วิศวกรรมสาร มข .ปีที่ 33 ฉบับที่ 5 (443 -457) กันยายน - ตุลาคม 2549
KKU Engineering Journal Vol .33 No.5 (443 -457) September – October 2006

ลักษณะงานด้านวิศวกรรมของการศึกษาเชิงชีววิทยาเกี่ยวกับความปลอดภัยของโทรศัพท์เคลื่อนที่

อาจณรงค์ ฐานสันโดษ, Gregory Gajda, James McNamee, Eric Lemay และ Pascale Bellier
Consumer and Clinical Radiation Protection Bureau, Health Canada
Ottawa, Ontario K1A 1C1, Canada

Email: art_thansandote@hc-sc.gc.ca

บทคัดย่อ

สาธารณชนทั่วไปมีความกังวลว่าพลังงานความถี่วิทยุจากโทรศัพท์เคลื่อนที่ชนิดมือถืออาจก่อให้เกิดผลร้ายแรง(เช่นมะเร็ง)แก่ผู้ใช้ ประเด็นสุขภาพนี้ได้ถูกนำเสนอเป็นข่าวปอยๆในช่วงทศวรรษที่ผ่านมา ถึงแม้ว่ายังไม่มีข้อมูลทางวิทยาศาสตร์ชี้แนะถึงความเสี่ยงภัย รายงานสื่อมวลชนได้กระตุ้นให้นักวิทยาศาสตร์ในหลายประเทศทำการศึกษาเรื่องความปลอดภัยของโทรศัพท์ที่เคลื่อนที่ การศึกษาในห้องปฏิบัติการเพื่อวิเคราะห์ผลกระทบเชิงชีววิทยาของพลังงานความถี่วิทยุนั้น งานด้านวิศวกรรมมีบทบาทสำคัญต่อคุณภาพ ความซ้ำรอยและความเชื่อถือได้ของข้อมูล งานเหล่านี้ประกอบด้วย การออกแบบและประเมินผลระบบที่ใช้ผึ่งเซลล์เพาะเลี้ยงและสัตว์มีชีวิตให้ถูกพลังงานความถี่วิทยุ ระบบดังกล่าวมักถูกออกแบบเพื่อรองรับความต้องการที่จะให้มีการควบคุมสภาพแวดล้อมและระดับการถูกพลังงาน (ปริมาณรังสี) ในบทความนี้ผู้เขียนนำเสนอระบบที่ใช้ผึ่งเซลล์เพาะเลี้ยงและสัตว์ให้ถูกพลังงานวิทยุความถี่ 1.9 กิกะเฮิรตซ์ ซึ่งพัฒนาขึ้นโดยกระทรวงสาธารณสุขแคนาดา (Health Canada)

คำสำคัญ : พลังงานความถี่วิทยุ, โทรศัพท์เคลื่อนที่และสุขภาพ, ระบบความถี่วิทยุที่ใช้ผึ่งเซลล์เพาะเลี้ยงและสัตว์, ผลกระทบเชิงชีววิทยา

Engineering Aspects of Biological Studies on Mobile Phone Safety

Artnarong Thansandote, Gregory Gajda, James McNamee, Eric Lemay and Pascale Bellier
Consumer and Clinical Radiation Protection Bureau, Health Canada
Ottawa, Ontario K1A 1C1, Canada

E-mail: art_thansandote@hc-sc.gc.ca

ABSTRACT

There exists considerable public concern that radiofrequency energy from handheld mobile phones might cause adverse health effects, such as cancer, to users. Although there are no persuasive scientific data suggesting a health risk, media coverage on this issue has frequently been made over the past decade. The media reports have prompted scientists in many countries to carry out studies on the safety and safe use of mobile phones. In carrying out laboratory studies of the biological effects of radiofrequency energy, engineering aspects play a fundamental role in the quality, reproducibility and reliability of data. These aspects include the design and evaluation of systems for exposing cell cultures and live animals to radiofrequency energy. Exposure systems are often designed to accommodate requirements for the control of environmental conditions and exposure levels (dosimetric quantities). In this paper, systems for exposing cell cultures and live animals at 1.9 GHz, developed by scientists at Health Canada, are discussed.

Keywords : radiofrequency energy, mobile phones and health, radiofrequency exposure systems, biological effects

Introduction

Since the early 1990s, mobile phones have become an integral part of modern telecommunications and gained popularity among users who wish to maintain continuous communication without hampering freedom of movement. It was reported that the number of mobile phone subscribers in the world surpassed 2 billion in September 2005. In Thailand, current estimates place the corresponding number at more than 30 million, i.e. about one in two Thais has a mobile phone. These numbers continue to grow. With the growing popularity of mobile phones, questions have been raised about the safety of being exposed to their radiofrequency (RF) energy emissions. Recently, the health concern has been exemplified by the mobile industry targeting of children (8-12 years) as potential users.

Following the highly publicized personal lawsuit against mobile phone companies in the U.S. (Fischetti, 1993) and frequent media reports on this subject, scientists around the world have conducted research to address the health issues with respect to RF exposure from mobile phones. The research includes (i) epidemiological studies to look at evidence for a causal association between adverse health effects (e.g. cancer) and RF energy, and (ii) laboratory investigations to examine the evidence of genotoxic and epigenetic potential as well as other biological effects. These studies are important for the development of RF exposure standards and public communication material. In carrying out laboratory investigations, engineering aspects play a fundamental role in the quality, reproducibility and reliability of data. These aspects include the design and evaluation of systems for exposing cell cultures and live animals to RF energy.

In this paper, general requirements for RF exposure systems are discussed as an introduction to the subject. This is followed by separate presentations of systems for exposing cell cultures (*in vitro*) and live animals (*in vivo*), which have been developed at Health Canada. Each presentation covers a brief review of existing systems, the design and fabrication of our system, dosimetric evaluation, and results and discussions. Our system for *in vitro* study has recently been used to evaluate whether exposure to RF energy, similar to that from mobile phones, can elicit primary DNA damage and/or induce micronucleus formation in cultured human leukocytes (McNamee, et al., 2002a; McNamee, et al. 2002b; McNamee et al., 2003).

General Requirements for RF Exposure systems

A necessary characteristic of any exposure system is that it exposes the target organism (whole animal, organ or cells) to a uniform, tightly controlled and readily quantifiable electromagnetic dose rate without producing an artefactual response in the organism. Artefactual responses may be due to undesired temperature rises in the target organism or due to differences in environmental conditions between the sham-exposed and exposed sample. For example, under certain *in-vitro* exposure conditions, mixing or movement of culture medium may occur due to mass convection caused when a liquid is heated from below. This may occur despite the temperature being maintained within acceptable limits. In this example, the sham-exposed sample would not experience the convective movement and thus be subject to different environmental conditions.

Temperature control is the single most important factor, especially for in-vitro systems. The rate of temperature rise in a substance, dT/dt, in the absence of any cooling mechanism is given by (IEEE, 1991):

$$dT/dt = SAR/c \quad (1)$$

where SAR is the Specific Absorption Rate and c is the specific heat capacity of that substance.

For a liquid with c close to that of water (4186 J/kg^{o}C), the rate of temperature rise is 0.86 ^{o}C per hour for each W/kg of SAR. The degree to which the desired temperature can be maintained often determines the maximum usable dose rate or the maximum exposure duration for a system. Liquid-cooled systems offer the best performance in temperature control and allow high dose rates. They tend to be more complicated than air-cooled systems, which are often enclosed in incubators.

Dose rate distribution in the target organism is another important factor as is the degree of difficulty needed to quantify it. Ideally, the intended target should receive the highest dose rate in order to reduce potential thermal stresses in the rest of the sample or organism. For example, if it is desired to expose the brain of a rodent, a system should be chosen that does not give inordinately higher doses to other parts of the body. Dose rate distributions should be quantified by as many means as possible including the use of numerical calculations and direct measurement. A system that offers a means of measurement for verification of numerical calculations, even if only spot measurements, is preferred.

Dose rate homogeneity refers to the spread or variation in values of SAR in the target. Quantitatively, the spread can usually be defined by a mean and standard deviation. For systems designed to investigate dose response behavior by exposing at a range of discreet SAR levels, the standard deviation should determine the SAR intervals. For example, in a system where the standard deviation is large, the steps in the SAR intervals should be correspondingly larger to avoid potential overlapping dose rates in neighboring SAR levels.

RF power efficiency refers to the ability of the system to convert available RF power to SAR in the target and can sometimes be an important parameter given the high cost of RF power amplifiers. Generally, systems that use resonant structures and small physical sample sizes have high RF power efficiency. These include waveguides, cavities, some transverse electromagnetic (TEM) cells and coaxial cells. On the other hand, systems that utilize traveling wave structures and encompass large number of samples or large sample volumes typically have low RF power efficiency (radial transmission lines, anechoic chambers, gigahertz TEM chambers and to some extent, TEM cells).

Other factors in the selection of exposure system type are sample capacity, pH or CO_2 control, humidity control, ease of sample handling, shielding, operator safety, cost, reliability and physical size.

System for *In-vitro* Study

1. Introduction

Various *in-vitro* exposure systems have been reported in the literature. These include TEM cells (Burkhardt et al., 1996), rectangular waveguides (Schonborn et al., 2000), radial transmission lines (RTLs) (Moros et al., 1999), striplines and open radiating structures (Kantor et al., 1977; Courtney et al., 1975). In closed systems such as TEM cells, RTLs and propagating waveguides, shielding and SAR uniformity is usually good. However, temperature control is difficult, often implemented with forced-air cooling and containment in incubators (Guy et al., 1999). These systems usually have a maximum attainable SAR of the order 10 W/kg if the sample temperature is to be kept within $\pm 1^{o}$ C (Tice et al., 2002). RF power efficiency is typically low for these systems, requiring expensive power amplifiers to achieve SARs in the range of 0.5 to 5 W/kg. Access to the samples and observation during exposure is also usually poor.

Open radiating structures such as open-ended waveguides and coaxial lines afford easy access to the sample for temperature control. Liquid or water-cooling is possible, allowing SARs into the hundreds of W/kg while maintaining sample temperatures within 1^{o} C (Guy, 1977). Being

an open structure, they require additional shielding and sometimes suffer from poor SAR homogeneity. RF power efficiency can be good if the sample lies close to the aperture or radiating element and is generally aligned with the electric field. This arrangement, however, can give rise to strong SAR gradients at menisci and media interfaces.

For the biological assays used in our laboratory at Health Canada, the requirements were to expose a stratified sample of whole blood in 60 mm Petri dishes at a frequency of 1.9 GHz. The whole blood component occupies the bottom 1 to 1.5 mm and is covered by a layer of cell media to a height of approximately 5 mm. In addition, the assays are sensitive to thermal confounding and a maximal SAR of 10 W/kg was desired. It was decided to utilize an open-ended waveguide with the sample situated at the mouth and surrounded by a bath of circulating, constant temperature water. A circularly-polarized, cylindrical waveguide structure was chosen (Figure 1a), since it offers circular symmetry of the exposure fields and the aluminum tubing of a diameter appropriate for operation at the design frequency of 1.9 GHz was commercially available. This structure also allows easy access to the sample for dosimetric measurements. Since the facility in which the exposure system was to be housed possessed an RF-shielded room, the problem of potential radio interference caused by the system was not an issue.

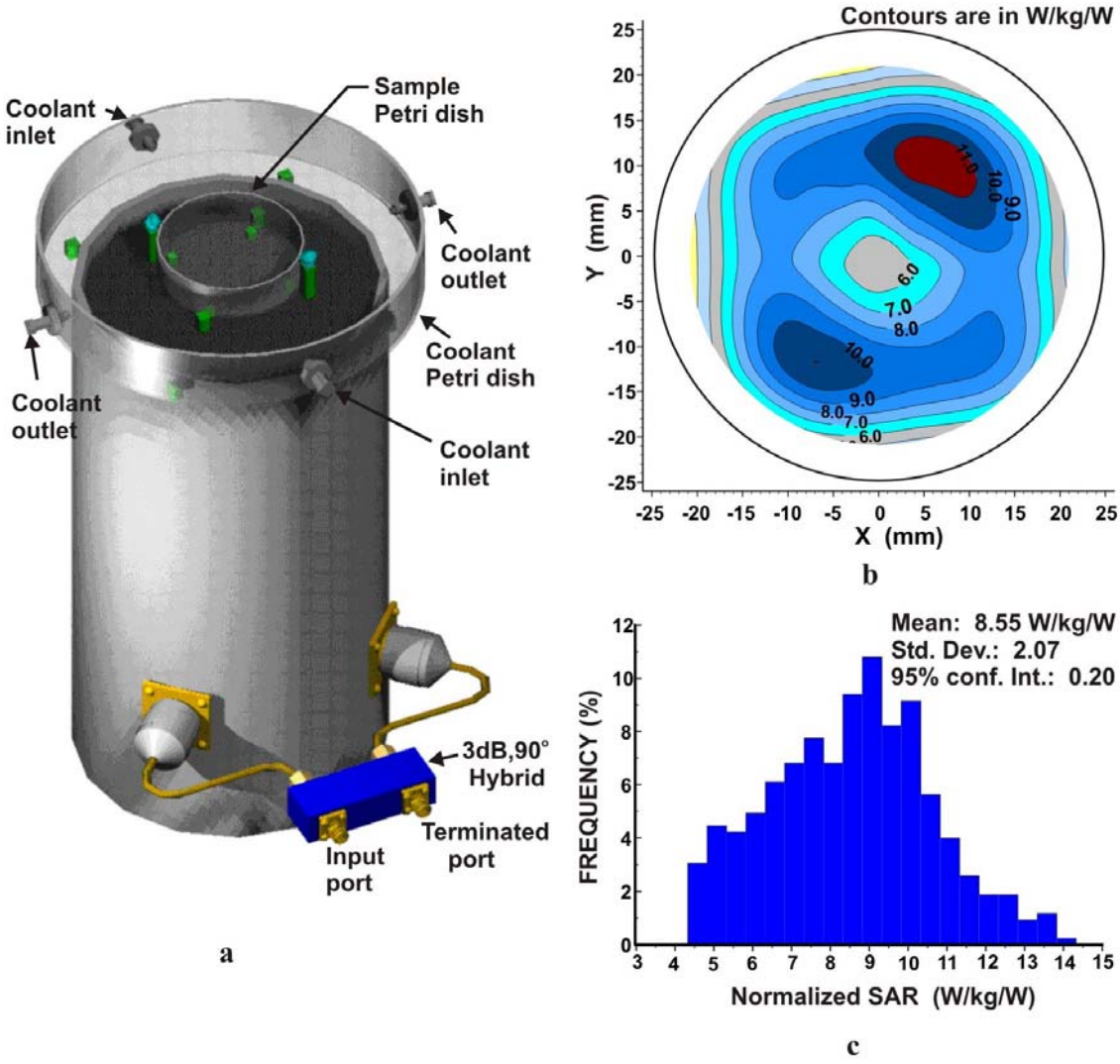

Figure 1. *(a) In-vitro waveguide exposure system (1.9 GHz) showing sample holder/cooling system. (b) Contour plot of SAR distribution in the plane z = 1.0 mm from bottom of sample dish. (c) Histogram of normalized SAR samples in the planes z = 0.5, 1.0 and 1.5 mm from bottom.*

2. Materials and Methods

The waveguide consists of a 110-mm inner diameter aluminium tube, 210 mm long with wall thickness of 3 mm. It is closed-off or shorted at one end and open at the other. The waveguide is fed from two identical excitation probes spaced ninety degrees apart, located 50 mm from the shorted end. The probes are monopoles (33 mm long by 4 mm in diameter) which are fed using flanged, N-type, coaxial connectors (Model 23N-50-0-1, Huber & Suhner). Circular polarization is achieved by feeding the two probes from a common signal, which is split in phase-quadrature using a 90-degree, 3 dB stripline hybrid (Model A7203, GHz Technologies Inc.). The two outputs of the stripline hybrid are connected to the coaxial inputs of the waveguide by two identical lengths of 3.6- mm diameter, semi-rigid cable assembled with N-type and SMA-type male (plug) connectors.

Typically, the reflection coefficient of a single coaxial-to-waveguide probe, with the open end of the waveguide perfectly loaded, was –15 dB or less over the frequency range 1.8–2.2 GHz. For two orthogonally positioned probes and a perfectly matched waveguide, the isolation between the two was greater than 16 dB over the same bandwidth. With the 3 dB hybrid and associated cables attached, the input reflection coefficient and transmission coefficient at the input and isolation ports were both less than –15 dB over the same band.

3. Sample Holder/Cooling System Design

The sample holder/cooling system arrangement is shown in Figure 1(a). The 60 mm sample dish sits concentrically within a 150 mm diameter Petri (coolant) dish on 3.2 mm plastic stand-offs. This allows coolant (distilled water) to be circulated around and underneath the sample dish. The sample dish is also held in place with plastic screws, which are threaded into stand-offs glued to the larger dish.

Entry and exit of the coolant is provided by four bayonet-mount spigots (inner diameter of 2.4 mm) installed in the walls of the coolant dish. Two of the spigots are used for inflow and two for outflow, with inlets and outlets mounted opposite each other. Peristaltic pumps are used to pump the coolant between the coolant dish and a temperature-controlled water bath (Isotemp 1006D, Fisher Scientific). Liquid levels in the coolant dish are maintained by locating the outlet spigots higher than the inlet spigots and by setting the pump's flow rate higher for the outflow. Using a 10 ml sample volume, SAR homogeneity was found to be optimal when the coolant level was approximately equal to the sample level. This resulted in a water volume in the coolant dish of approximately 130 ml.

4. Dosimetry

Two approaches were used to assess the magnitude of the SAR and its distribution within the sample region. Thermometry was used to establish absolute SAR values at various points in the sample. Scanned electric (E)-field probe measurements were made to assess the SAR distribution over the area of the sample dish in the bottom 1.5 mm depth. Both approaches made use of a 3-axis electromechanical positioner (MAC200SD, Techno-Isel Inc.) with a precision of 0.01 mm to position the respective probes.

Thermometric SAR measurements were made using a Vitek thermister probe (Model 21-10104-002, BSD Medical Corp.) and a digital multimeter (Model 3478A, Agilent Technologies) in 4-wire ohm configuration. The thermister was calibrated against an RTD-based digital thermometer (Model 421508, Extech Instruments) in a controlled-temperature water bath. For SAR measurements, recordings of temperature, time and power were made at 0.7 s intervals for three periods; a 20 s monitoring period to ensure temperature stability, an irradiation period for 30 s and finally a 20 s post irradiation period. The temperature slope with respect to time was computed using linear regression from the recorded data. The data interval over which the regression was computed began at the onset of irradiation and ended at a point where the instantaneous slope began to decay. Using equation (1), the resulting regression coefficient was multiplied by the specific heat capacity to obtain the SAR. The specific heat capacity was assumed to be the same value as for water, 4180 J/kg ^{o}C. Exposures were at power levels sufficient to cause temperature rises of 0.01 to 0.05 ^{o}C per s. The resulting SARs were in the range of 50 to 200 W/kg.

Instrumentation for SAR distribution measurements included a 1 mm resolution, isotropic E-field probe (3D-EMC Corp.), a custom-built 3-channel DC amplifier and a digital multimeter. The E-field probe was scanned in a 2 mm grid over the area of the sample Petri dish at levels of 0.5, 1.0 and 1.5 mm from the bottom of the dish. SAR calibration of the E-field probe was achieved by comparing SARs at co-located points where thermometric measurements had been taken and by setting the E-field probe calibration factor accordingly. The spherical isotropicity of the probe was measured to be ± 1.5 dB.

The relative dielectric constant and conductivity of the sample at 37°C were measured at 1.9 GHz using the open-ended coaxial probe method (Kraszewski et al., 1983) and were found to be 75 and 2.3 S/m, respectively. To facilitate the dosimetry, a saline equivalent medium having the same dielectric constant and conductivity at room temperature was developed which would allow measurements to be performed at room temperature. A solution of 8.3 g/L NaCl in double distilled H_20 was used for this purpose and had the same conductivity, but a slightly higher relative dielectric constant of 78, compared to the diluted whole human blood.

5. Results and Discussion

SAR distribution scans were performed on three planes (0.5, 1.0 and 1.5 mm from the bottom of the sample dish) in the saline equivalent medium. These planes were chosen as they represented the general area in which the blood cells settle. A contour plot of a scan performed 1.0 mm from the bottom, showing the SAR per watt of input power, is shown in Figure 1(b). A histogram of the composite data from the 3 scans is presented in Figure 1(c), indicating a mean SAR per W of 8.55 W/kg/W with a standard deviation of 2.07 W/kg/W.

A characteristic of this type of exposure system is the large SAR values and gradient occurring at the sample/air interface at the top of the sample. This is caused by the large discontinuity in dielectric constant between these two media. Fortunately the whole blood sample occupies the lowest depths of the sample dish where the SAR values and gradients are somewhat reduced. Co-located x-y coordinate points were used from the three scan planes to form an estimate of the SAR gradient with respect to z (height in the sample). The maximum gradient was 4.9 W/kg/mm while the mean was 2.2 W/kg/mm. Gradients with respect to x and y were also calculated from the data files and were approximately 5 and 6 times lower for the maximum and mean, respectively.

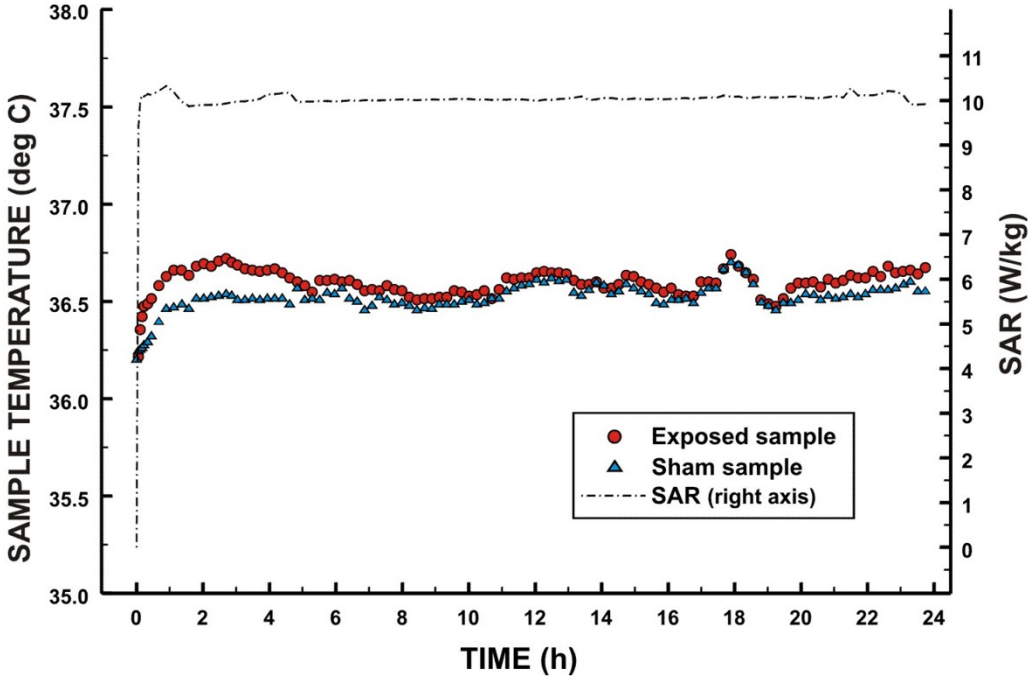

Figure 2. *Temperature versus time for sham exposed and 10 W/kg exposed samples.*

A 24 h evaluation of temperature regulation was performed with two waveguides, one serving as sham exposure and the other fed with sufficient power to give a nominal 10 W/kg SAR. Both were cooled from the same constant-temperature water bath. There was an initial temperature

rise in both samples before a steady state temperature was reached, as shown in Figure 2. The initial temperature rise was greater in the exposed sample than in the sham-exposed sample but was still limited to 0.3 ^{o}C. The slight rise in sham temperature was probably due to the fact that the system had not fully equilibrated prior to the onset of power and to the slight warming of ambient temperatures. Subsequent experiments have consistently demonstrated that the temperature in 10 W/kg exposed samples is within 0.3 ^{o}C of the sham (data not shown). Once steady state was achieved, both sample temperatures were held at 36.5 ± 0.2 ^{o}C over the remaining 24 h period.

System for Animal Study

1. Introduction

Exposure of live animals can be classified into two groups, those for whole body exposure and those for partial body exposure, usually the head–only. The former usually allows the animal to roam free in a cage with access to water and food. They permit long-term exposure, sometimes for the duration of the natural life of the animal. The latter usually requires either the use of physical restraints or the anaesthetization of the animal (Chou et al., 1999; Swicord et al., 1999). The choice often depends on the particular biological assay and the sensitivity of the animal or assay to stress induced by physical restraints or anaesthetization. The assays intended for use in our studies may potentially be affected by stress in the animal, so it was decided that a whole-body exposure system would be the most appropriate.

Various systems have been used for whole-body exposure such as waveguides, radial transmission lines (RTLs), rectangular horns, GTEM cells and linear antennae. Most of the systems referred to above offer the ability to expose numbers of animals simultaneously making them space efficient. Waveguides suffer the disadvantage that usually only a single animal can be exposed for each waveguide. As compensation however, they offer the ability to measure the whole-body average (WBA) SAR of the animal while it is being exposed by carrying out simple power measurements at each port of the waveguide.

A circularly polarized waveguide system was developed by Chou et at. (Chou et at., 1992) for use at 2450 MHz. The cylindrical waveguide has fundamental mode (TE11) sections at the launching end and the termination end, with a larger diameter multimode section in the middle. The waveguide axis and consequently the propagation direction is horizontal allowing space for animals (rats) up to 800 g to be exposed. The objective of employing circular polarization was to make the coupling of energy into the animal less dependent on its movements and/or orientation in the cage.

Other systems have been reported, in particular a horizontally mounted rectangular waveguide (WR-430, 109mm x 55mm) (Ho et al., 1973) for 2450 MHz. The system was designed for exposure of mice up to 36 g and contained a living volume of 109mm x 55mm x 114mm long. Tests of this system with unrestrained animals (Christman, 1974) shows a maximum range in WBA-SAR in excess of 4:1 due to animal movement in the waveguide for some of the test subjects.

The 1.9 GHz *in-vivo* exposure system that was developed at Health Canada is an extension of the waveguide design used for the *in-vitro* system described Section III. Unlike the system reported by Chou et al. (Chou et at., 1992), the waveguide diameter is maintained over its length since the system is intended for mice up to 35 g. Like the Chou system, circular polarization is employed in order to minimize variations in WBA-SAR in the mice due to movement. In addition, the waveguide is mounted vertically so that the long axis of the animal is aligned parallel to the plane of the rotating incident electric field. This produces maximal coupling of the field to the animal giving a relatively high RF power efficiency.

2. Materials and Methods

The height of the waveguide is 430 mm long and is broken into two sections at a point 240 mm from the bottom. Alignment pins and receptacles are fixed along the outer wall at the break to ensure repeatable opening and closing of the waveguide. The bottom shorting plate is perforated with 2.4-mm diameter holes and is removable by turning 4 wing nuts. This allows urine and faeces to be removed and the inside walls of the waveguide to be cleaned. The top shorting plate is similarly perforated and has a DC fan mounted above on a rubber shock mounting. The variable speed fan is used to provide ventilation.

The mouse cage is cylindrical with 90 mm height and 95 mm inner diameter yielding a volume of 638 cm^3. It is made of Plexiglas, which is perforated along the sides and top and bottom to allow airflow. The cage is held in the centre of the waveguide through means of a ring of nylon screws in the sidewalls of the tube at the appropriate height. Figure 3 shows a diagram of the waveguide and mouse cage. As in the *in-vitro* system, the waveguide is fed in quadrature through means of a 3 dB, 90-degree hybrid coupler which, in this case, was designed and built in-house.

Measurements of the WBA-SAR were made using the methods outlined in (Guy et al., 1999) and (Christman et al., 1974) with minor modifications. The measurement set up is shown in Figure 4. The procedure consists of measuring the residual power of the waveguide plus cage plus mouse and subtracting the residual power measured with waveguide plus cage only. Residual power is defined here as the net difference between the input power and all powers exiting the input and terminated ports. The latter includes the terminated or isolation port of the 3 dB, 90-degree hybrid. The input power and reflected power at the input port are separated using a dual directional coupler as shown in Figure 4.

For the WBA-SAR measurements, a 27.5 g mouse phantom was built from a modified 50 ml plastic centrifuge tube (cat. no. 21008-178, VWR International). A section of the middle of the tube was removed and the two remaining parts were welded back together so that the screw-top lid could be retained. Enough tube length was removed to give 27.5 g mass when filled to the top with the muscle simulant liquid. The muscle simulant consisted of 68.7% de-ionised water, 31% Diethylene Glycol Monobutyl Ether (DGME) and 0.3% NaCl. All percentages were by weight. The resulting dielectric parameters at 1.9 GHz, measured using the slotted transmission line method outlined in (IEEE, 2003), were ε_r = 51.5 and σ = 1.65 S/m. The mouse phantom has approximate dimensions: 28 mm outer diameter by 47 mm long with a conical section in the nose of approximately 14 mm length.

3. Results and Discussion

Whole-body averaged SAR measurements were performed using the residual power method for multiple positions of the phantom mouse. The results, which are normalized to the input power, are shown in Figure 5. The four most relevant scattering or S parameters of the empty waveguide and cage (no phantom) were nominally: $|S_{11}|$ = -14.6 dB, $|S_{41}|$ = -27.9 dB (isolation), $|S_{21}|$ = -1.75 dB and $|S_{31}|$ = -6.77 dB (See Figure 4 for port number references.) The phantom was oriented a) laying prone, facing outwards (towards the waveguide wall), b) laying prone, facing inwards, c) laying prone, parallel to the walls and d) standing vertically in the centre and at the edge. Multiple angular positions were measured for each orientation mentioned above with the position of the excitation probes used as a reference for the angle 0^o as shown in the legend of Figure 5.

From Figure 5, the range of WBA-SAR lies between 6.4 W/kg/W and 13.5 W/kg/W, a ratio of 2.1:1. If the data is grouped together, it has a mean of 10.7 W/kg/W and a standard deviation of 1.9 W/kg/W. If the data for the standing positions are excluded the range has a ratio 1.4:1, the mean is 11.6 W/kg/W and standard deviation is 1.1 W/kg/W. As expected, the standing position couples more weakly with the incident fields. The pattern of WBA-SAR with angle displays a slightly cyclic nature, which is probably due to the finite axial ratio of the circularly polarized fields. The axial ratio has been independently measured to be 1.5 dB for the in-vitro waveguide (Gajda et al., 2002).

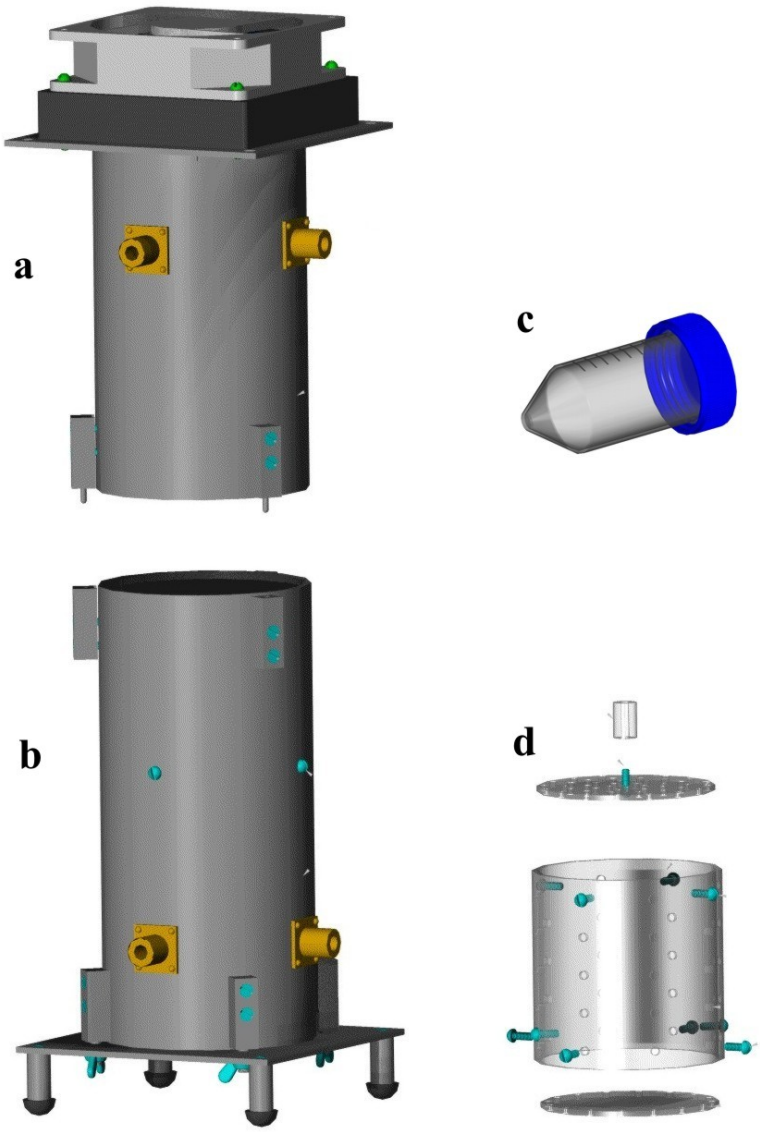

Figure 3. *Cylindrical waveguide, in-vivo exposure system. (a) top section of waveguide including fan, (b) bottom section of waveguide, (c) phantom representing a mouse (not to scale), (d) mouse cage. Not shown are the 3 dB, 90-degree hybrid coupler and connecting cables.*

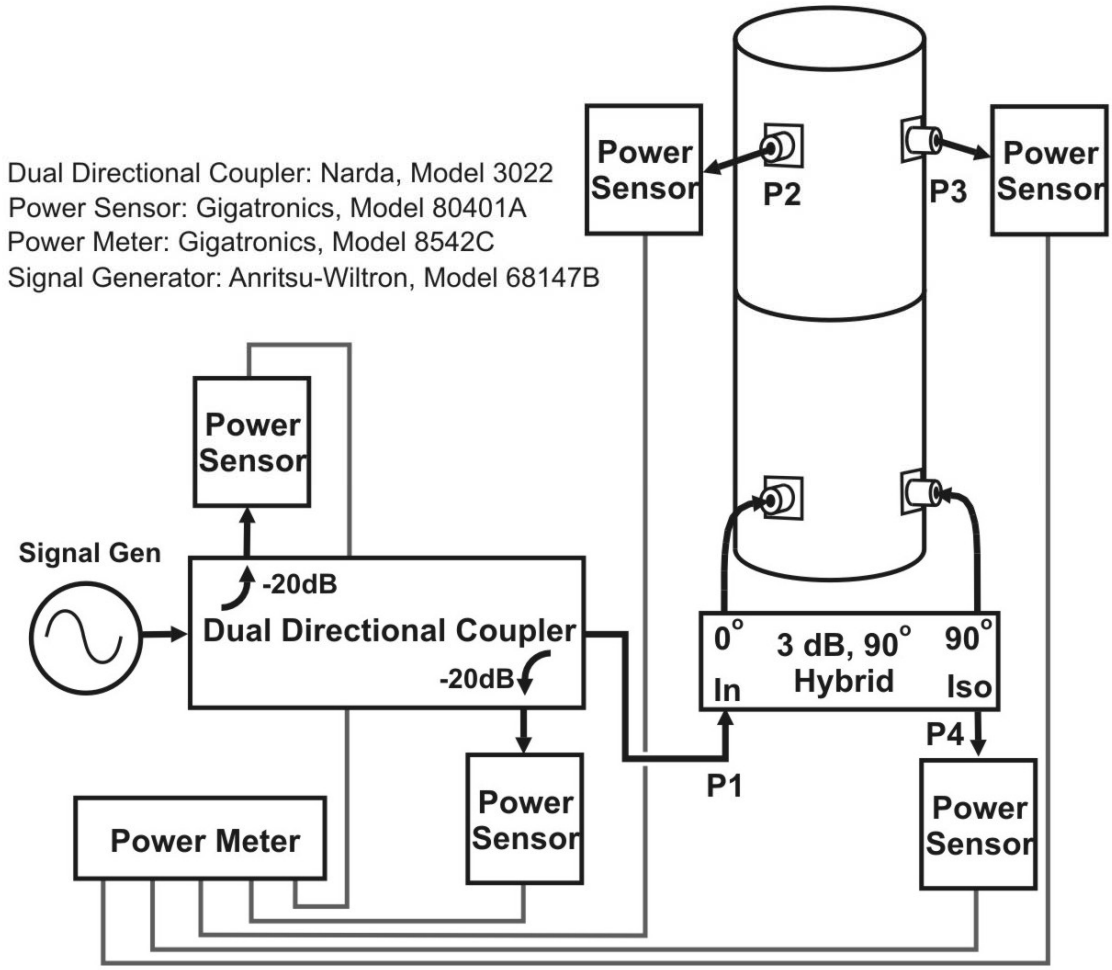

Figure 4. *Whole-body-average SAR measurement setup. Ports P1 through P4 define reference planes for scattering (S) parameter measurements.*

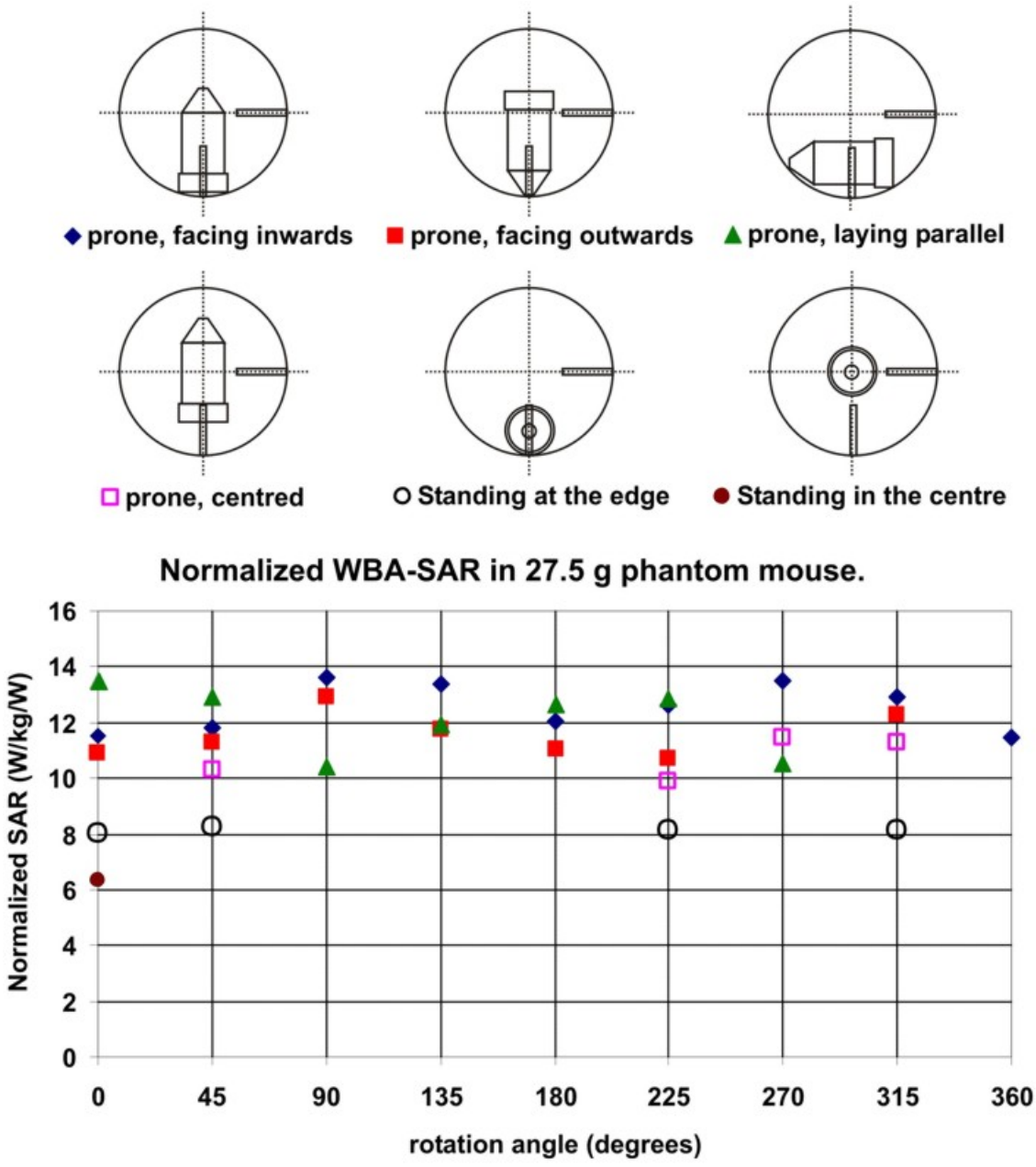

Figure 5. *Measured WBA-SAR for 27.5 g mouse phantom filled with liquid muscle simulant having dielectric properties ε_r = 51.5 and σ = 1.65 S/m.*

Conclusions

Two 1.9-GHz, RF exposure systems have been developed for cell culture and live animal experiments in our laboratory. For the *in vitro* system, the principal design consideration was the maintenance of constant temperature between sham and exposed samples owing to the high sensitivity of the biological assays to thermal confounding. This is a feature often overlooked by

some other research groups, which may be a major contributor to many of the inconsistencies and conflicting results in the literature. For the *in vivo* system, the principal design criterion was to maintain a low variation of whole-body SAR while still allowing the mouse to roam free. The *in vitro* system has been used in a large number of genotoxicity and gene expression studies at SAR levels up to 10 W/kg. Studies utilizing the *in vivo* system are anticipated to take place in the near future.

Acknowledgment

The authors would like to thank Messrs. Christian Lavoie and Yani Picard of the Consumer and Clinical Radiation Protection Bureau, Health Canada, for their editorial comments.

References

Burkhardt, M., Pokovic, K., Gnos, M., Schmid, T. and Kuster, N. 1996. Numerical and Experimental Dosimetry of Petri Dish Exposure Setups. **Bioelectromagnetics**. Vol. 17, Issue 6: pp. 483-493.

Chou, C.K., Guy, A.W., Kunz, L.L., Johnson, R.B., Crowley, J.J. and Krupp, J.H. 1992. Long-term, Low-level Microwave Irradiation of Rats. **Bioelectromagnetics**. Vol. 13, No. 6: pp. 469-496.

Chou, C.K., Chan, K.W., McDougall, J.A. and Guy, A.W. 1999. Development of a Rat Head Exposure System for Simulating Human Exposure to RF Fields from Handheld Wireless Telephones. **Bioelectromagnetics**. Vol. 20, Issue S4: pp. 75-92.

Courtney, K.R., Lin, J.C., Guy, A.W. and Chou, C.K. 1975. **Microwave Effect on Rabbit Superior Cervical Ganglion. IEEE Transactions on Microwave Theory and Techniques**. Vol. 23: pp. 809-813.

Christman, C.L., Ho, H.S. and Yarrow, S. 1974. A Microwave Dosimetry System for Measured Sampled Integral-Dose Rate. **IEEE Transactions on Microwave Theory and Techniques (Short Papers),** Vol. MTT-22: pp. 1267-1272.

Fischetti, M. 1993. The Cellular Phone Scare. **IEEE Spectrum**. Vol. 30, No. 6: pp. 43-47.

Gajda, G.B., McNamee, J.P., Thansandote, A., Boonpanyarak, S., Lemay, E. and Bellier, P.V. 2002. Cylindrical Waveguide Applicator for In Vitro Exposure of Cell Culture Samples to 1.9-GHz Radiofrequency Fields. **Bioelectromagnetics**. Vol. 23, Issue 8: pp. 592-598.

Guy, A.W. 1977. **A Method for Exposing Cell Cultures to Electromagnetic Fields under Controlled Conditions of Temperature and Field Strength. Radio Science**. Vol. 12, No. 6S: pp. 87-96.

Guy, A.W., Chou, C.K. and McDougall, J.A. 1999. A Quarter Century of In Vitro Research: A New Look at Exposure Methods. **Bioelectromagnetics**. Vol. 20, Issue S4: pp. 21-39.

Ho, H.S., Ginns, E.I. and Christman, C.L. 1973. Environmentally Controlled Waveguide Irradiation Facility. **IEEE Transactions on Microwave Theory and Techniques (Short Papers)**, Vol. MTT-21: pp. 837-840.

IEEE 1991. **Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields – RF and Microwave**. IEEE Std. C95.3-1991. New York: Institute of Electrical and Electrical and Electronics Engineers, Inc.

IEEE 2003. **Recommended Practice For Determining the Peak Spatial-average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques**. IEEE Std. 1528-2003. New York: the Institute of Electrical and Electronics Engineers, Inc.

Kantor, G., Witters, D.M. and Greiser, J.W. 1977. **The Design and Performance of Circularly Polarized Direct Contact Applicator for Microwave Diathermy**.

Symposium Digest, International MTT Meeting, San Diego, June 1977: pp. 364-367.

Kraszewski, A., Stuchly, S.S., Stuchly, M.A. and Symons, S.A. 1983. On the Measurement Accuracy of the Tissue Permittivity In Vivo. **IEEE Transactions on Instrumentation and Measurement**, Vol. IM-32, No. 1: pp. 37-42.

McNamee, J.P., Bellier, P.V., Gajda, G.B., Miller, S.M., Lemay, E.P., Lavallee, B.F., Marro, L. and Thansandote, A. 2002a. DNA Damage and Micronucleus Induction in Human Leukocytes after Acute *In Vitro* Exposure to a 1.9 GHz Continuous-Wave Radiofrequency Field. **Radiation Research**. Vol. 158, No. 4: pp. 523-533.

McNamee, J.P., Bellier, P.V., Gajda, G.B., Lemay, E.P., Lavallee, B.F., Marro, L. and Thansandote, A. 2002b. DNA Damage in Human Leukocytes after Acute *In Vitro* Exposure to a 1.9 GHz Pulse-modulated Radiofrequency Field. **Radiation Research**. Vol. 158, No. 4: pp. 534-537.

McNamee, J.P., Bellier, P.V., Gajda, G.B., Lavallee, B.F., Marro, L., Lemay, E. and Thansandote, A. 2003. No Evidence for Genotoxic Effects from 24 h Exposure of Human Leukocytes to 1.9 GHz Radiofrequency Fields. **Radiation Research**. Vol. 159, No. 5: pp. 693-697.

Moros, E.G., Straube, W.L. and Pickard, W.F. 1999. The Radial Transmission Line as a Broad-Band Shielded Exposure System for Microwave Irradiation of Large Numbers of Culture Flasks. **Bioelectromagnetics**. Vol. 20, Issue 2: pp. 65-80.

Schonborn, F., Pokovic, K., Wobus, A.M. and Kuster, N. 2000. Design, Optimization, Realization and Analysis of an *In Vitro* System for the Exposure of Embryonic Stem Cells at 1.71 GHz. **Bioelectromagnetics**. Vol. 21, Issue 5: pp. 372-384.

Swicord, M., Morrissey, J., Zakharia, D., Ballen, M. and Balzano, Q. 1999. Dosimetry in Mice Exposed to a 1.6 GHz Microwaves in a Carrousel Irradiator. **Bioelectromagnetics**. Vol. 20, Issue 1: pp. 42-47.

Tice, R.R., Hook, G.G., Donner, M., McRee, D.I. and Guy, A.W. 2002. Genotoxicity of Radiofrequency Signals. I. Investigation of DNA Damage and Micronuclei Induction in Cultured Human Blood Cells. **Bioelectromagnetics**. Vol. 23, Issue 2: pp. 113-126.