Assessment of Specific Energy Absorption Rate (SAR) in the Head from TETRA Handsets

Final Report

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Assessment of Specific Energy Absorption Rate (SAR) in the Head from TETRA Handsets

1 Executive Summary

The purpose of this project was to calculate the distribution of power absorbed in an anatomically realistic model of the head from a representative TETRA handset.

TETRA (Terrestrial Trunked Radio) is a modern digital private mobile radio system designed to meet the requirements of professional users, such as the police and fire brigade. The current frequency allocations in the UK are 380-385 MHz, 390-395 MHz for the public sector network (BT Airwave) and 410-415 MHz and 420-425 MHz for a commercial network (Dolphin). There are 4 time slots and in normal two-way voice transmission, only one of the slots will be used and this will result in a duty factor of ¼. Handsets are available with peak powers of 1 W and 3 W, giving average powers of ¼ W and ¾ W after consideration of the duty factor. The radios can be held to the ear like a mobile phone or dispatcher-style in front of the face, or mounted remotely on the body but this case will give much lower SAR values to the head than the former positions near to the head.

The TETRA radios can use either a monopole or a helical antenna. The latter is more difficult to model computationally and so it was important to verify the numerical description of the antenna and handset by measurement. A combination of experimental work and computer modelling was therefore used to gain an in-depth understanding of the electrical performance of the helical antennas used with TETRA handsets. A real handset was then set up to radiate continuously under isolated conditions in the absence of the body. Measurements of the near total electric fields in planes at 5-, 10- and 15 cm in front of the handset were made. The comparisons between the calculations and measurements at the three separation distances for both monopole and helical antennas show very good agreement in shape and magnitude.

The power absorbed in the body is quantified in terms of the specific energy absorption rate (SAR) in the unit of watt per kilogram ($W\ kg^{-1}$). A comprehensive set of calculations of SAR in the head were performed for an ensemble of positions for the handset in front of the face and for both sides of the head, with the handset along the cheek or tilted away from the cheek at an angle of 15° as specified by the European Standard for assessing SAR in physical phantoms.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) in its guidance on limiting human exposure to radio frequency electromagnetic fields advises restrictions based upon avoidance of adverse effects resulting from whole-body or partial body heating. It recommends that for occupational exposure the SAR should not exceed 10 $W\ kg^{-1}$ in any 10 g of the head. The restriction for public exposure is 2 $W\ kg^{-1}$. The SAR values are to be averaged over any 6 minute period.

The work described in this report shows that the representative TETRA handset considered, operating at 1 W in normal use with either the helical or monopole antenna will comply with both the ICNIRP occupational and public exposure restrictions.

The handset with a monopole antenna operating at 3 W in normal use will show compliance with both the ICNIRP occupational and public exposure restrictions. The handset with a helical antenna operating at 3 W in normal use will show compliance with the ICNIRP occupational exposure restriction but will be over the public exposure restriction by up to ~ 50 % if kept in the position of maximum SAR for 6 minutes continuously.

2 Aims and Objectives

TETRA (Terrestrial Trunked Radio) is a new digital system for mobile radio. It is designed to replace the older analogue radio systems that are currently used by professional and commercial organisations. There are two TETRA networks currently being implemented in the UK. The first was launched in late 1999 and is operated by Dolphin. This is a commercial network aimed at corporate users such as road haulage and delivery companies. The second network is designed to replace the public sector systems used by the emergency services (police, ambulance etc) and is operated by BT Airwave.

The current frequency allocations in the UK are 380-385 MHz, 390-395 MHz for the public sector network (BT Airwave) and 410-415 MHz and 420-425 MHz for a commercial network (Dolphin). There are 4 TDMA slots per frequency channel and 17 frames are transmitted per second. In normal two-way voice transmission, only one of the slots will be used and this will result in a duty factor of ¼. Handsets are available with peak powers of 1 W and 3 W, giving average powers of ¼ W and ¾ W after consideration of the duty factor. The radios are designed to be held to the ear or dispatcher-style in front of the face

The purpose of the study was to calculate the distribution of SAR in an anatomically realistic model of the head from a representative TETRA hand-held radio using the Finite-Difference Time-Domain (FDTD) method. The TETRA radios can use either a monopole or a helical antenna. The latter is more difficult to model computationally and so it was important to experimentally verify the FDTD description of the antenna and handset. The initial plan of the study was-

1. Perform an analysis of the performance of the helical antenna alone by a combination of experimental and computer modelling work.
2. Produce a FDTD model of the helical antenna and compare near field predictions with those from part 1.
3. Produce a calibration standard for measuring electric field strengths in the TETRA frequency bands.
4. Develop an FDTD model of the complete handset. A real handset will be configured to radiate continuously in free space, while electric fields are measured in the space around it and these data will be used to validate the FDTD model.
5. On the successful completion of objectives 1 to 4 the coupled head-handset calculations will be performed to characterise the SAR distribution in the head. Positions of the handset held to the ear, in front of the face and with a remote antenna placed on the shoulder will be investigated.
6. The calculated SAR values will be compared with the ICNIRP basic restrictions on SAR for both occupational and public exposure to assess compliance.

N.B. The project started with Simoco, Europe Ltd. providing technical support in terms of details of the structure of their handsets and helical antennas. The detailed analysis of the helical antenna was performed on the Simoco equipment. Unfortunately, Simoco went into receivership in 2002 and no longer appeared able to provide technical support. We subsequently approached Motorola and they were willing to provide technical support on their MTP700 handset and antennas. This handset can use a monopole antenna as well as a helical antenna. Inspection of the Motorola helical antenna revealed that it is very similar to the Simoco antenna and so a separate analysis of the helical antenna was not necessary and the project proceeded with the Motorola equipment.

3 Participants

Peter Dimbylow, Mohammed Khalid and Simon Mann from the National Radiological Protection Board.

4 Achievements
Modelling of the helical antenna

4.1.1 NEC Model

A combination of experimental work and computer modelling was used to gain an in-depth understanding of the electrical performance of the helical antennas used with TETRA handsets. Parameters examined included impedance and near field distributions.

The helical antenna from a Simoco handset consists of copper wire wound to form a helix of 8 mm diameter and 4 mm pitch. Figure 1 shows the result of an edge detection algorithm applied to a x-ray of the antenna.

Figure 1. Simoco helical antenna.

The Numerical Electromagnetics Code, NEC (Burke, 1992) uses the method of moments to solve an electric field integral equation and thereby predict the current flow on wire structures either excited by voltage sources or exposed to plane waves. A NEC model of the antenna was produced with a perfect ground plane supporting a cylinder, to represent the base of the antenna, and a helical wire section to represent the upper part. The cylinder was formed from meshed wires to represent its closed surfaces.

A source voltage was applied across 6 vertically directed segments of the cylinder that were at a height of 4 mm above the ground plane. The predicted impedance and resonant frequency of the basic model were compared with the measured values. Good agreement was established between the measured and NEC predicted resonant frequency and impedance.

4.1.2 FDTD model

The Finite-Difference Time-Domain (FDTD) method (e.g. Taflove, 1995) provides a direct solution of the coupled, time-dependent Maxwell curl equations. This structure of the FDTD method based on a lattice of rectilinear cells readily lends itself for application to voxel models.

The boundary conditions on the surface of conducting structures are that the tangential electric field components are zero. This can be applied to the wire of the helical antenna by setting the appropriate edge components of the cells to zero. The antenna is excited by driving a sinusoidal time-varying voltage across the base of the antenna. The current through this segment is calculated from the circulating magnetic fields and the radiated power is obtained by integrating the product of the current and voltage over time through a half-period. Predicted fields can then be normalised to unit radiated power from the antenna.

Two voxel models of the antenna over a ground plane were produced at resolutions of 2 and 1 mm. The helix has a pitch of 4 mm and a diameter of 8 mm. In the 2 mm resolution model this was simulated by setting the appropriate edge horizontal and vertical electric field components to zero in the individual voxels (i.e. not setting the entire voxel to be a

conductor) to produce a square thin wire helix. The more detailed 1 mm resolution model was produced by setting individual voxels to be conductors, i.e. all the 12 edge field components were set to zero. This finer resolution enabled the cylindrical base and circular helix to be modelled more accurately and the pitch of the antenna to be more smoothly represented. The antenna was excited by driving a voltage across the gap between the ground cylinder stub and the cylindrical base of the helix.

The near electric fields produced by the NEC and FDTD models were compared in a vertical plane 10 cm from the axis of the antenna. The plane is 10 cm high and is 20 cm wide. The fields were compared at 2 mm increments in the vertical and horizontal directions at a frequency of 380 MHz. There is very good agreement in the shape and magnitude of the electric field distributions between the NEC and FDTD calculations The mean percentage difference in the total field between the 2 mm FDTD model and the NEC model is 2.8 % and the difference between the 1 mm FDTD model and the NEC model is 4.5%.

Confidence in the applicability of the FDTD method to the TETRA helical antenna has been engendered by the agreement with the wire grid, NEC simulation approach. In particular, a 2 mm model of the antenna is sufficient to accurately model the helix. This resolution saves a factor of 16 in the computational run-time in comparison with a 1 mm resolution.

Comparison of FDTD predictions with measured near electric fields in front of the handset

4.1.3 FDTD model of Motorola MTP700 handset

The project started in co-operation with Simoco, who went into receivership in February 2002. We approached Motorola and they were willing to provide technical support by supplying information about their handsets and antennas, which would enable us to produce computational models.

The second generation Motorola handset, MTP700 can use a monopole antenna as well as a helical antenna. The handset is mainly to be used dispatcher-style in front of the face but can also be held to the ear like a mobile phone. However, it is not used remotely with the antenna and microphone placed on the shoulder. In fact, ancillary equipment is not available for this purpose. The helical antenna on the Motorola handset is very similar to the Simoco antenna. Therefore, the detailed antenna computational simulation and comparison work (between FDTD and NEC) which we performed with the Simoco antenna was not repeated with the Motorola helical antenna.

A FDTD model of the Motorola MTP700 handset was constructed at a resolution of 2 mm. The handset was dismantled and measurements were made of the concatenated metallic structures. These were represented by a conducting box of dimensions 34 x 50 x 134 mm. The model of the helical antenna previously produced was attached onto the basic handset model. A model of the 15 cm monopole antenna can also similarly be located.

4.1.4 Near field measurement

An IndexSAR probe was used to measure the electric fields from the handset. The probe has three orthogonal sensors in a delta formation, each sensor aligned at 54.7° on the three faces of a triangular prism. The probe's sensitivity in air was determined by the National Physical Laboratory in a Crawford TEM cell. The calibration was performed at 380 MHz for time averaged field strength levels from 3 to 100 V m^{-1} for both continuous wave and TETRA signals. The estimated uncertainty for the calibration factors was ±10%.
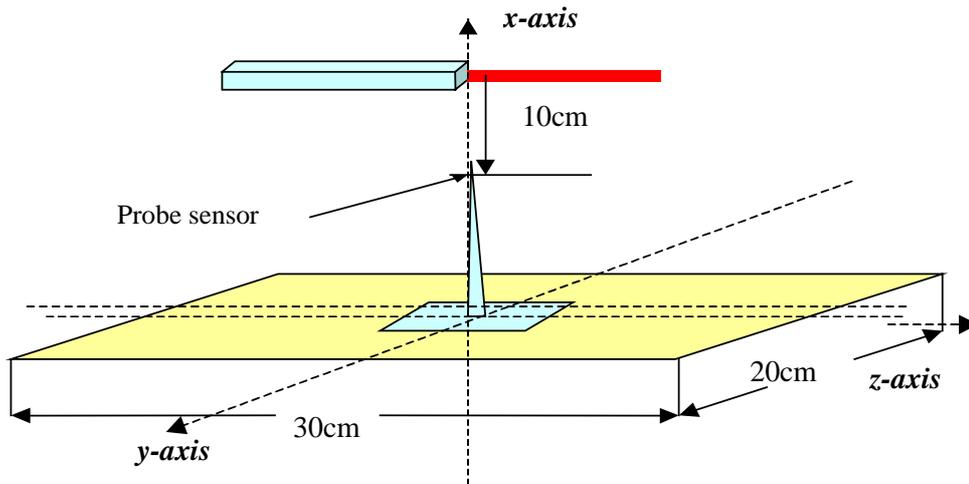
Figure 2. The electric field measurement geometry.

The handset was configured to radiate continuously in free space. The electric field probe was located vertically in a perspex holder and scanned in front of the handset in the yz-plane at distances of 5-, 10- and 15 cm from the antenna axis. The near electric field was measured in a 30 x 20 cm region in the yz-plane in 2 cm increments.

The radiated power from the handset was measured as 0.8 W. The measured field strength is based on the TETRA signal and rms values, whereas the FDTD model predicted values are based on the peak values of a continuous wave. The measured data were converted to be equivalent to the latter.

Figure 3 is a surface plot of total fields in the plane 10 cm in front of the handset antenna axis for a monopole. The base of the surface below the handset faces to the bottom right. The peak on the left corresponds approximately to the tip of the antenna. The minimum is opposite the antenna base.
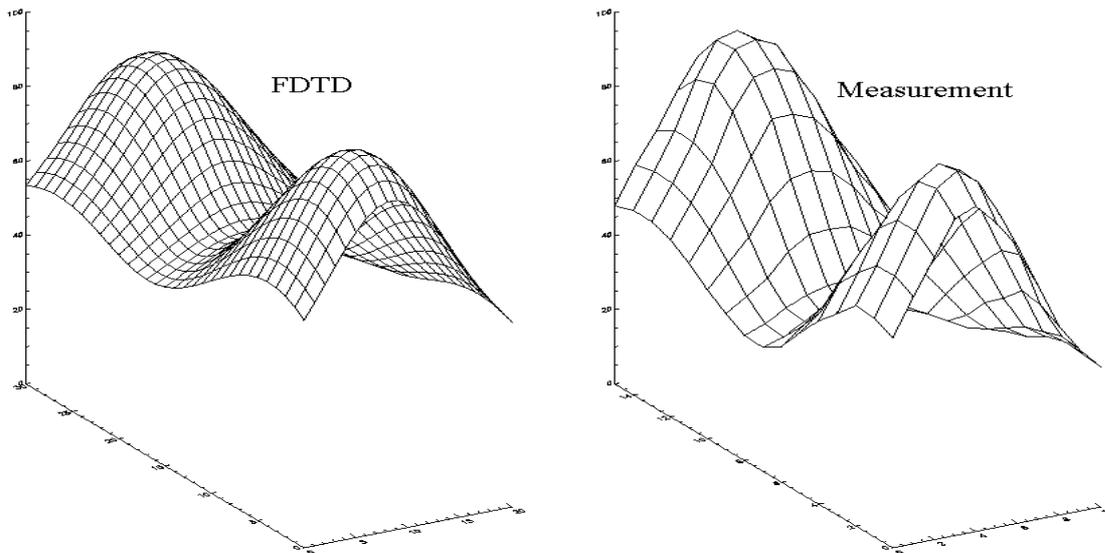

Figure 3. Comparison of total fields 10 cm in front of handset using the monopole antenna.

The comparisons between the FDTD calculations and measurement at the three separation distances for both antennas show very good agreement in shape and magnitude. When there is a divergence outside of the 10 % uncertainty on the measurements the FDTD calculations yield the higher field value so represent conservative values (i.e. they should overestimate the SAR in the head) of the fields produced by the handset.

4.3 Calculation of SAR in the head

A comprehensive set of coupled calculations of SAR in the head were performed at 380 MHz for an ensemble of positions for the handset in front of the face (AP) and for both sides of the head with the handset along the cheek (CHEEK) or tilted (TILT) away from the cheek at an angle of 15° as specified by the European Standard for assessing SAR in physical phantoms. Details of the anatomically realistic model of the head can be found in Dimbylow and Mann (1994).
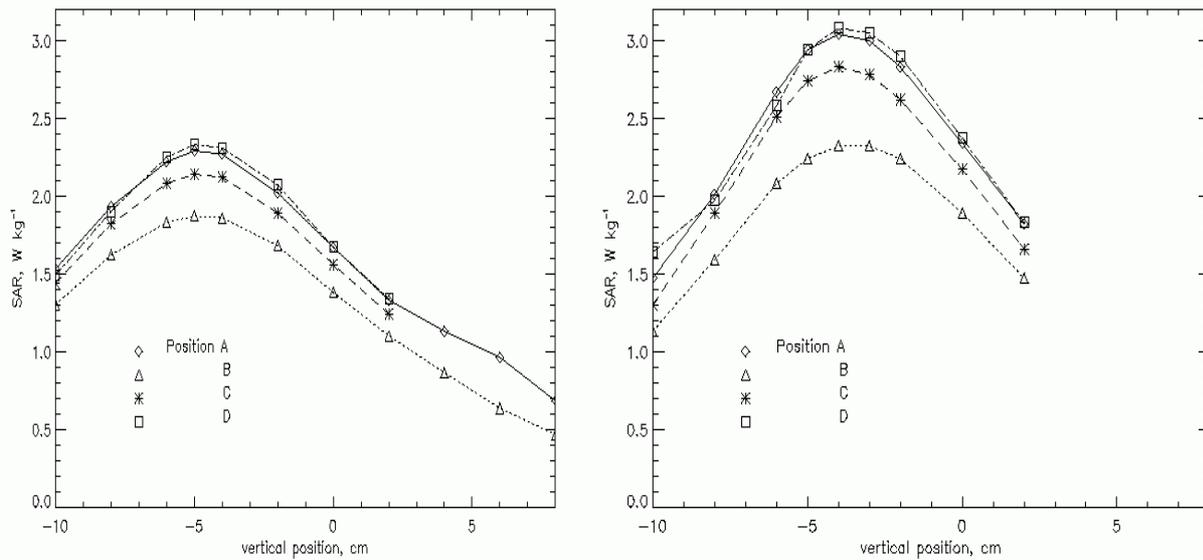
4.3.1 Handset in front of the face

Figure 4. The placement of the handset, in front of the face, aligned along the vertical mid-axis of the head.

Figure 5 presents the SAR averaged over 10 g of contiguous tissue for the handset with a monopole antenna held in front of the face. Position A is the handset aligned along the vertical mid-axis of the head. A standard placement of the handset that would represent practical usage is denoted by a vertical position, z=0 (see figure 4). The metallic structure of the handset is covered at the front by ~ 6 mm of polycarbonate material so the handset is placed 3 cells (of 2 mm size) from the nearest part of the head. Negative values of z represent a lowering of the handset with respect to the head. The antenna is aligned in front of the left eye in position B, in front of the right eye in position C and along the mid-axis in position D. Positions B-D had the same separation from the front of the head as position A. The maximum SAR over 10 g of contiguous tissue is 2.33 W kg^{-1} per W for the antenna aligned with the mid-axis of the head and for the handset displaced down 5 cm from the standard position. The maximum value at z=0 is 1.67 W kg^{-1} per W. The average over the contiguous region yields values that are approximately twice those from the more compact average over a cube.

Figure 6 presents a similar plot for the helical antenna held in front of the face. The maximum SAR over 10 g of contiguous tissue is 3.08 W kg^{-1} per W for the antenna aligned with the mid-axis of the head and for the handset displaced down 4 cm from the standard position. The maximum value at z=0 is 2.37 W kg^{-1} per W. Other positions of the handset were investigated and the highest SARs of 3.55 (helix) and 2.71 (monopole) W kg^{-1} per W were obtained by jamming the handset as close as possible in front of the left eye but this would not be a practical position to operate the handset.

Figures 5 and 6. The SAR per W of output power averaged over 10 g of contiguous tissue for the handset (monopole on left, helix on right) held in front of the face.

4.3.2 Handset at the side of the head

The handset can also be placed at the side of the head and used like a mobile phone. The CENELEC standard for measurement of SAR from mobile phones (BSi, 2001) specifies that phones shall be tested in the 'cheek' and 'tilted' positions. In the cheek position the vertical centre line of the handset is aligned between the ear and the mouth and touches the cheek. The tilted position is similar except that the base of the handset is moved outwards away from the mouth by 15º whilst pivoting against the ear. These positions are defined on the SAM physical phantom but analogous positions can be defined on the realistic anatomical phantom used in this work.

The FDTD method defines the geometry in terms of cuboid cells. When the handset and antenna are placed at an angle to this grid the edges of the radio are not smooth and take on a 'stair-case' pattern, increasing the electrical length of the conductor. It also becomes very difficult to follow the turns of the relatively tight pitched helical antenna. For these reasons it is better to keep the hand-set aligned with the rectilinear grid and rotate the model of the head. This involves a sampling routine to redefine the cubical voxels of the head after rotation. The head was rotated 60° forward to align the vertical centre line of the handset to the plane between ear and mouth to achieve the 'tilted' position. The 'cheek' position could then be obtained by a second orthogonal rotation of the head by 15° towards the handset. The FDTD calculations were then performed in this rotated geometry.
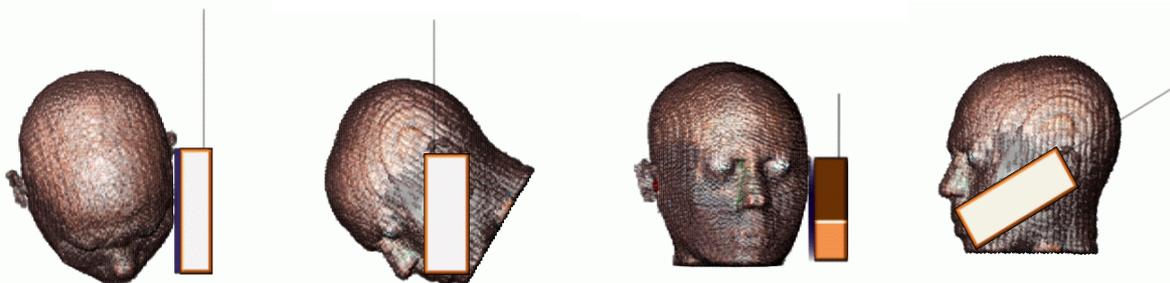

Figure 7 displays the 'cheek' position on the left hand side of the face. (The imaging software was the used to rotate the image back to get the two equivalent positions on the right.)

Figure 8 presents SAR values using the monopole antenna for variations on the cheek position on the left side of the face. The standard placement (see figure 7) of the handset to produce the cheek position is denoted by a vertical position of z = 0 and a position along the side of the head of x = 0. Negative values of z represent a lowering of the handset with respect to the head. Positive x-values represent a displacement of the handset forwards towards the nose and negative values represent a displacement backwards. The maximum SAR over 10 g of contiguous tissue is 2.08 W kg^{-1} per W. The value for the standard position is 1.55 W kg^{-1} per W. Figure 9 presents SAR values for the helical antenna. The maximum SAR over 10 g of contiguous tissue is 3.36 W kg^{-1} per W. The value for the standard position is 2.22 W kg^{-1} per W.
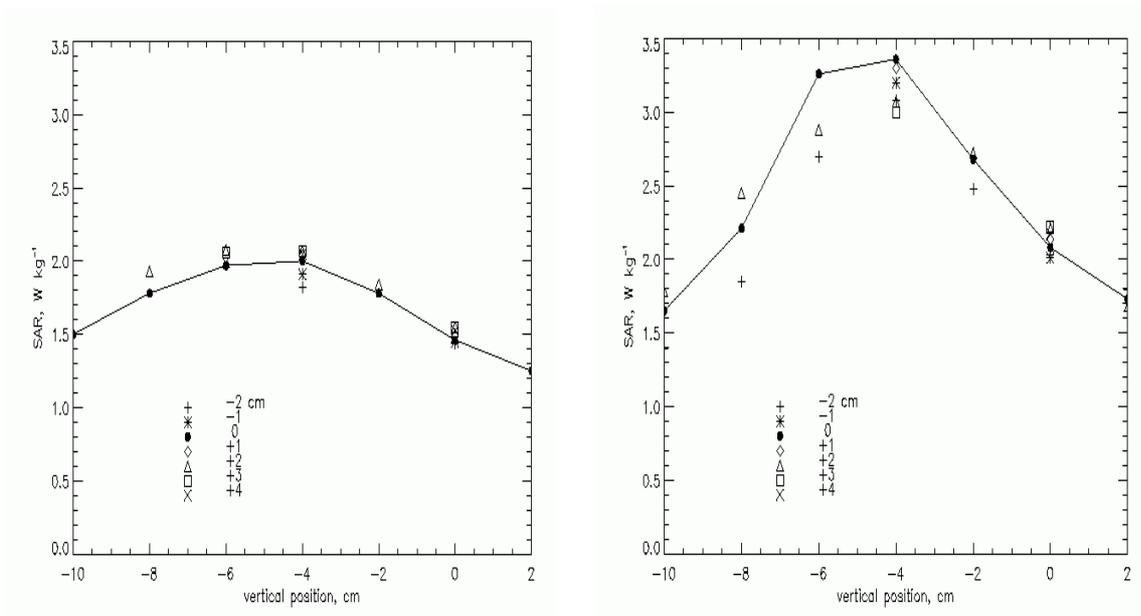
Figures 8 and 9. SAR per W of output power averaged over 10 g of contiguous tissue for handset (monopole on left, helix on right) in left cheek position. The symbols refer to the horizontal displacement, x from the standard position. Positive values are forwards towards the nose.

The maximum SAR for the monopole antenna from variations on the tilted position on the left side of the face is 1.71 W kg^{-1} per W. The value for the standard position is 1.64 W kg^{-1} per W. For the helical antenna the maximum SAR is 2.74 W kg^{-1} per W and 2.34 W kg^{-1} per W for the standard position. Other positions of the handset were investigated and the highest SARs of 5.33 (helix) and 2.27 (monopole) W kg^{-1} per W were obtained by lowering the handset in the tilt position so that the ear piece was below the ear and opposite the cheek with the antenna adjacent to the ear. However, this location would not be a practical position to operate the handset. Corresponding calculations were performed for the antenna on the right side of the head. The highest SARs of 6.87 (helix) and 2.23 (monopole) W kg^{-1} per W were found as above for the non-practical operating position with the ear piece low on the cheek.

4.4 Compliance with ICNIRP standards

Table 1 gives the SAR for the handset in the 'standard' positions whilst table 2 presents the maximum SAR from the ensemble of possible practical operating positions considered in each handset geometry and described in section 4.3. The shorter helical antenna produces SAR values that are approximately 50-100 % higher than those produced by the monopole antenna. The dispatcher style position in front of the face produces the highest SAR (2.33 W kg^{-1} per W) for the monopole antenna whilst the cheek position produces the highest value

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(3.90 W kg^{-1} per W) for the helical antenna. The corresponding values for the left and right sides are similar but there is some difference due to variations in anatomy of the model.

Handset position	SAR in 10g of contiguous tissue, W kg^{-1} per W	
	monopole	helix
AP	1.67	2.37
left CHEEK	1.55	2.22
right CHEEK	1.63	2.24
left TILT	1.64	2.34
right TILT	1.27	1.70

Table 1. SAR values for the handset in the 'standard' operating positions.

Handset position	SAR in 10g of contiguous tissue, W kg^{-1} per W	
	monopole	helix
AP	2.33	3.08
left CHEEK	2.08	3.36
right CHEEK	1.96	3.90
left TILT	1.71	2.74
right TILT	1.27	2.61

Table 2. The maximum SAR values from the ensemble of possible practical operating positions considered in each handset geometry.

There are 4 TDMA slots per frequency channel. In normal two-way voice transmission, only one of the slots will be used and this will result in a duty factor of ¼. Handsets are available with peak powers of, predominantly, 1 W but also 3 W, giving average powers of ¼ W and ¾ W after consideration of the duty factor. Table 3 gives the maximum SAR values, derived from table 2, for the handset operating at 1 W with a duty cycle of ¼ to give a time-weighted output power of 0.25 W.

Handset position	SAR in 10g of contiguous tissue, W kg^{-1} for 0.25 W	
	monopole	helix
AP	0.582	0.770
CHEEK	0.520	0.975
TILT	0.427	0.685

Table 3. The maximum SAR from the ensemble of positions considered in each handset geometry. The handset is operating at 1 W with a duty cycle of ¼ to give a time-weighted output power of 0.25 W.

ICNIRP (1998) in its guidance on limiting human exposure to RF electromagnetic fields advises restrictions based upon avoidance of adverse effects resulting from whole-body or partial body heating. It recommends that for occupational exposure the SAR should not exceed 10 W kg^{-1} in any 10 g of the head. The restriction for public exposure is 2 W kg^{-1}. The SAR values are to be averaged over any 6-minute period.

The representative MTP700 TETRA handset considered, operating at 1 W in normal use will show compliance with the ICNIRP occupational exposure restriction of 10 W kg^{-1} and also with the public exposure restriction of 2 W kg^{-1}.

A handset with a monopole antenna operated at 3 W in normal use will show compliance with the ICNIRP occupational exposure restriction and also the public exposure restriction. A handset with a helical antenna operated at 3 W in normal use will show compliance with the ICNIRP occupational exposure restriction but will be over the public exposure restriction by up to ~ 50% if kept in the position of maximum SAR for 6 minutes continuously.

Acknowledgement

We would like to thank Richard Bond and Chris Wright of Motorola for providing us with technical assistance on the design and operation of the MTP700 and for providing us with handsets.

5 Analysis of Objectives Met

1. Perform an analysis of the performance of the helical antenna alone by a combination of experimental and computer modelling work. A combination of experimental work and computer modelling was used to gain an in-depth understanding of the electrical performance of the helical antennas used with TETRA handsets.

2. Produce a FDTD model of the helical antenna and compare near field predictions with those from objective 1. Very good agreement was obtained between the FDTD method and the wire grid, NEC simulation approach. In particular, a 2 mm model of the antenna is sufficient to accurately model the helix. This resolution saves a factor of 16 in the computational run-time in comparison with a 1 mm resolution.

3. Produce a calibration standard for measuring electric field strengths in the TETRA frequency bands. There were difficulties with non-isotropy of the NRPB diode probe when trying to measure the fields from the handset. This problem was solved by NPL lending us an IndexSAR probe. The probe was calibrated in air for a TETRA signal.

4. Develop an FDTD model of the complete handset. A real handset will be configured to radiate continuously in free space, while electric fields are measured in the space around it and these data will be used to validate the FDTD model. The project started in co-operation with Simoco, who went into receivership in February 2002. We approached Motorola and they were willing to provide technical support by supplying information about their MTP700 handset and antennas, which would enable us to produce computational models. A FDTD model of the Motorola MTP700 was developed. Measurements of the near total electric fields in planes in front of the handset were made. The comparisons between the FDTD calculations and measurement at the three separation distances for both monopole and helical antennas show good agreement in shape and magnitude.

5. On the successful completion of objectives 1 to 4 the coupled head-handset calculations will be performed to characterise the SAR distribution in the head. Positions of the handset held to the ear, in front of the face and with a remote antenna placed on the shoulder will be investigated. The Motorola MTP700 handset is not used remotely with the antenna and microphone placed on the shoulder, so this configuration was not considered. A comprehensive set of coupled calculations of SAR in the head were performed for an ensemble of positions for the handset in front of the face and for both sides of the head, with the handset along the cheek or tilted away from the cheek at an angle of 15° as specified by the European Standard for assessing SAR in physical phantoms.

6. The calculated SAR's will be compared with the ICNIRP basic restrictions on SAR for both occupational and public exposure to assess compliance. A compliance assessment of the representative TETRA handset with the ICNIRP basic restrictions has been made.

6 Interpretation

ICNIRP in its guidance on limiting human exposure to RF electromagnetic fields advises restrictions based upon avoidance of adverse effects resulting from whole-body or partial body heating. It recommends that for occupational exposure the SAR should not exceed 10 W kg^{-1} in any 10 g of the head. The restriction for public exposure is 2 W kg^{-1}. The SAR values are to be averaged over any 6 minute period.

The representative MTP700 TETRA handset considered, operating at 1 W in normal use will show compliance with the ICNIRP occupational exposure restriction of 10 W kg^{-1} and also with the public exposure restriction of 2 W kg^{-1}.

A handset with a monopole antenna operated at 3 W in normal use will show compliance with the ICNIRP occupational exposure restriction and also the public exposure restriction. A handset with a helical antenna operated at 3 W in normal use will show compliance with the ICNIRP occupational exposure restriction but will be over the public exposure restriction by up to ~ 50% if kept in the position of maximum SAR for 6 minutes continuously.

TETRA handsets can also be mounted on the shoulder and abdomen and it seems likely that these will be the preferred positions of deployment but with the ability to use the handset close to the head in the dispatcher-style in front of the face or held to the ear like a mobile phone. These remote body positions will give much lower SAR values to the head than the positions near to the head investigated in this work.

7 Future Priorities

Further validation of the SAR assessment from TETRA handsets could be obtained by comparing FDTD calculations with measurements of SAR in a physical phantom of the head.

8 Publications

Having finished this final report, work will now begin on preparing a paper on the assessment of SAR in the head from TETRA handsets for submission to the peer-reviewed literature.

9 Financial Summary

Summary as of March 31, 2003

Contract Value	£ 74900
Invoiced	£ 71073
Left to Invoice	£ 3827

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