Doctoral Qualifying Exam

Averaging Schemes for Assessment of Incident and Absorbed Power Density on Skin Surface

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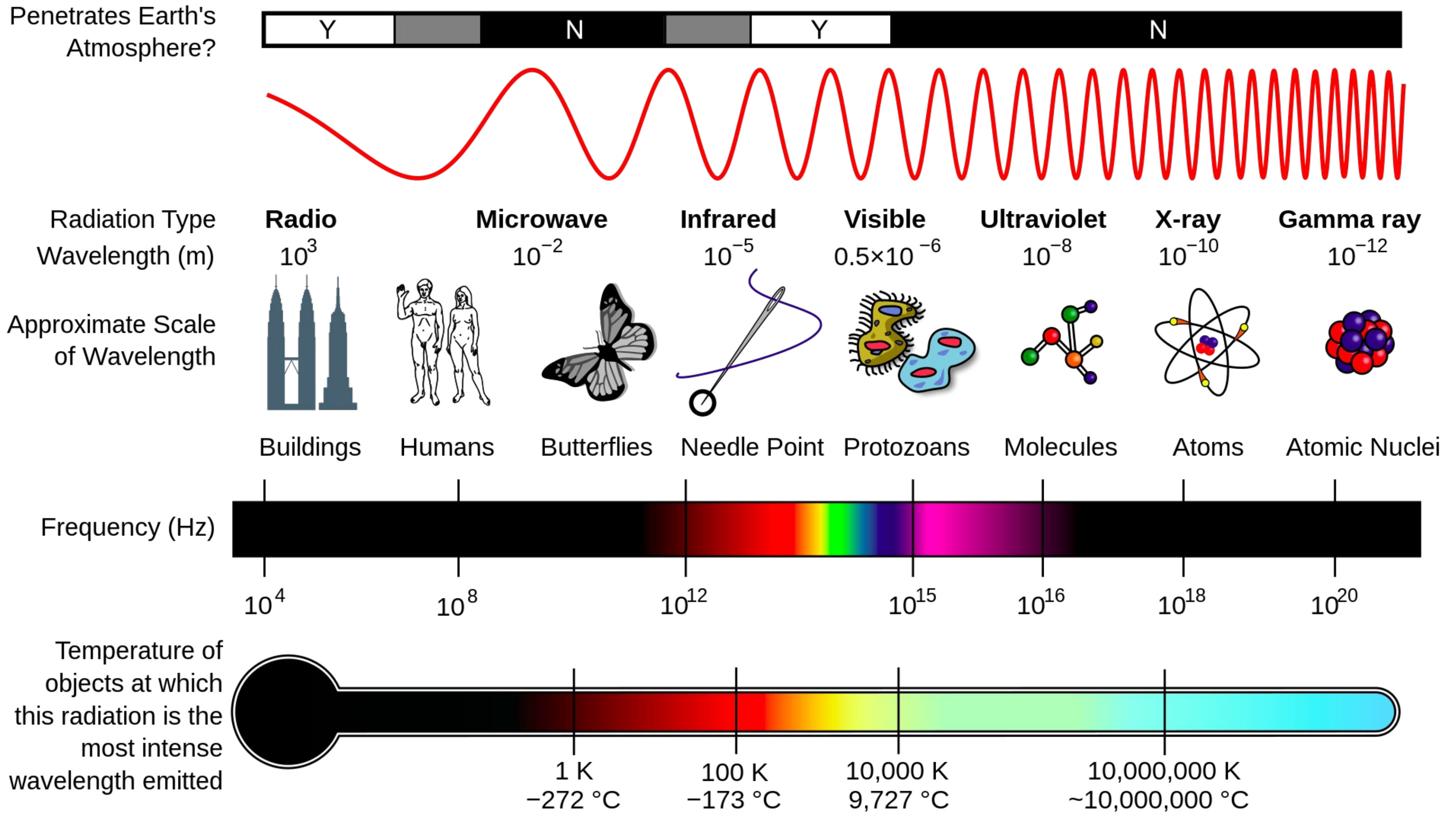
Table of Contents

1. General Introduction in Human Exposure to EMFs

EM Radiation

- is created due to **periodic changes** of electric and/or magnetic fields
- Periodicity → **frequency**
- Non-ionizing vs. ionizing radiation
  - Single photon energy up to vs. above 10 eV
- EM waves in lossy medium transfer kinetic energy to surrounding bounded atoms/molecules of material → “vibrations” → **temperature rise**
  - Wavelength of the incident field ~ dominant dimension of material
  - Biological tissue ~ microwave up to low-energy UV spectrum


Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Approximate Scale of Wavelength
Radio
10^{3}
Microwave
10^{-2}
Infrared
10^{-5}
Visible
0.5×10^{-6}
Ultraviolet
10^{-8}
X-ray
10^{-10}
Gamma ray
10^{-12}
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

Non-Ionizing EM Radiation Effects on Biological Tissue

- are any **change** (physical, chemical, or mechanical) induced in tissue
- Feedback repair mechanism
  - Preservation of homeostasis within **threshold limits**
- Limits exceeded → **adverse health effects**
- Non-thermal vs. thermal effects
  - Frequency dependent with transition at ~100 kHZ
- Non-thermal effects at RF → no scientific consensus

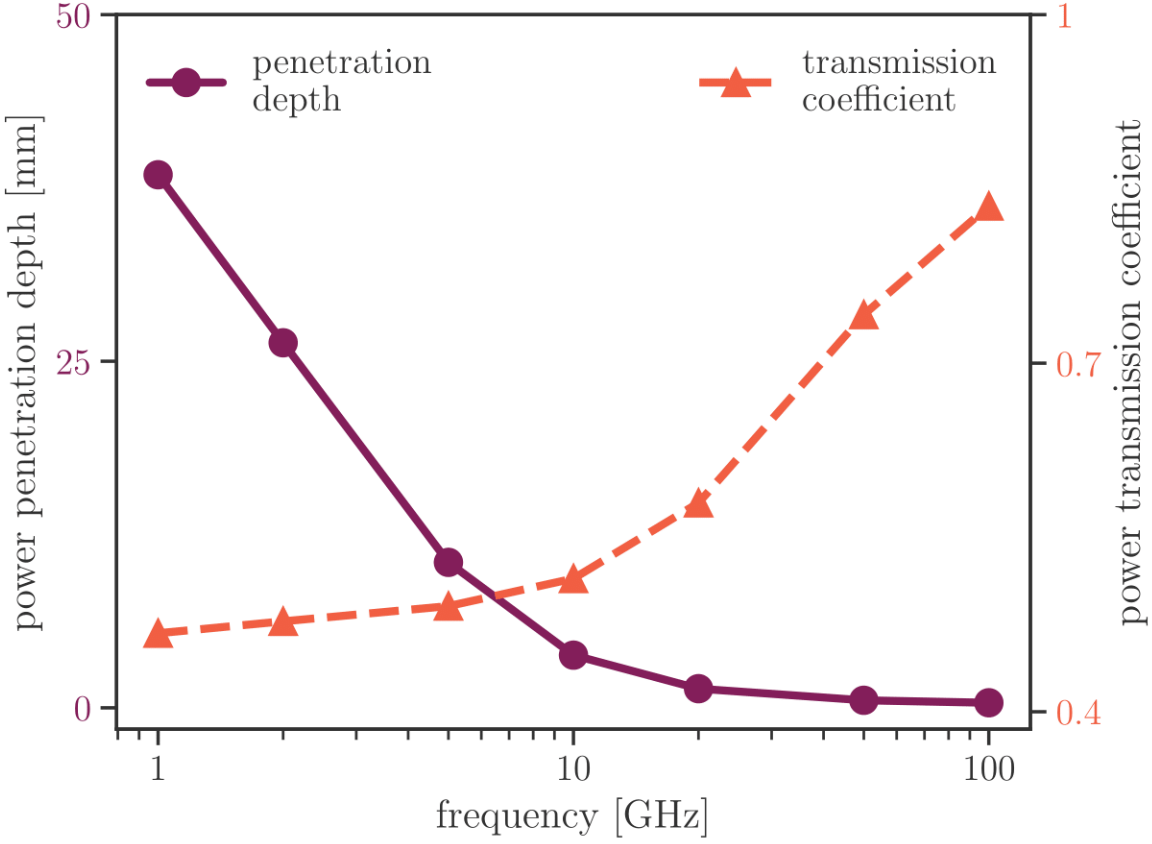
Summary of Non-Ionizing Radiation Effects on Biological Tissue

exposure to	static H-fields	LF	RF	IR	visible light	low-energy UV
frequency [Hz]	0	1 up to 100 k	100 k up to 300 G	300 G up to ~400 T	~400 T up to 790 T	> 790 T
interaction effects	induced fields & currents	stimulation of excitable cells	→ ←	tissue heating		

Assessment Basis for Heating Effects

- Interaction between induced E-fields and polar molecules within tissue → kinetic energy
- Increased kinetic energy → frequent interaction of polar molecules and charged particles → thermal energy
- Heating effects depend on the distribution of EM power within exposed tissue
  - Steady state conditions vs. brief exposure
  - Local vs. whole-body exposure
  - Tissue type-1 vs. type-2

Power transmission and penetration depth into dry skin



Homogeneous block of tissue with dielectric properties of dry skin.

Limiting Exposure to Artificial EMFs

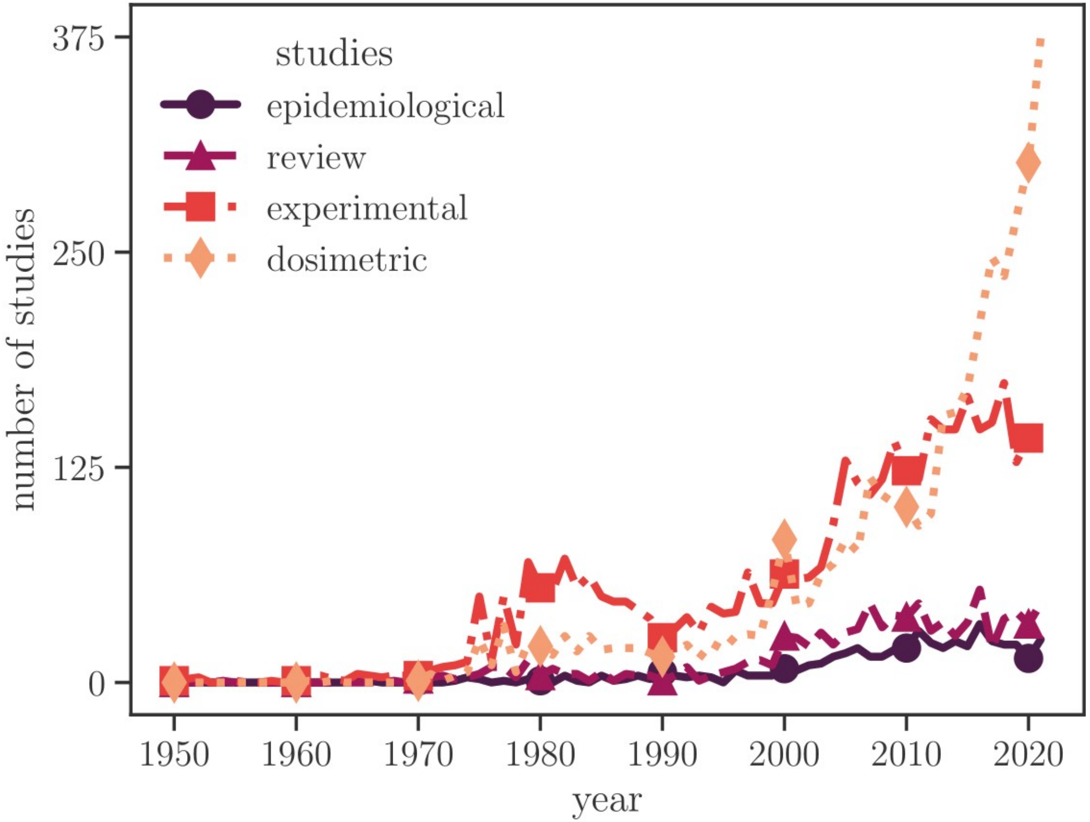
- Widespread use of wireless RF consumer electronics
- International bodies prescribe exposure limits within guidelines (ICNIRP) or standard (IEEE C95.1)
  - Occupational vs. general public
- Protection against adverse health effects – respecting the frequency and exposure scenario dependent limits
  - Derived upon published literature
  - Applied reduction factors
- Threshold values → BRs → RLs

(Very) Brief Historical Overview

- 1960s – Tri-service program, first set of C95.1.*x*
- 1970s – large number of wireless devices operate in close proximity of human body → public distrust → many controversies
- 1970/80s – termographic studies, comprehensive environmental studies → RF dosimetry handbook[1]
- 1990s – IRPA → INIRC → ICNRIP
- 2020s – new C95.1 standard[2] and ICNIRP guidelines[3]

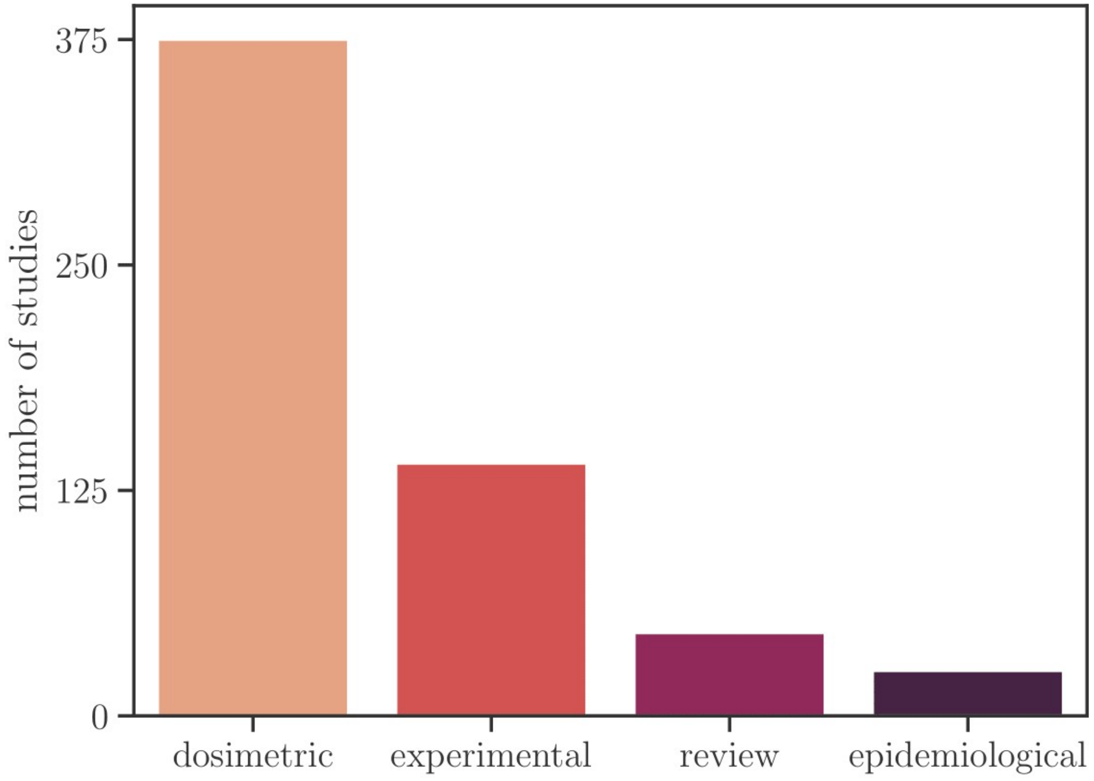
[1] Durney et al. Brooks Air Force Base, TX: USAF School of Aerospace Medicine, AFSC, 1986
[2] IEEE Std C95.1-2019:1–312, 2019
[3] ICNIRP, Health Physics 118:483–524, 2020

Evolution of research related to bioeffects of RF fields (50s to date)



Compiled from the database of publications at http://emf-portal.org.

2021 studies related to bioeffects of RF fields



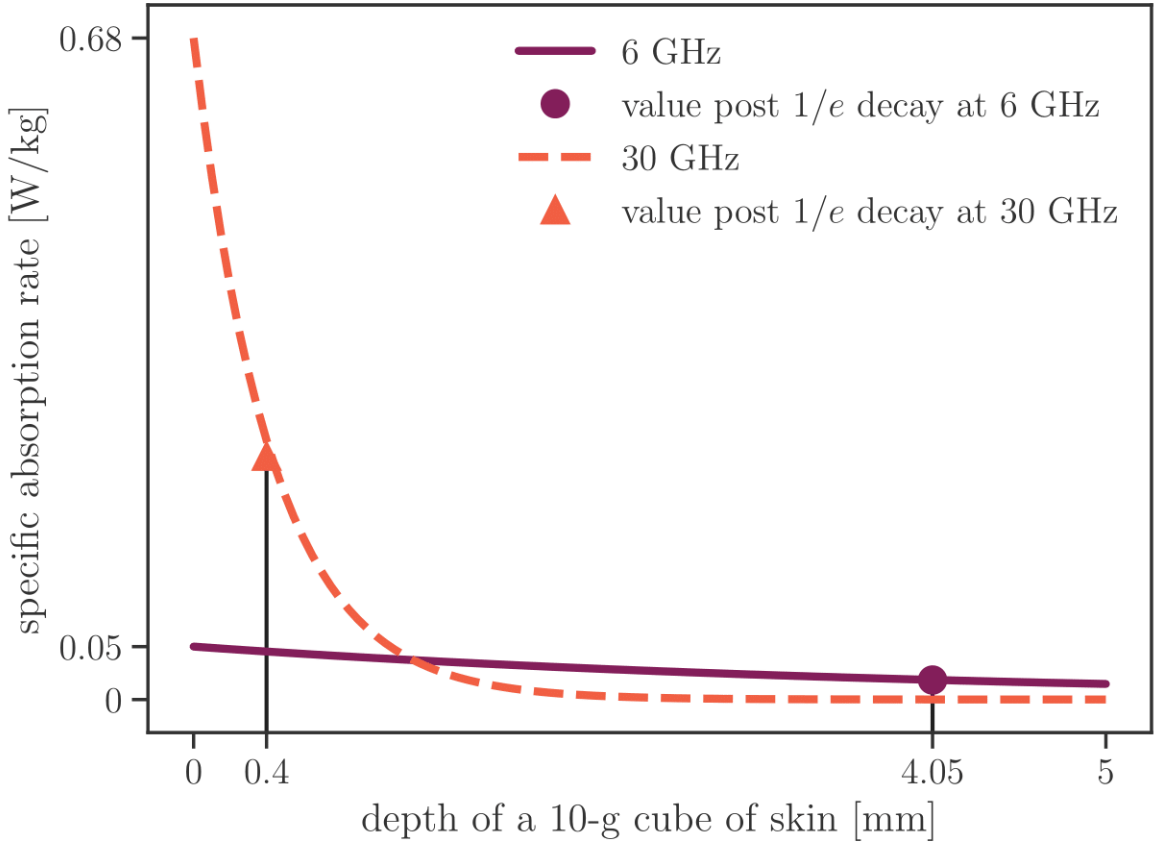
Compiled from the database of publications at http://emf-portal.org.

Dosimetric Quantities in Terms of BRs

- are derived from the levels of RF EMFs that correspond to (operational) adverse health effects
- are frequency dependent dosimetric quantities at the appropriate spatio-temporal scale of exposure, e.g.:
  - Whole-body exposure (over 30 min): **SAR** = 4 W/kg ~ 1 °C
    - Reduction factors of 10 for workers and 50 for general public
  - Local exposure up to 6 GHz (over 6 min): 10-g or 1-g SAR
  - Local exposure above 6 GHz (over 6 min): 4-cm^2 or 1-cm^2 APD
    - Reduction factor of 2 for workers and 10 for general public
- RLs provide more **practical** means of demonstrating compliance by estimating IPD in free space

2. Exposure Assessment and Dosimetry in Era of 5G

~ 90% EM power is dissipated in the uppermost skin layer above 6 GHz



Homogeneous block of tissue with dielectric properties of skin exposed to a plane wave of 100 mW/cm^2.

Definition of the Spatially Averaged APD Derived from the Poynting vector

- *A* – frequency-dependent averaging area
- ***E***, ***H****** – peak values of the electric and complex-conjugate magnetic fields
- ***n*** – unit normal vector on *A*
- d*A* – integral element of *A*

$$S_{\mathrm{ab},\,1} = \frac{1}{2A} \iint_A \Re\left[\boldsymbol{E} \times \boldsymbol{H}^*\right] \boldsymbol{n}\, dA$$

Definition of the Spatially Averaged APD via Volume-Averaged SAR

- Tissue surface is positioned at *$z = 0$*
- z_{max} should be sufficiently larger than the EM penetration depth
- ρ – tissue density in kg/m^3
- SAR is defined as $\sigma|\boldsymbol{E}^2|/\rho$
- σ – tissue conductivity in S/m

$$S_{\mathrm{ab},\,2} = \frac{1}{2A} \iint_A dA \int_{z=0}^{z_{max}} \rho\,\mathrm{SAR}\,dz$$

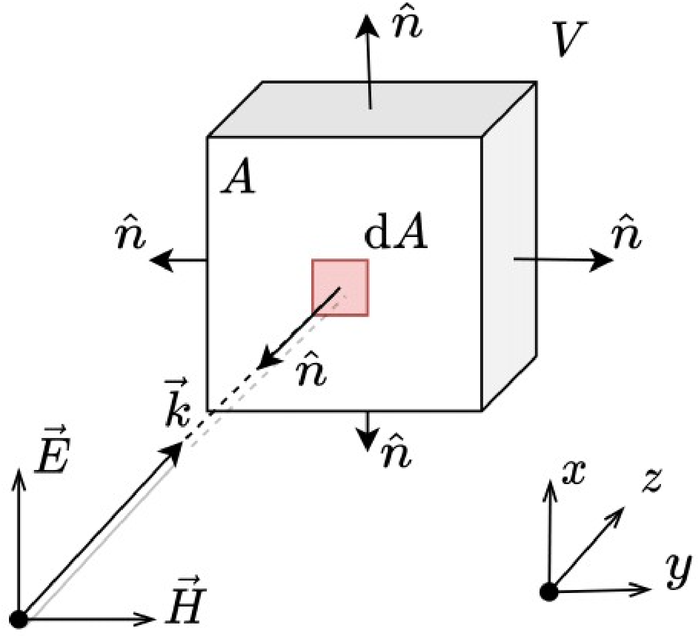
Practical Considerations for Power Density Spatial Averaging

- [2, 6] GHz → peak value of the incident PD
- > 6 GHz → averaging across **4 cm²** square evaluation plane[4, 5]
- > 30 GHz → averaging across **1 cm²** area in addition to 4 cm² to account for narrow beams at high frequencies[6]

[4] Hashimoto et al. Phys. Med. Biol. 62(8):3124–3138, 2017
[5] Funahashi et al. IEICE Trans Electronics 8:644-646, 2018
[6] Foster et al. Health Physics 111(6):528-541

$S_{ab,\,1}$ and $S_{ab,\,2}$ are equivalent

- provided that the surface surrounding a given volume of the tissue is closed and no active sources are present in this volume of interest



Mathematical details are omitted
for your – you are welcome ,
but can be found in
Doctoral Qualification Paper in
Chapter 3.3.2.

Mathematical Defintion of the IPD

- Modulus of the time-averaged power density vector
- Assuming that the separation distance is ≳ λ/2π, spatially averaged IPD is a valid proxy for local max. temp. rise[7]

$$S_{\text{inc}} = \left| \boldsymbol{E} \times \boldsymbol{H}^{*} \right|$$

$$S_{\text{inc, n}} = \frac{1}{2A} \iint_{A} \Re\left[\boldsymbol{E} \times \boldsymbol{H}^{*} \right] \boldsymbol{n} \, dA$$

$$S_{\text{inc, tot}} = \frac{1}{2A} \iint_{A} \left| \Re\left[\boldsymbol{E} \times \boldsymbol{H}^{*} \right] \right| dA$$

[7] IEEE Std 2889-2021:1–152, 2021

3. State of Research

3.1. Tissue Models and Control Surface

Tissue-Equivalent Model Configuration

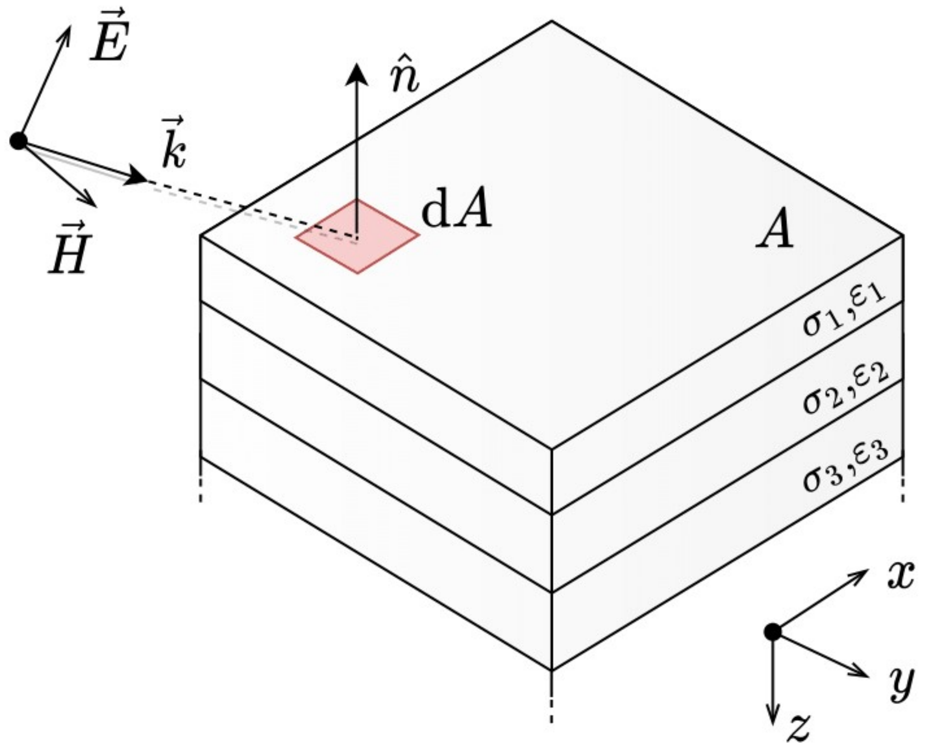
- 1- or 3-/4-layer block tissue model[8] > 6 GHz
- Anatomy of skin

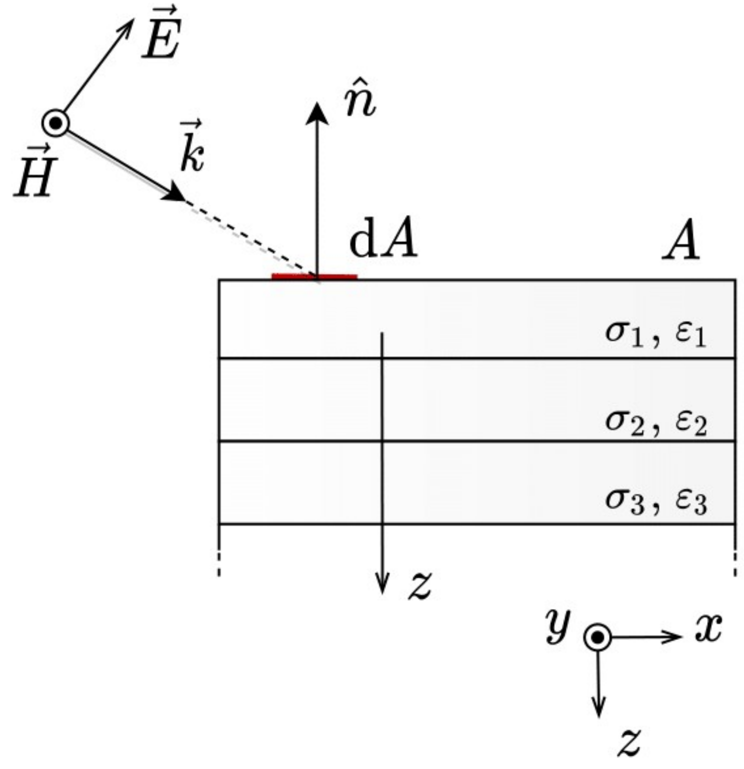
horny layer	clear layer	granular layer	prickle cell layer	basal cell layer	papillary layer	reticular layer
epidermis					dermis	

- Hypodermis – low heat transfer → thermal barrier
- Muscle
- Dielectric properties ← 5-term Cole-Cole model[9]

[8] Ziskin et al. Bioelectromagnetics 39(3):173-189, 2018
[9] Gabriel. TR-1996–0037, US Air Force, 1996

Control Surface during Spatial Averaging on the Multi-Layer Tissue-Equivalent Block Model





3. State of Research

3.2. Power Density Averaging Schemes

Prior to IEEE C95.1 and ICNIRP 2020...

- ICNIRP 1998[10]
  - Whole-body exposure above 10 GHz in the far-field zone → the IPD spatially averaged on 20 cm^2 planar control surface
  - Local exposure → the spatially-averaged IPD over the most exposed region of 1 cm^2
- IEEE C95.1-1999[11]
  - Spatial averaging – the root-mean-square of the power density over an area equivalent to the vertical cross-section of the human body (projected) at a distance of no less than 20 cm

[10] ICNIRP, Health Physics 74 (4):494-522, 1998
[11] IEEE Std C95.1-1999:1–83, 1999

State of the Art

- Transition frequency of 6 GHz
  - Anderson et al 2010[12], McIntosh and Anderson 2010[13]
- Harmonization of control surfaces between standards
  - Colombi et al 2015[14], Thors et al 2016[15], Xu et al 2018[16]
- Square averaging surface of 2 x 2 and 1 x 1 cm^2
  - Hashimoto et al 2017[4]
- Spatially averaged transmitted power density
  - Funahashi et al 2018[17]

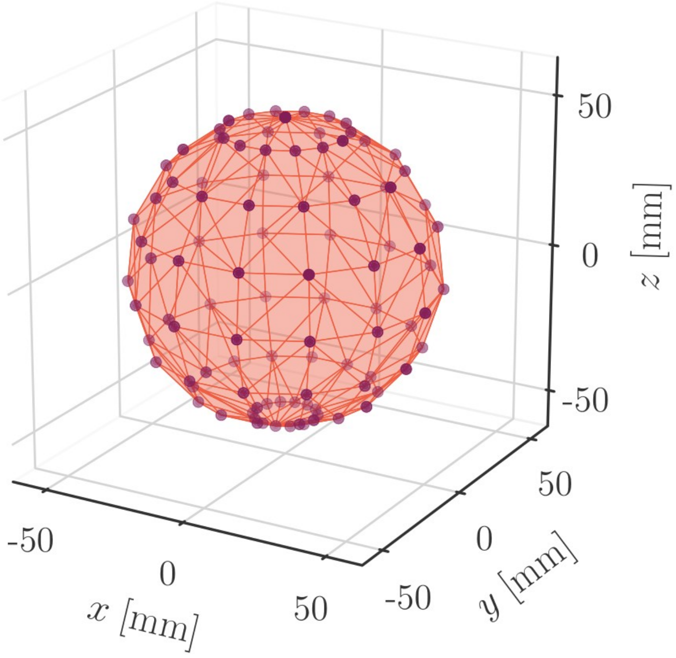
[12] Anderson et al. Bioelectromagnetics 31(6):454–466, 2010
[13] McIntosh and Anderson, Bioelectromagnetics 31(6):467–478, 2010
[14] Colombi et al. IEEE Antennas Wirel. Propag. Lett. 14:1247–1249, 2015
[15] Thors et al. IEEE Access 4:7469–7478, 2016
[16] Xu et al. IEEE Access 6:830–838, 2018
[17] Funahashi et al. IEEE Access 6:77665-77674, 2018

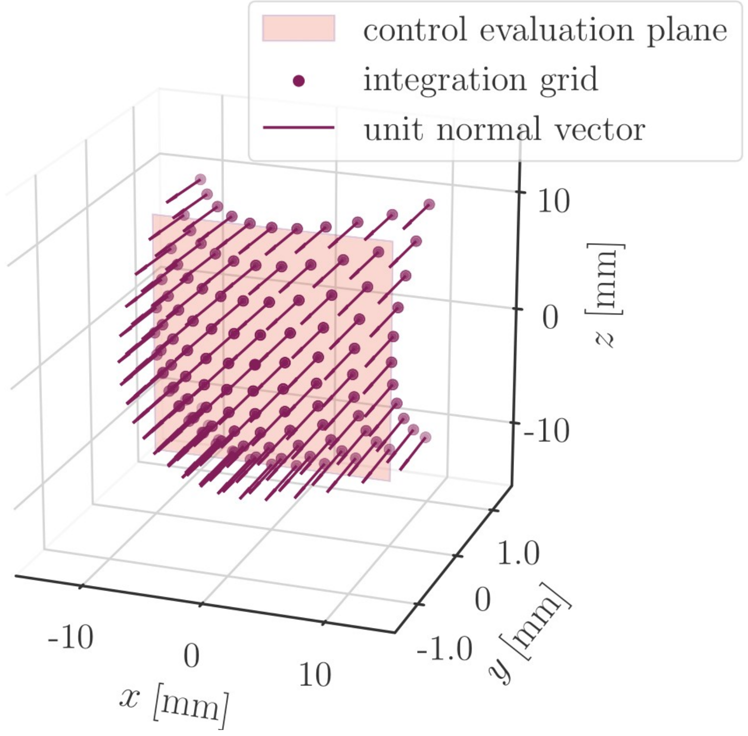
Going beyond the State of the Art

- Non-planar body parts, e.g., fingers[18], ears[19], with the curvature radius ~ wavelength of the incident EMF → underestimation of the area-averaged qauntities
- Non-planar tissue models currently discussed within IEEE ICES TC95 SC6 WG7
  - Canonical shapes, e.g., sphere & cylinder
  - Anatomical models

[18] Li et al. IEEE Trans. Microw. Theory Tech. 60(7):2267–2276, 2012
[19] Sacco et al. IEEE J. Electromagn. RF Microw. Med. 6(3):413–419, 2022

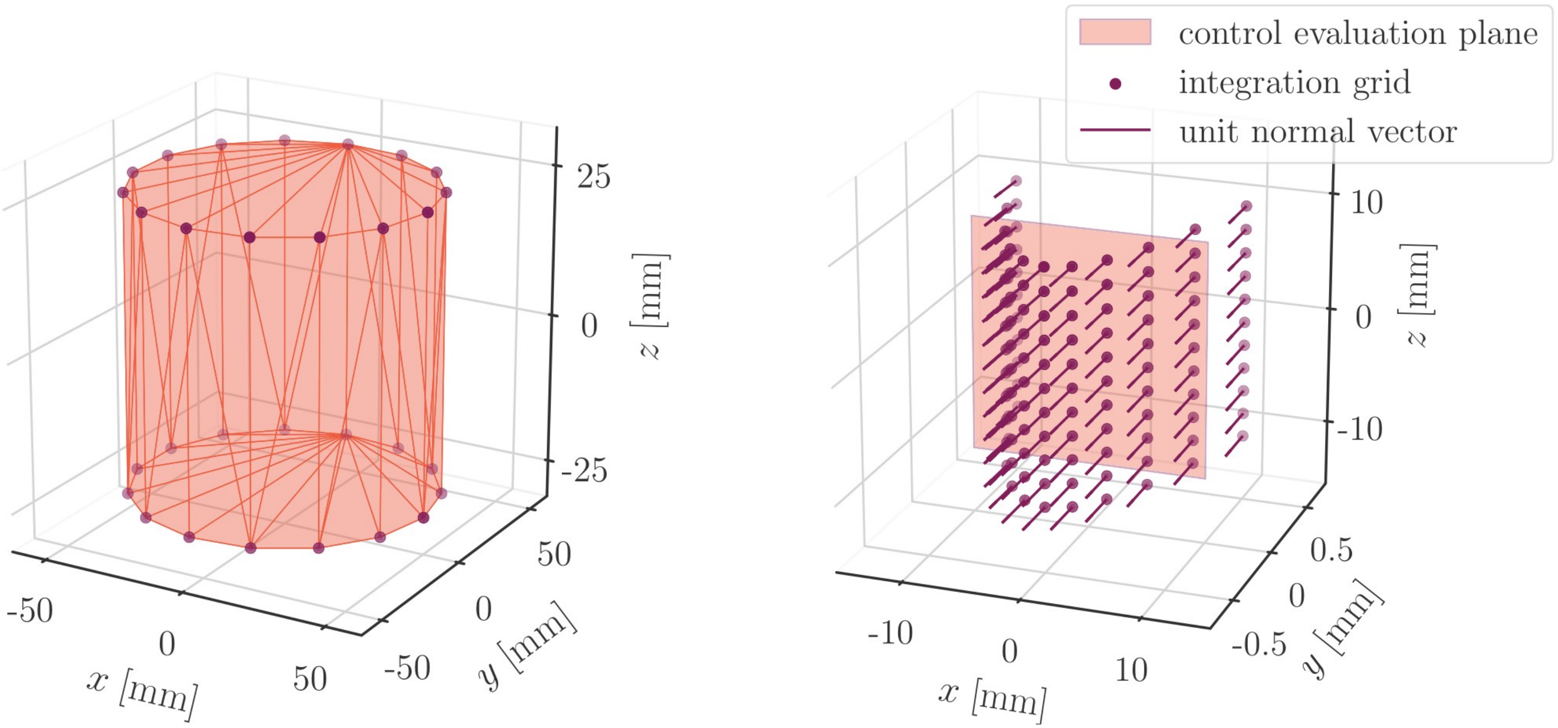
Spherical Model with Radius Set to 5 cm[20, 21]





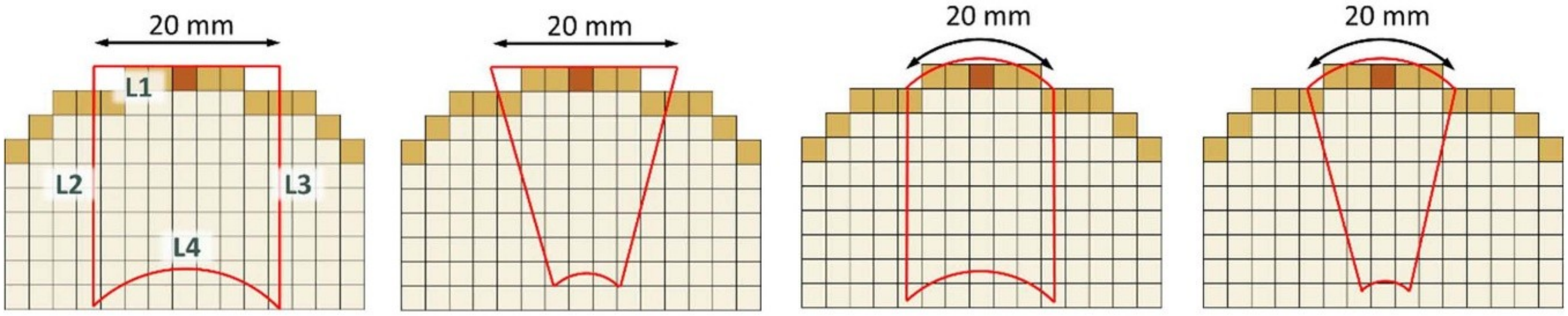
[20] Kapetanovic and Poljak. IEEE Trans. Electromagn. Compat. 64(5): 1296–1303, 2022
[21] Kapetanovic et al. In proceedings SoftCOM 2023

Cylindrical Model With Radius Set to 5 cm[22]



[22] Kapetanovic and Poljak. To appear in Radiat. Prot. Dosimetry, 2023

Reference Averaging Surface for Non-planar models[23]



(a) (b) (c) (d)

- (a) and (b) L1 - parallel to the grid axis to match the standard evaluation plane
- (a) and (b) L1 - bent along the surface to match the curvature of skin
- Side bounds - parallel to the grid axis in (a) and (c)
- Side bounds - parallel to the internal E-field gradients at the surface in (b) and (d)
- L4 - defined as the contour where the E-field is at 1/1000 of max value in the volume

[23] Diao and Hirata. 55(22):224001, 2020

4. Conclusion and Future Work

Summary

- Recent updates of international exposure limits are motivated with the deployment of 5G worldwide
- Steady-state local exposure above 6 GHz – APD/IPD
- Valid proxies for temperature rise on flat surfaces
- Curvature of local body parts is pronounced → compromised accuracy & compliance assessment
- Future work
  - Analytical spatial averaging on non-planar surfaces (ICES TC96 SC6 WG7)
  - Numerical & data-driven techniques for surface integration across conformal surfaces of anatomical tissue models

Thank You for Your Attention

Q&A

Abbreviations in Order of Appearance

- EMF – electromagnetic field
- 5G – fifth generation
- EM – electromagnetic
- UV – ultraviolet (radiation)
- RF – radio-frequency
- LF – low-frequency
- IR – infrared (radiation)
- ICNIRP – Internation commission on non-ionizing radiation protection
- IEEE – Institute of Electrical and Electronics Engineers
- BR/DRL – basic restriction or dosimetric reference limit
- RL/ERL – refernce level or exposure reference level
- IRPA - International Radiation Protection Association
- INRC – International Non-Ionizing Radiation Committee
- SAR – specific absorption rate
- APD – absorbed power density
- IPD – incident power density