Tissue heating during MR examination as function of RF exposure and local thermoregulation, consequences for the MR safety standard IEC 60601-2-33

Manuel Murbach
Esra Neufeld, Eugenia Cabot, Earl Zastrow, Juan Córcoles, Wolfgang Kainz, Niels Kuster
Exposure Chain in MRI

RF incident field (B1) → Induced fields (SAR) → Temperature increase (T) → Thermal dose (CEM43)
Exposure Chain in MRI

RF incident field (B1) → Induced fields (SAR) → Temperature increase (T) → Thermal dose (CEM43)

B [μT]  whole-body average SAR: wbSAR [W/kg]

local SAR: psSAR10g [W/kg]

T [°C]  CEM43 [min]
Exposure Safety Management, IEC 60601-2-33

• about 1 billion scans performed within IEC 60601-2-33 limits
• remarkable history of safe use

• **normal** operating mode, **first level controlled** operating mode
• governing limits in temperature (first level: \( T < 40^\circ\text{C} \))
  - derived limits mainly in \( \text{wbSAR} \) (first level: \( \text{wbSAR} < 4 \text{ W/kg} \))
• local SAR is NOT limited for body coils
  - advanced electrothermal simulation modeling shows:
    - local SAR levels are higher than originally thought
      - up to \( > 80 \text{ W/kg psSAR10g} \) possible in first level operating mode
    - local temperature may be higher than envisaged (\( > 40^\circ\text{C} \))
MRI as a Very Specific RF Exposure Scenario

- exposure configuration well characterized (frequency, incident field distribution)
- patient with respect to the field well defined (posture & landmark position)
- environment very well defined (temperature, clothing, humidity)
- benefit (excellent)
  ▶ specific safety concepts possible
Whole-Body vs. Local Heating

- wbSAR limit is generally providing sufficient protection against **whole-body heating**
  - can be measured reliably via overall dissipated power
  - systemic stress can be assessed, e.g., via subjective well-being of the patient
  - slow changes
- **local heating**, however, may exceed assumed limits
  - cannot be measured directly, simulation models are necessary
  - local temperatures may not be adequately perceived (e.g., limited heat sensation in muscle tissue)
  - multitransmit / pTx makes predictions more complex
- environment (air temperature, ventilation, sweating) does NOT affect local temperature hotspots inside the body
Study Overview

• non-implant RF heating
  – 2011: local SAR enhancements [Murbach et al., 2011]
  – 2011: multitransmit SAR [Neufeld et al., 2011]
  – 2014: correlation with anatomy [Murbach et al., 2014b]
  – 2014: thermal damage evaluations [Murbach et al., 2014a]
  – 2015: RF-Shimming with pregnant women [Murbach 2015, in preparation], [Murbach et al., 2014c]
  – 2015: RF-Shimming with pregnant women [Murbach 2015, in preparation]
  – 2015: pTx for pregnant women [Murbach 2015, in preparation]

• implant RF heating
  – 2009: MRI implant heating [Neufeld et al., 2009]
  – 2011: implant safety [Kyriakou et al., 2011]
  – 2012: RF heating of DBS [Cabot et al., 2012]
  – 2014: validation system of Tier 3 method [Zastrow et al., 2014]

• other
  – 2013: CEM43 Tissue Damage Thresholds for MR [van Rhoon et al., 2013]
Incident Field

- body coil model ("antenna")
  - excitation scheme (CP, RF shimming)
  - birdcage dimensions:

Duke  Fats
Anatomical Models: Posing / Morphing

- anatomical human models, e.g., Virtual Population
- posing: volume preserving posture changes
- physics-based morphing to enhance range of coverage
  - increased population/situation coverage
ViP 3.0 - Approaching Clinical Realism

Exposure Pathway through Induced Eddy Currents

B1-Field in CP

induced eddy-currents in CP

vertical B1 polarization

B1 field

typical «hotspot» locations
Example High-SAR Scan Scenario

- Fats (obese model)
- pelvis imaging position
- 1.5T CP
  - maximum allowance (wbSAR = 4 W/kg)
2011: Local SAR Enhancements (1.5T)

- local SAR (psSAR10g) can reach > 80 W/kg
  (in First Level OM)

Local Thermoregulation Model

- Local thermoregulation is the most important parameter for local temperature increases [Laakso & Hirata 2011] for MR exposures (> 20 W/kg)
  - thermally induced blood-flow increase of factor > 10
  - the ability to up-regulate the local blood-flow has often been underestimated
Local Thermoregulation Models

- we suggest the following definitions
  - normal thermoregulation: factor 32 (skin) and 16 (other) increase
  - impaired thermoregulation: 70% reduction in perfusion change
    - impaired thermoregulation for conservative estimations
    - thermal hyperaemia is impaired in: diabetes, age, smokers, renal failure, cardiovascular disease. (range: 21% - 61%)
Local Temperature Evaluations (1.5T)

Local Temperature (3T)

- data from 3T 2-port shimming
- 4 worst-case scenarios with Fats, Ella, and Louis, considering various RF shimming excitations
- good correlation with theoretical approximations published in [Neufeld 2015]
Reality Check: In Vivo (swine)

- data from MRI+ partners Charité/Siemens
  - Evaluation of #24, wbSAR=4 W/kg, t_expo=60 min
  - NOTE: this exposure level is allowed for human exposure
Local Temperature Validation in Human

Thermal Dose Accumulation

Worst-Case

SAR

Realistic

Hotspot temperature

CEM43

\[ CEM43 = \int_0^{t_{\text{duration}}} R \left(T(t) - 43\right) \, dt \]
Rapid Method for Dose Estimation


• exponential approximations of temperature, based on SAR
• peak temperature and time constant derived from simulations
• model can include local thermoregulation
• good agreement between model prediction and full simulation results
Conclusions

• enforcement of ICNIRP localized SAR limits would be too conservative
• strict enforcement of the current temperature limits (39°/40°) may be very restrictive and overly conservative regarding the history of safe use
  ▸ risk-benefit analysis and the well controlled environment (exposure/environment) justify a more progressive safety concept
  ▸ governing limitations should be based on thermal dose (CEM43) rather than temperature or local SAR
Consequences for MR Safety Standard IEC 60601-2-33

- thermal dose considerations are more appropriate than current limits
- thermal dose considerations may provide improved rationales for current/future exposure safety management
- proposed multi-tier approach:
  - TIER1: Conservative SAR considerations
  - TIER2: SAR-based conservative thermal dose (CEM43) estimation
  - TIER3: Modeling of the thermal response of the patient
    considerable progress in recent years. However, workflow for patient-specific estimates is not yet ready
- find agreement on safe thermal dose limits (e.g. CEM43 = 2min)
Open Questions

• reset time of CEM43
  – when can we start again with CEM43=0, after X hours?
  ▶ 3 hours [Yarmolenko], safety margin?
• large low- or non-perfused regions (pathological, temporary constrictions)
• highly localized hotspots, e.g. RF loops
• conservativeness, how and where apply appropriate safety margins
• patients in anesthesia (no patient feedback)
• medication potentially compromising thermoregulation
• thermal hysteresis, thermal memories, resilience
Thank You

Manuel Murbach