Non-ionizing radiation: RF & Microwaves

Mike Yost, MS PhD
Radiation Safety: Principles, Practice, and Emerging Issues
Section #1: Current Issues + Some hot topics

• RF, cell phones & cancer
  – NTP animal study of RF and cancer
  – Interphone Epi study of mobile phones & cancer

• RF dosimetry & Bioeffects
  – Brain dose for different ages
  – Endpoints other than cancer
Topic A: Mobile Phones & Cancer

Does phone radiation give you cancer?

Probably not, but scientists are still looking into it

By Jacob Kastrenakes | @jake_k | Updated Mar 9, 2018, 11:18am EST


https://ntp.niehs.nih.gov/results/areas/cellphones/
Mobile phone subscriptions per capita in the US, by year

Little M P et al. BMJ 2012;344:bmj.e1147
RF and Cancer

- Evidence on health effects and exposure to ELF & RF EMF:
  - The IARC classified RF (2011) as “possibly carcinogenic to humans” (Group 2B) based on epidemiologic studies of exposure to mobile phones and brain cancer
  - Evidence for brain cancer from occupational RF exposure was judged inadequate

Why inadequate for occupational?
- Limited exposure assessment in previous studies based on surrogate measures, expert judgement, but:
  - No exposure measurements!
- Previous studies based mainly on JEMs that apply a job’s average exposure to all individuals with that occupation
  - Berkson error increases uncertainty
The Interphone Study: Interview with Dr. Elizabeth Cardis

Living on Earth Radio Program, May 21, 2010

Table 3: ORs between mobile phone use and brain tumors by cumulative call time, stratified by recency of starting regular use - excludes use with hands-free devices

| Cumulative Call time (h) | Meningioma | | | Glioma | | |
|--------------------------|------------|----------------|----------------|
|                          | Cases      | Controls       | OR (95% CI)    | Cases      | Controls       | OR (95% CI)    |
| Non-regular users        |            |                |                |            |                |                |
| 1147                     | 1174       | 1.00           | 1042           | 1078       | 1.00           |                |
| Short-term users: start of phone use 1–4 years before reference date |            |                |                |            |                |                |
| <5 h                     | 150        | 186            | 0.92 (0.69–1.22) | 127        | 182            | 0.68 (0.50–0.93) |
| 5–114.9                  | 401        | 500            | 0.74 (0.61–0.90) | 449        | 533            | 0.82 (0.67–0.99) |
| 115–359.9                | 95         | 126            | 0.79 (0.55–1.12) | 121        | 154            | 0.74 (0.52–1.03) |
| 360–1639.9               | 67         | 72             | 0.77 (0.49–1.20) | 80         | 95             | 0.75 (0.50–1.13) |
| ≥1640                    | 22         | 5              | 4.80 (1.49–15.4) | 23         | 8              | 3.77 (1.25–11.4) |
| Medium-term users: start of phone use 5–9 years before reference date |            |                |                |            |                |                |
| <5 h                     | 7          | 9              | 0.67 (0.23–1.96) | 10         | 13             | 0.86 (0.32–2.28) |
| 5–114.9                  | 122        | 145            | 0.73 (0.54–0.98) | 180        | 208            | 0.86 (0.66–1.12) |
| 115–359.9                | 95         | 140            | 0.67 (0.48–0.93) | 156        | 192            | 0.71 (0.53–0.95) |
| 360–1639.9               | 129        | 131            | 0.83 (0.60–1.14) | 174        | 204            | 0.72 (0.54–0.95) |
| ≥1640                    | 64         | 62             | 1.03 (0.65–1.65) | 94         | 73             | 1.28 (0.84–1.95) |
| Long-term users: start of phone use ≥10 years before reference date |            |                |                |            |                |                |
| <5 h                     | 3          | 2              | 1.31 (0.21–8.07) | 4          | 2              | 1.13 (0.16–7.79) |
| 5–114.9                  | 14         | 15             | 0.79 (0.36–1.73) | 20         | 25             | 0.63 (0.32–1.25) |
| 115–359.9                | 14         | 22             | 0.49 (0.24–1.01) | 41         | 42             | 0.89 (0.53–1.50) |
| 360–1639.9               | 35         | 33             | 1.00 (0.58–1.72) | 94         | 90             | 0.91 (0.63–1.31) |
| ≥1640                    | 44         | 40             | 0.95 (0.56–1.63) | 93         | 73             | 1.34 (0.90–2.01) |
Appendix 2 Table – ORs between mobile phone use and brain tumours (meningioma and glioma separately) by time since start of regular use, cumulative call time and cumulative number of calls, excluding use with hands-free devices; analyses restricted to ever regular-users

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<th>Time since start of regular use (years)</th>
<th>Meningioma</th>
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<th></th>
<th>Glioma</th>
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<td>Controls</td>
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<td>95 % CI</td>
<td>Cases</td>
<td>Controls</td>
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<td>1.00</td>
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<td>76</td>
<td>67</td>
<td>0.86</td>
<td>0.51</td>
<td>1.43</td>
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</tbody>
</table>

| Cumulative call time with no hands-free devices (hours)$^1$ | | | | | | | |
|-------------------------------------------------------------|-----------|--|-----------|-----------|--|-----------|
| <5 hours                                                    | 113       | 88      | 1.00 |           | 90    | 114      | 1.00 |           |
| 5.0-12.9                                                   | 83        | 88      | 0.79 | 0.48      | 1.29  |           | 92   | 124       | 0.88 | 0.56      | 1.39  |
| 13-30.9                                                    | 95        | 107     | 0.72 | 0.45      | 1.15  |           | 127  | 118       | 1.37 | 0.87      | 2.14  |
| 31-60.9                                                    | 70        | 87      | 0.59 | 0.35      | 0.99  |           | 108  | 126       | 1.13 | 0.72      | 1.77  |
| 61-114.9                                                   | 74        | 88      | 0.58 | 0.35      | 0.97  |           | 121  | 135       | 1.06 | 0.68      | 1.67  |
| 115-199.9                                                  | 69        | 95      | 0.64 | 0.39      | 1.06  |           | 129  | 119       | 1.13 | 0.71      | 1.78  |
| 200-359.9                                                  | 74        | 81      | 0.58 | 0.35      | 0.96  |           | 116  | 138       | 1.00 | 0.63      | 1.58  |
| 360-734.9                                                  | 83        | 80      | 0.85 | 0.51      | 1.41  |           | 142  | 139       | 1.17 | 0.74      | 1.84  |
| 735-1639.9                                                 | 85        | 69      | 0.81 | 0.49      | 1.36  |           | 126  | 125       | 1.09 | 0.69      | 1.72  |
| 1640+                                                     | 96        | 71      | 1.10 | 0.65      | 1.85  |           | 160  | 113       | 1.82 | 1.15      | 2.89  |

| Cumulative number of calls with no hands-free devices (in hundreds)$^1$ | | | | | | | |
|--------------------------------------------------------------------------|-----------|--|-----------|-----------|--|-----------|
| <1.5 x 100 calls                                                         | 109       | 81      | 1.00 |           | 92    | 102      | 1.00 |           |
| 1.5-3.4                                                                  | 86        | 98      | 0.54 | 0.32      | 0.90  |           | 91   | 123       | 0.95 | 0.59      | 1.52  |
| 3.5-7.4                                                                  | 92        | 97      | 0.76 | 0.46      | 1.27  |           | 108  | 148       | 0.85 | 0.55      | 1.32  |
| 7.5-13.9                                                                 | 88        | 91      | 0.76 | 0.45      | 1.26  |           | 121  | 111       | 1.19 | 0.74      | 1.89  |
| 14-25.4                                                                  | 75        | 107     | 0.56 | 0.34      | 0.92  |           | 133  | 134       | 1.10 | 0.70      | 1.73  |
| 25.5-41.4                                                                | 71        | 72      | 0.60 | 0.35      | 1.02  |           | 121  | 124       | 1.19 | 0.75      | 1.88  |
| 41.5-67.9                                                                | 85        | 94      | 0.63 | 0.38      | 1.05  |           | 126  | 122       | 1.02 | 0.64      | 1.62  |
| 68-127.9                                                                 | 102       | 89      | 0.79 | 0.49      | 1.29  |           | 136  | 147       | 1.13 | 0.73      | 1.77  |
| 128-269.9                                                                | 79        | 63      | 0.76 | 0.44      | 1.32  |           | 154  | 120       | 1.49 | 0.94      | 2.36  |
| 270+                                                                     | 55        | 62      | 0.66 | 0.37      | 1.17  |           | 129  | 120       | 1.31 | 0.82      | 2.11  |

$^1$ ORs adjusted for sex, age, study centre, ethnicity in Israel, and education.
What is already known on this topic…

- The IARC recently re-evaluated brain tumor risks associated with mobile phone exposure and classified microwave radiation produced by mobile phones as a possible human carcinogen, largely based on relative risks reported by two epidemiological studies, the 2010 Interphone study and a 2011 Swedish study by Hardell and colleagues.
- However, trends in USA brain cancer incidence have not mirrored the substantial increase in mobile phone use since the mid-1990s, and have generally remained constant.
- Based on relative risks from the (Hardell) Swedish study, predicted rates of glioma in the USA were much higher than observed rates. However, based on relative risks from the Interphone study, projected rates could be consistent with the observed data.
Estimates of RF absorption into the brain based on age (courtesy from http://www.environmentalhealthtrust.org).

*Risk of Brain Tumors from Wireless Phone Use
Example of bio-effects study…
Effects of Cell Phone Radiofrequency Signal Exposure on Brain Glucose Metabolism
Nora D. Volkow, MD; Dardo Tomasi, PhD; Gene-Jack Wang, MD; et.al.

Figure 2. Brain Glucose Metabolic Images Showing Axial Planes at the Level of the Orbitofrontal Cortex

Images are from a single participant representative of the study population. Glucose metabolism in right orbitofrontal cortex (arrowhead) was higher for the “on” than for the “off” condition (see “Methods” for description of conditions).

JAMA. 2011; 305(8):808-813.
Current assumptions that may be important….

Increasing phone usage or prevalence = increases in exposure

Usage of phones is a good proxy for exposure to RF

Dose response is monotonic

Health effects are same regardless of age or history of prior usage

Nature of RF Technology change does not change exposure over time

(Possible role of bias in observations?)
Lasers in the News…

- **Aircraft Lasers Strikes**
- October 22, 2015: ferry master and chief mate of the Tokitae injured with a blue laser
- **Still no charges for man accused of injuring ferry employees with high-powered laser (...6 mos...)**
- **Whidbey Island man charged for injuring ferry captains with laser**
- **Washington man fined $100K for pointing laser at ferry, injuring 2 crewmembers**
- **Laser lights still a problem for Oregon pilots** (Seattle times: 11/17/17)
Section #2:
RF - Introduction & Concepts
Radiant (Electro-magnetic) Energy

• Non-ionizing Radiation
  – Not capable of ionizing tissue (~water or DNA)
• Ionizing Radiation
  – IS capable of ionizing tissue (DNA)
Electric Charges create Electric Fields
Electric Fields represent the force on a charged particle or objects nearby

- The amount of charge is proportional to the **voltage**
- Polarity (+/-) determines the direction of force: opposites attract!
- Force depends on the **distance** between the charges and the **amount** of charge on the objects: Inverse Square Law (Coulomb’s Law)
Magnetic Fields

- *Invisible* “lines of force” that start at the north pole of a magnet and come back around, land on the south pole of the magnet, and complete a circuit by going through the body of the magnet to reemerge at the north pole.
Magnetic fields are created by moving charges (current flows: Ampère's law)

\[ F = q UB \sin \theta \]

Magnetic fields exert a force on other moving charges nearby
Magnetic Fields are proportional to currents

- Moving electric charges create magnetic fields
- Field lines form closed loops around a wire
- Direction of field lines depends on current flow
Connections of electricity and magnetism

Click for Video Demo

- Current flow
- Induced Electric potential
- Induced Current flow
- Changing Magnetic field
- Induced Magnetic field
Magnetic Fields from Alternating currents

• When the polarity and strength of the current and voltage keeps changing between positive and negative, we call this an **alternating current**—AC

• The frequency of the AC describes the number of times per second that the current undergoes a complete (+/-) cycle. Frequency = Hz = cycles/sec

• AC creates alternating electric and magnetic fields
  – Example: in USA, polarity of voltage and current flowing in power lines changes 60 times per second.
AC Current and Voltage

Ohm’s Law $V = IR$  
Joule’s law $P = IV$  
$V =$Voltage; $I =$Current; $R =$Resistance $P =$Power
Time varying fields can have special properties: Electromagnetic Radiation

- Maxwell’s equations: electric and magnetic fields can act together as to create a self propagating wave
- Electromagnetic radiation
Electromagnetic Radiation

- Magnetic and Electric Fields change polarity and strength
  - rigidly bound together
  - Field is pointing in some direction, the magnetic field must move in a direction perpendicular to the electric field
  - the wave must travel in yet another direction perpendicular to the other two
Two field components in a free propagating electromagnetic wave

- **Electric Field (E)**
  - Perpendicular to direction of travel
  - Units of Volts/meter
- **Magnetic field (H)**
  - Perpendicular to E and direction of travel
  - Units of Amps/meter
- **Combined fields carry power $S$ over space**
  \[(\text{Amps/m}) \times (\text{Volts/m}) = \text{Watts/meter}^2\]
  \[E \times H = S\]
Recap: Electromagnetic Radiation

• C = speed of light ~ 300 x 10^6 m/s (in vacuum)
• Period = p = the amount of time elapsed during one cycle
• Frequency = f = the inverse of the period = # cycles/sec
• Wavelength (λ) the distance the wave travels in one cycle.
• Frequency * wavelength must equal C = speed of light
  – as frequency increases, wavelength decreases
Dual nature of electromagnetic energy: waves and photons

- Photons are “packets” of electromagnetic energy
- Photon energy is directly proportional to frequency
- Photon energy = $J = h \cdot f$
- $J$ has units of Joules or electron-volts (eV)
- $f$ = frequency in cycles/second (Hz)
- $h =$ planck’s constant ($4.144 \times 10^{-15}$ eV/Hz)
- Recall $C = f \cdot \lambda = 3 \times 10^8$ m/s (speed of light)
- Ionizing radiation has $J \approx > 10$ eV
  - 10 eV approx. threshold for ionizing tissue/water
Electromagnetic spectrum

• Arrange EM radiation in order of energy
• This defines regions of related EM waves
• Increasing frequency related to higher energy
• Ionizing vs Non-ionizing boundary in the UV
## The Electromagnetic Spectrum

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<th>Wavelength</th>
<th>EV</th>
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<td>'Hard' X rays</td>
<td>10^-12</td>
<td>10^6</td>
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<td>3 x 10^19</td>
<td>X-rays</td>
<td>10^-11</td>
<td>10^5</td>
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<td>3 x 10^18</td>
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<td>1000</td>
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<td>100</td>
</tr>
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</tr>
<tr>
<td>3 x 10^14</td>
<td>Visible (400-700 nm)</td>
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<td>10^-1</td>
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<td>Infrared</td>
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Click 4 NASA Video
# Radiofrequency Region

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Absorption causes heating due to energy deposition
Energy transfer depends on wavelength, polarization and geometry
Analogy to a light source

• Color → frequency of RF emission
• Bulb wattage → power of the RF source
• Light intensity at a distance → power density
• Warming → SAR
RF Terminology

- Frequency = Cycles per second (Hertz)
- Power = Rate of energy transfer (watts)
- Power density = Exposure at body surface = Power/surface area (Watts/meter$^2$)
- SAR = Absorbed dose in tissue = Absorbed power/body mass (Watts/kg)
Free Field EM Plane wave propagation (1)

- In the far/free field: $E \perp H$
- Propagation $\perp$ to both $E$ and $H$;
- (No field in direction of propagation)
- Speed = speed of light in medium $1/\sqrt{\varepsilon \mu}$
- i.e. depends on permittivity ($\varepsilon$) and permeability ($\mu$) of the medium
- For biological materials, permittivity ($\varepsilon$) dominates

In a vacuum:
\[
\varepsilon_0 = 8.854\,187\,817\ldots \times 10^{-12} \text{ F/m (Farads per meter)}
\]
\[
\mu_0 = 4\pi \times 10^{-7} \text{ V·s/(A·m) (Newtons / A$^2$)}
\]
Free Field EM wave propagation (2)

- Wavelength ($\lambda$) is speed / frequency
- Ratio of $E/H$ is characteristic impedance $Z$
  - $Z$ approximately constant for air
- Power in free space (Poynting’s Vector)
  - Power = $S = E \times H = E \cdot H \sin \theta$
  - $Z = E/H = 377$ ohms in free field
  - or $S = E^2/377 = 377 \, \text{H}^2$

This is in SI units!
How does RF transmission work?
Current in a Radio Antenna

Current distribution in $2^{nd}$ half cycle
Radio wave propagation

Click Here for a Video Summary
https://www.youtube.com/watch?v=iszFnJcNhwM
Far field power density approximation

• Power density = \( S = \frac{G \cdot P_o}{4\pi r^2} \)
• \( G \) is antenna gain,
• \( P \) is transmitter power
• **Note** \( G \) is a power ratio: the power in given direction compared to isotropic radiation \( (P_o) \) (often expressed in dB = 10 \( \log \frac{P}{P_o} \))
Antenna Power Gain

Isotropic source
Power density = \( S = \frac{P}{4\pi r^2} \)

Directional source
Power density = \( S = \frac{G \cdot P}{4\pi r^2} \)

Receptor located at a fixed distance

Absolute gain
\[
\text{ABSOLUTE GAIN} = \frac{\text{PD(2)}}{\text{PD(1)}}
\]

dB gain
\[
\text{dB GAIN} = 10 \times \log \left( \frac{\text{PD(2)}}{\text{PD(1)}} \right)
\]
The NEAR field is Different!

- Near a source (antenna) E and H are not perpendicular
- Also, there are reflection and fields due to currents flowing in nearby objects
- Define far field as distance $\sim r > \frac{2L^2}{\lambda}$
- Where L is largest dimension of antenna
Near / Far Field regions

Near Field
- reactive
- radiative (Fresnel)

Far Field
- (Fraunhofer)

\[ S \approx \frac{4P}{A} \]
\[ S \approx \frac{A}{2\lambda} \]
\[ S \approx \frac{AP}{\lambda^2 r^2} \]

Far field E/H = 377 ohms

Approx. Near/Far boundary distance

Source: ANSI C95.3-1973
RADIATING NEAR-FIELD

L > \lambda
HORN ANTENNA

FAR-FIELD
2L^2/\lambda

L < \lambda
DIPOLE ANTENNA

FAR-FIELD
\lambda/2\pi

REACTIVE NEAR-FIELD
Calculation Example:

- Horn antenna
- $f = 300$ MHz, $P = 10$ kW, $\lambda = 1.0$ meters,
- aperture $L = 2$ meters; $G = 50$ (17 dB)
- Far field is distance $> 2L^2/\lambda$ (or 8 m)
- At distance of 30 meters from source
- $S = 44.2$ W/m$^2 = 4423$ $\mu$W/cm$^2$

Note: dB Gain $= 10 \cdot \log_{10}(50) = 10 \cdot (1.699) \approx 17$ dB
Short Break!

• Topics to review:
  – Calculation and estimation of EM field power density from antenna power and distance
  – Properties of electric, magnetic and EM fields
Quick Questions

• What is the power density for a 1kW source with an antenna gain (G) of 126 at a distance of 100m from the source (assume far field)?
• What is this antenna gain expressed in dB?
• What would the power density be at 200m?
Quick Questions

• What is the power density for a 1kW source with an antenna gain (G) of 126 at a distance of 100m from the source (assume far field)?
  – ANS: ~1 W/m^2

• What is this antenna gain expressed in dB?
  – ANS: 21 dB

• What would the power density be at 200m?
  – ANS: 0.25 W/m^2
RF Exposure Bio-effects
What’s behind the standards
Factors in RF Bioeffects

• Absorption, Reflection, Transmission
• Absorption causes heating due to energy deposition
• Energy transfer depends on wavelength, polarization and geometry
Depth of penetration depends on wavelength:

<table>
<thead>
<tr>
<th>Wavelength (cm)</th>
<th>skin depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 (10 GHz)</td>
<td>&lt;1 mm</td>
</tr>
<tr>
<td>3-10</td>
<td>0.1-1 cm</td>
</tr>
<tr>
<td>10-20</td>
<td>1 - 10 cm</td>
</tr>
<tr>
<td>20-100</td>
<td>10-30 cm</td>
</tr>
</tbody>
</table>

Polarization of EM wave also a factor
How RF Transfers Energy

How RF Causes Motion

Atomic level
No E field
Local E field

Molecular level
Electron polarization
Atomic polarization

Structural level
Dipole alignments
Ion drift

In solutions
Tissue electrical properties vary with frequency

- $\alpha$ dispersion - interaction with "counterions" outside cell. Cell contents shielded.
- $\beta$ dispersion - interaction with macromolecules. Intracellular fluid, but not organelles, affected.
- $\gamma$ dispersion - water absorption occurs. All parts of cell affected.
Polarization refers to the orientation of E or H relative to vertical /horizontal axis; usually E vertical is "worst case" (circular polarization also common)
Body Resonance: when wavelength ~ body dimensions

- People act as good antennas when the wavelength is similar in size to the body
- Whole body coupling is to the vertical (long) axis or the body, vertical E field
- Higher frequencies can couple to body parts; head arms legs, etc.
- Similar frequency effects for children.
Specific Absorption Rate
Absorbed power in Watts/kg

SAR vs. Frequency

Fig. 4. The calculated peak specific absorption rate (SAR) distribution in human subjects exposed to an electric field with feet grounded. From: Guy (1987).

The peak SAR occurring in the muscle and blood vessels of the ankle, when the feet are grounded, reaches a value of 100 W/kg.
Body Resonance and SAR

Sub-resonant: (<3 MHz)
Body and parts don’t act as antennas. Current flows dominant, SAR proportional to $f^2$

Resonant: (3 MHz – 6 GHz)
Body and parts act as good antennas, both current flows (, 100 MHz) and local absorption important. Absorption increases in proportion to $f^2$ from 3 to 30 MHz. Max effect @ 30-300 MHz.

Transition:
(<300 MHz – 6 GHZ)
absorption drops $1/f$

Super-Resonant: (6 GHz – 300GHz)
Body does not act as an antenna; absorption constant with $f$, approx 8% of incident power. Quasi optical focusing 6-15 GHz; skin absorption dominant > 15 GHZ
SAR = absorbed dose

- SAR measures the energy transfer per unit body mass,
- Depends on many things (shape polarization, frequency, etc.)
- SAR = $E^2\sigma/\rho$
- $\sigma =$ tissue conductivity (siemens/m)
- $\rho =$ tissue density (kg/m$^3$)
Summary of biological effects: SAR and power density

• Tissue energy absorption proportional to incident EM power/unit area
• Power density = Exposure in Watts/m² or mW/cm²
• $S = (\text{Poynting vector})$ is a measure of this incident energy
• Exposure used for setting ‘external’ exposure limits
• SAR measures a bio-effect(s) of dose (e.g. heating)
Energy transfer or dosimetry is related to SAR absorbed dose;

- $\text{SAR} = \frac{\text{power absorbed}}{\text{tissue mass}} \text{ or Watts/kg}$
- where $\text{SAR}$ is the "specific absorption rate"
- $\text{SAR}$ used to set ‘internal’ dose limits (basic restrictions on exposure)
- $\text{SAR} = \frac{E^2 \sigma}{\rho}$
- $\sigma = \text{tissue conductivity (siemens/m)}$
- $\rho = \text{tissue density (kg/m}^3\text{)}$
Protective clothing
Personal Alarm
Cooperative RF Program for Shared Tower
Cooperative RF Program for Multiple Broadcasters
Fence to Limit Access
RF Protective Suits
PPE Must Be Tested for Application
PPE Must Be Inspected & Maintained

From Ric Tell
END

• Bonus slides & extra material follow
Table 11–C. Relationships Between Electric Field Strength, Magnetic Field Strength, and Power Density (Irradiance) for Electromagnetic Radiation

\[
S_m = \frac{E^2}{3,770} \\
S_m = 37.7 \, H^2 \\
E^2 = 3,770 \, S_m \\
E = (3,770 \, S_m)^{1/2} \\
H^2 = \frac{S_m}{37.7} \\
H = \left(\frac{S_m}{37.7}\right)^{1/2}
\]

- \(S_m\) = Power density in units of mW/cm
- \(E^2\) = Electric field strength\(^2\) (V\(^2\)/m\(^2\))
- \(E\) = Electric field strength (V/m)
- \(H^2\) = Magnetic field strength\(^2\) (A\(^2\)/m\(^2\))
- \(H\) = Magnetic field strength (A/m)

Note some in CGS units!!
### (A) Limits for Occupational/Controlled Exposure

| Frequency Range (MHz) | Electric Field Strength (E) (V/m) | Magnetic Field Strength (H) (A/m) | Power Density (S) (mW/cm²) | Averaging Time $|E|^2, |H|^2$ or S (minutes) |
|-----------------------|-----------------------------------|-----------------------------------|---------------------------|---------------------|
| 0.3-3.0               | 614                               | 1.63                              | (100)*                    | 6                   |
| 3.0-30                | 1842/f                            | 4.89/f                            | (900/f²)*                 | 6                   |
| 30-300                | 61.4                              | 0.163                             | 1.0                       | 6                   |
| 300-1500              | --                                | --                                | f/300                     | 6                   |
| 1500-100,000          | --                                | --                                | 5                         | 6                   |

### (B) Limits for General Population/Uncontrolled Exposure

| Frequency Range (MHz) | Electric Field Strength (E) (V/m) | Magnetic Field Strength (H) (A/m) | Power Density (S) (mW/cm²) | Averaging Time $|E|^2, |H|^2$ or S (minutes) |
|-----------------------|-----------------------------------|-----------------------------------|---------------------------|---------------------|
| 0.3-1.34              | 614                               | 1.63                              | (100)*                    | 30                  |
| 1.34-30               | 824/f                             | 2.19/f                            | (180/f²)*                 | 30                  |
| 30-300                | 27.5                              | 0.073                             | 0.2                       | 30                  |
| 300-1500              | --                                | --                                | f/1500                    | 30                  |
| 1500-100,000          | --                                | --                                | 1.0                       | 30                  |

$f = \text{frequency in MHz}$

*Plane-wave equivalent power density
Induced current limits (whole body)

- Induced Current limits for each foot or grasping contact:
  - $I \leq \frac{1000}{f}$ where $0.03 < f < 0.1$ MHz
    
    \{30 kHz to 100 kHz\}
  - $I \leq 100mA$ for $0.1 < f < 100$ MHz
    
    \{100 kHz to 100 MHz\}
  - Note: 1 s averaging time

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- Pulsed fields $<100mS$ 0.1kHz to 15 GHz
  - Peak TLV = TLV*360/ 5*pulse-width
  - Pulse width in seconds
Summary of Contact Current

<table>
<thead>
<tr>
<th>Condition</th>
<th>Contact current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare wire, no gloves of any kind</td>
<td>111</td>
</tr>
<tr>
<td>Conventional work glove</td>
<td>110</td>
</tr>
<tr>
<td>With KW-GARD™ suit, gloves and socks</td>
<td>7.2</td>
</tr>
<tr>
<td>With KW-GARD™ suit, gloves and socks with addition of conventional work gloves</td>
<td>7.0</td>
</tr>
</tbody>
</table>
### Antenna Equations

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| **a)** | \[ W_{nf} = \frac{AP}{A} \] | \( W_{nf} = \) Max Power Density in near field of the antenna.  
\( P = \) Power Output (watts)  
\( A = \) Area of antenna (m\(^2\)) |
| **b)** | \[ W_{ff} = \frac{AP}{\lambda^2r^2} \] | \( W_{ff} = \) Max Power Density in the far field of antenna |
| **c)** | \[ r_{ff} = \frac{A}{2\lambda} \] | \( r_{ff} = \) distance to far field  
\( \lambda = \) wavelength of radiation |
| **d)** | \[ r = \left( \frac{PG}{\pi EL} \right)^{\frac{1}{2}} \] | \( r = \) distance to hazard zone boundary from source  
\( EL = \) Exposure Limit (mWatts/cm\(^2\)) |
| **e)** | \[ G = \frac{4\pi A}{\lambda^2} \] | \( G = \) Antenna Gain |
| **f)** | \[ t = \frac{ML}{BL} \times 0.1hr \] | \( t = \) Allowed time of exposure at ML  
\( ML = \) Measured exposure (mW/cm\(^2\))  
\( EL = \) Exposure Limit (mW/cm\(^2\)) |