Section 4

Detection and Measurement of Radiofrequency Waves

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4.1 RF Exposure Metrics

4.1.1 RF field parameters

RF electromagnetic fields (EMF) are described by the following four parameters:

1. The frequency **F** (Hz) of the waves or the wavelength **λ** (m) which are related by:
2. $\lambda = \frac{c}{f}$ (c is the velocity of light) ***(4.1)***
3. The electric field intensity **E** in Volts per meter (V/m) at any point in space
4. The magnetic field strength **H** in Ampere per meter (A/m) at any point in space
5. The power density **S** in Watts per meter-squared (W/m²) in the far field only where plane wave conditions apply

The magnetic flux density **B** in **SI** units of Tesla (T) or **CGS** units of Gauss (G) is also described as exposure from static magnetic fields.

4.1.2 Measurements in the near field region

The near field is the EMF from the RF source itself to a distance of one wavelength from the source.

In the near field region, the antenna gain and the angular distribution of the RF field vary with distance because of interactions between RF waves of different amplitudes and phases emitted from different segments of the RF antenna.

As a result, the relationship between the electric field **E**, the magnetic field **H**, and the power density **S** is unpredictable. Further, the measurements of the electric field intensity **E** and the magnetic field strength **H** at any point within the near field must be carried out independently.

Power density (RF power per unit area) measurements are inappropriate in the near field because of the non-uniformity of the RF field within a unit area.

4.1.3 Measurements in the far field region

The far field is the EMF located beyond the near field. In the far field, the antenna gain and the angular distribution of the RF field do not vary with distance. Hence, the relationships between the power density **S**, the electric field **E** and the magnetic field **H** in the far field are well defined, as shown below[1]:

$$S\left(\frac{W}{m^2}\right) = E\left(\frac{V}{m}\right) . H\left(\frac{A}{m}\right) \quad \textit{(4.2)}$$

And:

$$E\left(\frac{V}{m}\right) = Z_0\ (\Omega) . H\left(\frac{A}{m}\right) \quad \textit{(4.3)}$$

Where Z_0 is the impedance of free space. Since Z_0 is equal to **377 Ω** in the far field, the relationships between **E**, **H** and **S** become:

$$E = 377 \, . \, H \tag{4.4}$$

$$S = \frac{E^2}{377} \tag{4.5}$$

$$S = 377 \, . \, H^2 \tag{4.6}$$

Therefore, it is sufficient to measure only one of the quantities **E, H** or **S** in the far field and to calculate the other two using equations ***(4.4)***, ***(4.5)***, *or* ***(4.6)***.

<u>Example</u>:

A surveyor is requested to carry out compliance power density measurements in a residential area located near GSM-900 base stations.

The maximum RF power density allowed for the public in Canada is $S_{limit} = \frac{6 \text{ Watt}}{m^2}$ at a frequency of 900 MHz.

Suppose no power density probe is available and the surveyor needs to find an alternative. Since the measurements take place in the far field, the surveyor could use either an electric field probe to measure the electric field strength **E** or a magnetic field meter probe to measure the magnetic field strength **H** and compare the readings to the corresponding **E** or **H** limits.

The electric field limit E_{lim} and magnetic field limit H_{lim} corresponding to a power density of $\frac{6 \text{ Watt}}{m^2}$ are:

$$E_{limit} = \sqrt{377 \, S} = \sqrt{377 \text{ x } 6} = 47.56 \text{ Volt/meter} \tag{4.7}$$

$$H_{limit} = \sqrt{\frac{S}{377}} = \sqrt{\frac{6}{377}} = 0.126 \text{ Ampere/meter} \tag{4.8}$$

4.2 RF Detection Techniques

The detection and measurement of radiated RF waves is achieved by means of a measuring system consisting of an antenna (probe) and a receiver (Figure 4.1). For low RF levels, the signal passed on by the probe to the receiver needs to be amplified.

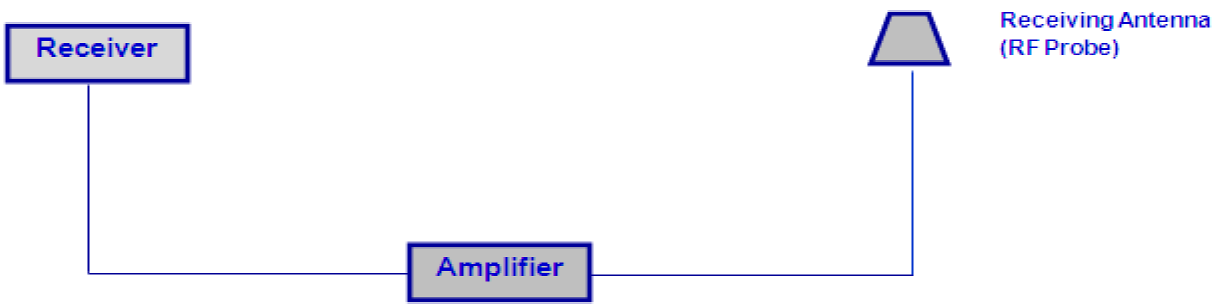

Figure 4.1 Schematic representation of a basic RF-measuring meter

4.2.1 RF detectors

Receiving RF antennas, also called RF probes, are devices designed to detect electromagnetic waves traveling through space. Some antennas serve both as receiver and transmitter of electromagnetic waves.

Probes come in different designs, depending on the purpose of use. Some are designed to be "broadband" antennas capable to receive or transmit RF waves over a large frequency range, while others are "narrowband" antennas designed to receive or transmit at some specific frequencies.

All receiving antennas are designed to capture electromagnetic energy and deliver the related signals to a receiver.

4.2.2 RF receivers

A receiver (or reader) is a device that collects the signal delivered by the antenna and processes it to extract needed information such as RF frequencies, electric fields, magnetic fields, power densities, etc.

4.2.3 RF survey meters

Portable RF-measuring instruments are adequate and practical for the detection of RF waves and the measurement of their strength (**E**, **H**, **S**).

For occupational exposure, the RF levels are usually measured close to the emitting antenna, while for public areas measurements are typically taken far from the source.

A standard RF survey meter is basically a combination of a receiving antenna (probe) and a meter.

Figure 4.2 Portable RF survey meter

4.2.4 Characteristics of RF survey meters

RF survey meters come in a variety of types and the choice of a particular meter is dictated by the type of RF environment to be surveyed: single source or complex RF fields, continuous or pulsed waves, near field or far field.

Industry Canada's "Guidelines for the Measurement of Radio Frequency Fields at Frequencies from 3 kHz to 300 GHz"[2] recommend a set of technical requirements to be considered in choosing a survey meter.

Table 4.1 lists the technical parameters of importance that should be provided for each survey meter.

Table 4.1 RF survey meter technical parameters

Parameter	Characteristics
Frequency range	Narrow band for known fields or broadband for unknown fields
Measurement range	Minimum and maximum RF exposure levels (**E** field, **H** field, power density **S**)
Linearity of the response	Percentage error over a range of exposure levels
Frequency sensitivity	Percentage error on the response over a frequency range
Directional response	• Isotropic probe: responds to incident signals in 3 directions X, Y, and Z. • Non-isotropic probe: responds to incident signals in only one or two directions in space
Continuous wave overload	Highest measurable exposure from continuous RF beams
Peak overload	Highest measurable exposure from pulsed RF beams
Calibration	Periodicity (usually every 2 years)
Environmental conditions	Influence of temperature and humidity on the response of the RF survey meter

4.2.5 Time- averaging of E, H, and S

Time-averaging is warranted when the exposure intensity changes with time. Therefore, time-averaged values of the electric field intensity **E**, the magnetic field strength **H**, and the power density **S** can be calculated on the basis of their respective sampled values.

For frequencies ranging from 100 kHz to 15,000 MHz, Health Canada Safety Code 6[3] specifies a time-averaging period of six minutes.

The time-averaged root-mean-square (rms) electric field E_{rms}, rms magnetic field H_{rms}, and rms power density S_{rms} can be obtained using the following formulas:

$$E_{rms} = [\frac{1}{6}\sum_1^n E_i^2 \ \Delta t_i]^{0.5} \quad (4.9)$$

$$H_{rms} = [\frac{1}{6}\sum_1^n H_i^2 \ \Delta t_i]^{0.5} \quad (4.10)$$

$$S_{rms} = \frac{1}{6}\sum_1^n S_i \ \Delta t_i \quad (4.11)$$

Where:

- E_i, H_i, and S_i are the sampled rms electric field, magnetic field, and power density readings, respectively, which are considered to remain constant in the i-th time period.

- Δti the interval time, in minutes, of the ith time period
- n the number of time intervals within six minutes

In addition, the sum of all time intervals Δt_i must be equal to six minutes:

$$\sum_{i=1}^{n} \Delta t_i = 6 \text{ min} \qquad \textit{(4.12)}$$

4.2.6 Spatial- averaging of E, H, and S

To determine the spatially averaged value of **E**, **H**, or **S**, local values (including the maximum value) are measured over the projected surface area (flat plane), equivalent to the head and trunk region of persons (adults or children) who would occupy the area of the incident fields. E_{rms},H_{rms} and S_{rms} can be calculated[3] as follows:

$$E_{rms} = [\frac{1}{n}\sum_{1}^{n} E_i^2]^{0.5} \qquad \textit{(4.13)}$$

$$H_{rms} = [\frac{1}{n}\sum_{1}^{n} H_i^2]^{0.5} \qquad \textit{(4.14)}$$

$$S_{rms} = \frac{1}{n}\sum_{1}^{n} S_i \qquad \textit{(4.15)}$$

- Where n is the number of locations and $E_i, H_i,$ and S_i the electric field, the magnetic and the power density readings, respectively, are measured at the ith location.

4.2.7 Output of pulsed systems

The output of a pulsed system is expressed in terms of peak power P_{peak} and the average power P_{avg} is equal to the product of peak power by the duty cycle D_c:

$$P_{avg} = D_c.P_{peak} \qquad \textit{(4.16)}$$

4.3 Individual RF Monitors

Individual RF monitors (dosimeters), also called individual exposimeters, are direct-reading electronic devices worn by workers for the monitoring of their instant exposure to RF fields while carrying out their duties near RF sources.

Workers who are exposed over the long term to RF fields should wear individual RF dosimeters whenever they enter RF controlled areas to ensure that the exposure levels they are subjected to are below the occupational Limits of Health Canada Safety Code 6.

The exposure of individuals to RF fields is influenced by the following factors[4]:

- Location of the exposed person with respect to the surrounding RF sources
- Traffic, fading, and power variation of RF signal
- Frequency of the RF waves
- Polarization and direction of arrival of incident electromagnetic fields

The first RF personal dosimeter was designed to measure RF exposure from mobile phone base stations.[5]

A practical personal RF dosimeter should have the following properties:

- Small, light in weight, and reasonable in cost
- Direct-reading (display)
- Broadband response to cover the entire RF spectrum
- Isotropic (reading independent of direction)
- Near field and far field readings
- Large measurement range of electric field and power density
- Capable of data recording

4.4 Absorption of RF Waves – SAR

The absorption of RF waves in the human body is important in the frequency range 100 kHz–10 GHz and is expressed by the Specific Absorption Rate (SAR). SAR is the rate of RF energy absorbed per unit mass of tissue. It is defined in units of Joules per second per kilogram (J/s/Kg) equivalent to Watts per kilogram (W/kg).

According to the International Commission on Non-Ionizing Radiation (ICNIRP), SAR is important in the frequency range 100 kHz–10 GHz and must be determined for situations where exposure of the whole body or parts of the body takes place at a distance of 20 cm or less from the RF source.[2,3] However, SAR cannot be measured directly in human tissue. Instead, it can be estimated by the three methods described below.

4.4.1 Determination of SAR by a calorimetric method

The calorimetric method[2] uses a temperature probe inserted in a tissue-like phantom to measure the rate of temperature increase $\frac{\Delta T}{\Delta t}$ in the phantom generated by absorption of RF waves.

"Human phantom SAR" courtesy of Indexsar.com (CC BY-NC-ND)

Figure 4.3 Example of a head phantom for SAR measurements[6]

SAR is determined by calculating the heat produced within a unit mass of the phantom as follows:

$$\mathrm{SAR}\left(\frac{\mathrm{W}}{\mathrm{Kg}}\right) = \mathrm{C}\left(\frac{\mathrm{J}}{\mathrm{Kg}\ ^{\circ}\mathrm{C}}\right) . \frac{\Delta \mathrm{T}(^{\circ}\mathrm{C})}{\Delta \mathrm{t(sec)}} \quad \textit{(4.17)}$$

- Where C is the specific heat capacity of the phantom material, in J/(kg ºC)

In Equation (4.17), the rate of temperature increase is assumed to be linear during the test with no thermal losses.

4.4.2 Assessment of SAR by E- field measurements

The E-field method measures the root-mean-square electric field $\mathrm{E_{rms}}$ induced inside a tissue-simulating phantom (e.g., Figure 4.4) by an external RF field by means of implantable electric field probes.

"Human phantom SAR" courtesy of Indexsar.com (CC BY-NC-ND)

Figure 4.4 Example of a head phantom assembly for inner probe measurements[6]

SAR is then determined using the formula[3]:

$$\mathrm{SAR} = \left(\frac{\sigma}{\varrho}\right) \mathrm{E_{rms}^2} \quad \textit{(4.18)}$$

Where:

- σ is the electrical conductivity of body tissue in units of Siemens per meter (S/m)
- ϱ, the mass density of tissue in Kg/m³
- $\mathrm{E_{rms}^2}$, the rms electric field squared in V²/m² induced in the tissue-like phantom

The dielectric properties of tissue play an important role in the absorption of RF waves by the body. Table 4.2 gives values of the relative dielectric constant (**ε**), the electric conductivity (**σ**), and the penetration depth (**δ**) for muscle tissue at various RF frequencies.[7]

Table 4.2 Approximate dielectric parameters for muscle tissue at various frequencies

Frequency	Relative Dielectric Constant (ε)	Conductivity (σ), in Siemens/Meter	Penetration Depth (δ), in Centimeters
100 kHz	1850	0.56	213.0
1.0 MHz	411	0.59	70.0
10 MHz	131	0.68	13.2
100 MHz	79	0.81	7.70
1 GHz	60	1.33	3.40
10 GHz	42	13.3	0.27
100 GHz	8	60.0	0.03

Important: If the RF field is not continuous but pulsed, the pulse duration and the pulse repetition rate are necessary for the determination of the duty cycle of the RF generator.

4.4.3 Determination of SAR by a graphical method

SAR values can be determined from a graph as shown in Figure 4.5.[8]

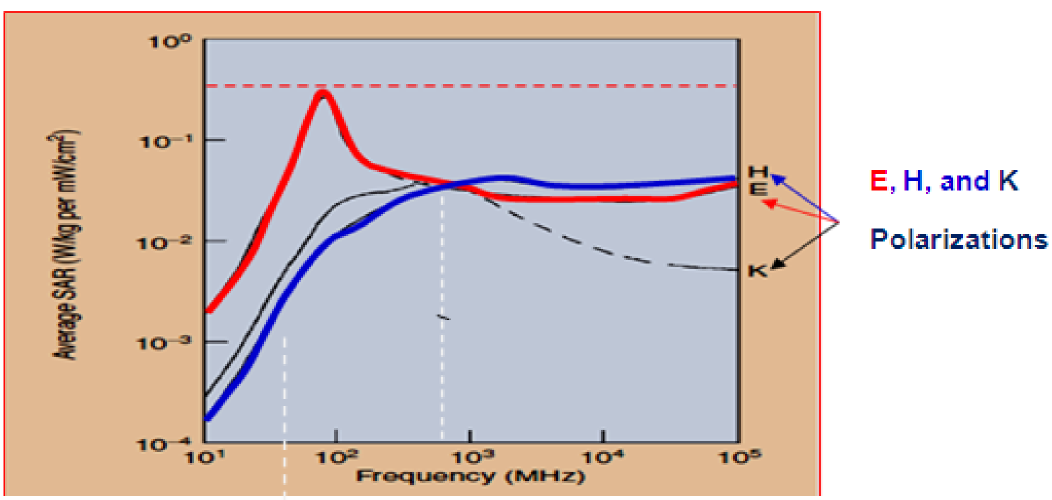

Figure 4.5 Calculated whole-body average SAR (W/Kg per mW/cm²) versus frequency for models of the average man for three standard polarizations

On the Graph:

- E-polarization is where the electric field **E** is parallel to the main axis of the body
- H-polarization is where the magnetic field **H** is parallel to the main axis of the body
- K-polarization is where the direction of propagation of RF waves is parallel to the main axis of the body
- The highest RF absorption occurs for **E**-polarization at frequencies 70 to 80 MHz.
- At about 700 MHz, the SAR is the same for all three polarizations.

For conditions where SAR determination is not practically possible, the measurement of field strength (**E** or **H**, near field, far field)) or power density (far field only) can be carried out as an alternative.

4.4.4 SAR measurements in time- varying RF fields

Note: If the RF exposure changes with time, the time-averaged SAR over a period of six minutes can be calculated as follows[3]:

$$\mathrm{SAR} = \frac{1}{6}\sum_{i=1}^{n}(\mathrm{SAR})_i\,\Delta t_i \qquad (4.19)$$

Where:

- $(\mathrm{SAR})_i$ the sampled SAR in the i-th time period
- Δt_i the time interval of the i-th time period

4.5 References

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