A. Basic underlying MR safety principles and building blocks

1. Static magnetic field ($B_0$, $dB_0/dx$)
   a. Basic Physics
      i. Quantities and units
      ii. Field lines/gradients
      iii. Magnetic properties of matter
   b. Biological Effects
      i. Magnetophosphenes
      ii. Magnetohydrodynamic effect
      iii. Flow potentials/EKG perturbations
      iv. Vertigo, dizziness/nystagmus, nausea with motion in the static field
      v. Teratogenesis?
      vi. Pregnancy-related issues: Spontaneous abortion, premature delivery, gender of offspring, low birth weight, infertility
   c. Mechanical Forces
      i. Translational Forces (Missile Effect)
         1. Magnetic spatial gradient exposure ($dB_0/dx$)
         2. Static field exposure ($B_0$)
         3. Spatial and force-related effect of magnetic shielding
            a. Active
            b. Passive
         4. 3D location of maximal translational force (i.e., force product; location of maximum ($dB_0/dx$)($B_0$))
      ii. Rotational Forces (Torque)
         1. 3D location of maximal rotational force (i.e., location of maximum $B_0$)
         2. Field orientation (horizontal, vertical)
      iii. Lenz’s Forces
         1. Dependence predominantly on:
            a. Static field $B_0$ and static field gradient $dB_0/dx$
            b. Orientation of electrical conductor relative to the lines of magnetic force
            c. Rate of motion of electrical conductor relative to $B_0$
            d. Dimensions of moving electrical conductor
2. Time varying magnetic fields
   a. Basic physics
      i. Induction – Faraday’s law
      ii. E field, Current density J
      iii. Near and far field
      iv. Tissue properties – conductivity, dielectric constant
   b. Rapidly changing - RF magnetic fields \( (B_1) \)
      i. Potential biological concerns
      ii. Potential thermal concerns; multifactorial determinants, including among others:
         1. SAR and energy deposited
            a. SAR modes
               i. Normal
               ii. First level controlled
               iii. Second level controlled
         2. Rate of exposure
         3. Route of exposure
         4. Transmitting RF coil
            a. Proximity of patient tissue/device to transmitting RF coil
         5. Diameter of induced current loop
         6. Orientation of induced current loop relative to transmitted RF power
         7. Concentration of induced voltages/currents
            a. Predominantly in leads, wires, devices with sharp edges/points
            b. Field strength/transmitted RF frequency relative to the object in which there is an induced voltage/current
            c. “Hot spots”
            d. Resonant conditions, critical lengths relative to field strength/frequency dependence
         8. Presence/absence of heat sink (other than patient tissue!)
         9. Use of padding/insulation
            a. Between patient and bore (cylindrical magnets)
            b. Skin to skin contact avoidance vis à vis large caliber induced loops
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c. Slowly changing - Gradient magnetic fields (dB/dt)
   i. Acoustic/auditory considerations
   ii. Direct neuromuscular stimulation potential
       1. Muscular twitching, fasciculations
       2. Arrhythmogenesis potential
d. Very slowly changing magnetic fields (dB₀/dt)
   i. System quench
   ii. Movement/motion within the static magnetic field

3. Gadolinium based contrast agents (GBCA)
   a. Short term adverse effects
      i. Non-allergic type: Nausea, emesis, headache, local injection site
         adverse reactions, etc.
      ii. Allergic type: Hives, sneezing, swelling, etc.
      iii. Anaphylaxis/anaphylactoid reactions
      iv. Risk assessment
         1. Previous adverse event with a GBCA
         2. Previous adverse event with iodinated agents
         3. History of allergies or allergic respiratory disorders
   b. Long term adverse effects
      i. Nephrogenic Systemic Fibrosis
      ii. Dose related dentate/globus pallidus T1 shortening; retained
gadolinium
      iii. Gadolinium Associated Plaques (GAP)
      iv. Anthropogenic gadolinium
      v. Self-published patients with normal renal function and complaints
         since GBCA administration; elevated 24 hour urinary gadolinium
         excretion?

4. Cryogen safety considerations
   a. Quench vent pathway considerations
   b. Hypothermia/frostbite
   c. Asphyxia
   d. Changing magnetic fields
   e. Explosive/flammable risk
   f. Pressure related risks (if quench vent pathway failure)
      i. Ruptured eardrums
      ii. Pressure “locking” of doors/access
5. Claustrophobia/Anxiety

6. Monitoring
   a. MR environment effects on ability to accurately monitor
   b. Effects of the monitoring device(s) on MR imaging (artifacts)

B. Clinical situations and considerations

   2. General implant safety considerations
      a. Maximum spatial gradient (clinical application and decision making)
         i. System maximum (may be behind system shroud/enclosure)
         ii. Maximum exposure to the patient and health care personnel
      b. Thermal (clinical application and decision making)
      c. Induced voltages
      d. Artifact induction (clinical application and decision making)

   3. Specific implant/device safety considerations
      a. Patient implants/devices
         i. Ferromagnetic risk
            1. Magnetic implants (dental, breast implants, ICP monitors, etc.)
            2. Intraocular or adjacent to other delicate tissues/organs
            3. Artifact consideration
         ii. Active implants/devices (specific examples follow)
            1. Device interfering with the MR scanner/artifact
            2. MR fields interfering with the implanted device function
            3. Pacemakers
               a. Classical, one or more leads
               b. Newest intracardiac, “leadless”
            4. ICDs
            5. Depth electrodes
            6. Neurostimulators (including deep brain stimulators)
            7. Bone growth stimulators
iii. Passive implants/devices (specific examples follow)
   1. Wires/leads/sutures
   2. Special consideration/circumstances
      a. Copper 7/copper T
      b. Foreign bodies (bullets, shrapnel, BBs, etc.)
      c. Tattoos
         i. Thermal
         ii. Migration
      d. Foil backed (i.e., electrically conductive) medication patches
      e. Multiple adjacent or contiguous implants (e.g., skin staples, multiple dermal anchors, piercings)

b. Fixed Parameter Option: B Operating Mode

c. Healthcare worker implants

d. Device labeling and proper use of terminology
   i. MR Safe
   ii. MR Unsafe
   iii. MR Conditional

4. Pregnancy MR safety considerations
   a. Patient pregnancy issues
      i. Unenhanced
      ii. Enhanced
   b. Research subject pregnancy considerations
      i. Risk-benefit assessments we use in clinical scanning do not apply, as the individual undergoing the risk is not the same as the one receiving the potential benefit
      ii. Unenhanced
      iii. Enhanced
   c. Healthcare pregnancy issues
      i. Risk-benefit assessments we use in clinical scanning do not apply, as the individual undergoing the risk is not the same as the one receiving the potential benefit
5. Limits and standards
   a. IEC, FDA, ICNIRP
      i. Static field, movement in static field
      ii. Time varying gradients
      iii. RF
   b. Occupational exposure

6. Non-MR personnel in the MR environment
   a. Anesthesiologists
   b. Referring physicians (neurosurgeons, neurologists, cardiologists, etc.)
   c. ICU personnel (nursing, respiratory)
   d. Patient transport
   e. Security
   f. Housekeeping/maintenance
   g. Firefighters, police, first responders
      i. Training content, frequency
   h. Accompanying family/friends/guardians
   i. Prisoners
      i. House arrest bracelet
      ii. Handcuffs, other restraining device(s)

7. Screening considerations
   a. Standardization
      i. By whom?
      ii. Of whom?
      iii. How many times?
      iv. Written? Oral? Both?
   b. Ferromagnetic detection; pros and cons, advances (far fewer false positives)
   c. Standard conventional “airport style” metal detectors are NOT recommended
   d. Gowning considerations
      i. Decrease risks from ferromagnetic and thermal considerations
      ii. Whom? (patient? Accompanying family? Accompanying healthcare workers?)
      iii. How much? (i.e., what constitutes gowning? Top? Whole body? Underwear/socks?)
8. Handling codes in the MR environment
   a. Prospective designation outside of Zone IV (except anesthesia)
      i. Location
      ii. Events/steps to execute
   b. Prospective site design (oxygen, suction, location with ability to safely and reliably defibrillate)

9. 4 Zones concept
   a. Site access restriction for:
      i. Humans
      ii. Ferromagnetic devices/objects
      iii. Ferromagnetic devices/objects
          i. Ancillary equipment in Zone 4 (MRI scanner room)
   b. Site access restriction relative to:
      i. The MR magnet room/Zone IV
      ii. The quench vent exhaust port
   c. Signage
      i. Relative to the MR magnet room/Zone IV
      ii. Relative to the quench vent exhaust port
   d. Authority and responsibility for enforcement

10. Siting considerations for MR safety
    a. Defined at least in part by the patient population to be scanned (e.g., in-patient versus out-patient, pediatric versus adult, sedation, anesthesia and recovery, monitoring, how will codes be handled, etc. etc. etc.)
    b. Diagnostic versus interventional (intraoperative) care
    c. Hybrid scanners (PET/MR, etc.)
    d. Access control, line of sight from MR Technologist/Operator, etc. (4-zone integration)
    e. Siting of ferromagnetic detection units
    f. Patient screening areas
    g. Area for running codes
    h. Area for running induction/recovery (if/as applicable)
    i. Metal/ferromagnetic material storage/quarantine area (e.g., lockers)
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j. Site planning for gases, suction, etc. access
k. Proper quench venting pathways
   i. Design
   ii. Maintenance
   iii. The entirety of the cryogen vent pathway falls with Zone III definitions and as such requires physical restriction from inadvertent access by non-MR personnel, even though it may be physically removed from the MR suite itself

11. Infection control (cleaning, venting between patients, etc.)

C. Medicolegal implications of MR safety
   1. Legal foundations and building blocks
      a. Standard of care
         i. This is the basis of it all
         ii. Expectation of how another similarly trained individual would have behaved in the same clinical situation
         iii. HOWEVER, defined by the patient’s expectation
      b. Medical malpractice
         i. Breach of standard of care = Negligence
         ii. The breach of the standard of care was a proximate cause of an injury
      c. “Captain of the ship” doctrine for medical malpractice in US
      d. There can be multiple parties responsible/liable for an injury
      e. Vicarious liability
         i. NOT determined by who hires/fires the employee
         ii. If they respond to your guidance, you can be held vicariously liable for their actions/inactions