useful in determining whether an implant requires detailed assessment for a person exposed up to the upper tier limits of the ICNIRP Guidelines (1998) or the IEEE C95.1 standard (2006). These recommendations are based on the canonical modelling in section 3 and the specific implant assessments reviewed in section 4.

5.1 General observations

1. RF field enhancements around an implant are affected by the frequency of exposure, the shape and size of the implant, its orientation with respect to the polarization of the in situ field and the dielectric properties of the surrounding tissue medium.

2. The absolute level of the SAR around an implant will also depend on the incident RF field levels in the body area around the implant. Thus, the potential for excessive localized SARs around an implant is only likely in parts of the body where in situ fields are already relatively high. Conversely, implants located in parts of the body which are relatively well shielded would not generally require assessment, especially in low conductivity tissues like bone.

3. A metallic implant is a passive re-radiator, and of itself cannot create additional RF power absorption in the body. Thus the overall RF heating in the general vicinity of the implant will remain about the same. One possible exception to this rule is the case of a large implant in one leg (e.g., a metal rod in the tibia), which by providing a lower impedance conductance path preferentially diverts additional current flow to that leg for exposure frequencies around and below whole body resonance frequencies.

4. Constructive and destructive interference effects can enhance or diminish the RF field level in a skin or skin/muscle layer above bone depending on the thickness of the layers and the frequency of exposure, thereby affecting the incident exposure of an implant located there. See Figures 3-7 for point SAR plots vs frequency for various tissue layer thicknesses.

5. SAR attenuation at the skin surface is very substantial at frequencies above 6 GHz and thereby provides RF shielding protection against metallic implant enhancements in the body (see Figures 3-7).

6. 10 cm³ average Volumetric Absorption Rate (VAR) is a better metric for assessing RF heating effects around implants than 10 g average SAR as it is not affected by mass density changes between the metal implant and the surrounding tissue and is more closely related to temperature rise.

5.2 Thermal effects

7. Some implants are located in a thermal environment where efficient heat transfer mechanisms will greatly mitigate any localized heating around parts of the implant. For example, the temperature of an arterial stent is strongly controlled by the convective heat transfer of the arterial blood flow passing through it. Metal plates located close to the skin (e.g., plates on the outside of the cranium) are another example, as are all forms of body-worn metallic objects (e.g. spectacles, jewellery, and the external component of a cochlear implant system).

5.3 Rods and other linear objects

8. In low loss tissues such as bone, a maximal resonant response for $E$ parallel rods occurs when the rod length is equal to one third of the exposure wavelength (see Figure 15). This resonant enhancement increases linearly with the length of the rod (see Figure 16). Long rods can cause
very substantial field enhancement at their tips, and hence are more likely candidates for detailed assessments. This resonance effect is damped out in tissues with higher electrical conductivity such as muscle (see Figure 20).

9. A common mechanism for RF enhancement around a metallic implant is the field concentrations that appear at the opposite ends of an implant where the projected length of the implant against the incident RF electric field vector is the longest. For rods and other linear structures, the enhancement mostly occurs at the end tips (see Figure 14). The level of enhancement depends on the size of the implant with respect to the wavelength of the exposure, which in turn is inversely proportional to the exposure frequency.

10. Short rods less than 20 mm in length do not cause any significant field enhancement around the implant, which may in part be due to the averaging effect of the 10 cm³ VAR volume (or 10 g SAR mass). It is probably reasonable to infer from this that all objects with a maximum dimension of 20 mm or less will not require assessment.

11. The diminished enhancement of SAR at the tips of implants for supra-resonance removes the need to assess a large class of implants of certain lengths above certain frequencies which are located at certain distances below the skin (use Figure 20 in combination with Figures 3-7 for assessment guidance).

12. For rods of all length immersed in muscle, the 10 cm³ VAR enhancement is low (< ×1.4) for frequencies above 500 MHz (see Figure 20). Similar observations may apply in other high loss tissues. The re-radiated fields around an implant tend to decay very quickly in a lossy dielectric tissue environment.

13. The RF field enhancement at the ends of an implant is constant for frequencies below resonance. The level of this enhancement increases with the rod length (see Figure 17) and is independent of the dielectric properties of the surrounding tissue (see Figure 20).

14. There is no significant RF enhancement at the ends of an implant in the supra resonant frequency range. The supra resonant range occurs at lower frequencies for longer implants (see Figure 20).

15. The 10 cm³ VAR enhancement at the tips of linear implants diminishes substantially for non parallel $E$ polarizations. No field enhancement is seen for $E$ polarizations that are perpendicular to rods. Hence, a person moving with respect to the exposure source would likely reduce implant SAR enhancements when averaged over time.

16. The tip shapes on rods have negligible impact on localised RF heating. This is probably a consequence of the small size of tips relative to the 10 cm³ VAR averaging volume. Likewise, RF field enhancements that occur around any sharp point in the implant would be so localized that their influence would not be noticeable in a 10 cm³ VAR of 10 g SAR averaging mass.

5.4 Screws

17. No assessment required for screws up to 20 mm in length. Longer screws may require assessment depending on the frequency of exposure and the level of RF shielding at the implant body location. The pointed end of a screw (where the localised $E$-field can be elevated) does not require specific assessment when determining 10 g mass averaged SAR (see Figure 18).

5.5 Arterial stents

18. Detailed studies published so far show no cause for concern for stents up to 34 mm in length (see section 4.3). In addition, the potential for adverse heating around stents is substantially mitigated by the convective cooling from blood flow within the artery. Hence no assessments are required for all stents.
5.6 Wide Plates

19. Metal plates that lie directly beneath the skin may enhance SAR in the skin at microwave frequencies due to constructive interference which is maximized when the thickness of the skin is equal to a quarter wavelength of the RF exposure in that tissue. For skin thicknesses between 3 to 8 mm, the quarter wave resonance for a normally incident exposure ranges from 4.1 to 1.5 GHz (see Table 3). This enhancement however does not appear to cause the 10 g average SAR to exceed the 10 W/kg upper tier limit for ambient field exposures below the upper tier reference levels for $E$ or $H$ of the ICNIRP Guidelines (1998).

20. The peak linear SAR enhancement is generally more spread around the circumference of a wide plate compared to a rod which reduces the peak 10 g average SAR. As seen in figure 20, the level of enhancement rises with increasing implant length. For exposure frequencies less than 200 MHz, plates larger than 50 mm in diameter may need to be assessed for linear enhancement effects if situated close to the skin where shielding is low (see sections 3.2 and 4.4).

5.7 Pacemakers

21. The body of the pacemaker should not be of concern based upon the studies listed above for wide plates, particularly as they are usually located deep inside the body. Further studies are required in regards to the influence of the pacemaker leads.

5.8 Loops

22. A loop shaped metal implant which is oriented normal to the in situ $H$-field may produce enhanced SAR in any gap in the loop. This phenomenon requires further investigation.

5.9 Cochlear Implant Systems

23. No assessment required. See section 4.7 for further details.

5.10 Spectacles

24. No assessment required. See section 4.8 for further details.

5.11 Jewellery

25. Even though there have been limited assessments performed on jewellery (see section 4.9) there should be no requirement for an assessment. Jewellery is not usually positioned near vital body tissues, the exception being piercings near the eye but these are typically small (< 20 mm) and do not require assessment. Heat transfer mechanisms will easily dissipate any localised heating.

5.12 Tooth fillings, caps, and orthodontic braces and plates

26. No assessment required. The oral cavity is naturally adapted to higher heat loads (e.g. from a hot cup of coffee) which in part is due to the convective and evaporative cooling from respiration air flow. This may reasonably be expected to provide a larger margin of safety from RF heating around metallic implants in the mouth. Tooth fillings and caps are also small in size.
5.13 Shrapnel and shotgun pellets

27. No assessment required for pieces up to 20 mm in length. Longer shrapnel pieces may require assessment depending on the frequency of exposure and the level of RF shielding at the implant body location.
6 References


Australian Radiation Protection and Nuclear Safety Agency. 2002. Radiation Protection Standard: Maximum exposure levels to radiofrequency fields – 3 kHz to 300 GHz. ARPANSA Radiation Protection Series No 3.


