During an MR procedure, most of the transmitted RF power is transformed into heat within the patient’s tissue as a result of resistive losses. Not surprisingly, the primary bioeffects associated with the RF radiation used for MR procedures are directly related to the thermogenic qualities of this electromagnetic field. This review article discusses the characteristics of RF energy-induced heating associated with MR procedures, with an emphasis on thermal and other physiologic responses observed in human subjects. J. Magn. Reson. Imaging 2000;12:30–36. © 2000 Wiley-Liss, Inc.

Index terms: magnetic resonance imaging; bioeffects; safety; heating; radiofrequency

RADIOFREQUENCY (RF) ENERGY is nonionizing, electromagnetic radiation in the frequency range of 0–3000 GHz (1–4). The RF spectrum includes radar, ultra high frequency (UHF), and very high frequency (VHF) television, AM and FM radio, and microwave communication frequencies.

Research studies conducted over the past 35 years have indicated that exposure to RF radiation may produce various physiological effects including those associated with alterations in visual, auditory, endocrine, neural, cardiovascular, immune, reproductive, and developmental function (1–10). These biological changes are generally felt to occur due to RF energy-induced heating of tissues (1–10).

During MR procedures, the majority of the RF power transmitted for imaging or spectroscopy (especially for carbon decoupling) is transformed into heat within the patient’s tissue as a result of resistive losses (11–21). Not surprisingly, the primary bioeffects associated with the RF radiation used for MR procedures are directly related to the thermogenic qualities of this electromagnetic field (11–21).

RF radiation may also cause athermal, field-specific changes in biological systems that are produced without increase elevation in temperature (1,4,5,22). However, athermal effects are not well understood and have not been studied in association with the use of MR systems. Those interested in thorough discussions of this topic are referred to the extensive reviews by Adey (5) and Beers (22).

Prior to 1985, there were no published reports concerning thermal or other physiological responses of human subjects exposed to RF radiation during MR procedures. In fact, there was a general lack of quantitative data on thermal responses of human subjects exposed to RF radiation from any source. Previous investigations performed on this topic typically examined physiological responses to therapeutic applications of diathermy or thermal sensations related to exposure to RF radiation (1–4,23,24). Notably, these studies involved exposures of human subjects to RF energy that were limited or localized to a small regions of the body.

Although many investigations have been performed using laboratory animals to determine thermoregulatory reactions to tissue heating associated with exposure to RF radiation, these experiments do not directly apply to the conditions that occur during MR procedures, nor can they be extrapolated to provide useful information for various reasons (2,3). For example, the pattern of RF absorption or the coupling of radiation to biological tissues is primarily dependent on the organism’s size, anatomical features, duration of exposure, sensitivity of the involved tissues (eg, some tissues are more “thermal sensitive” than others), and a myriad of other variables (1,3,4,17,25). Furthermore, there is no laboratory animal that sufficiently mimics or simulates the thermoregulatory responses of an organism with the dimensions and specific responses to that of a human subject. Therefore, experimental results obtained in laboratory animals cannot be simply “scaled” or extrapolated to predict thermoregulatory or other physiological changes in human subjects exposed to RF radiation-induced heating during MR procedures (17,18,25).

Elaborate models have been devised to predict worst case scenarios of how human subjects may respond to the RF energy that is absorbed during MR procedures (26–28). However, a recognized major limitation of modeling is that it is difficult to account for the numerous critical variables (ie, the subject’s age, the amount of subcutaneous fat, the physical condition of the indi-
vidual, etc.) that can affect the thermoregulatory responses of a human subject.

Many individuals that are exposed to RF radiation during MR procedures have underlying health conditions (eg, hypertension, diabetes, cardiovascular disease, etc.) or are taking medication(s) (eg, beta-blockers, calcium channel blockers, vasodilators, vasoconstrictors, tranquilizers, sedatives, etc.) that can alter or seriously impair their ability to dissipate a heat load (29–37). More importantly, none of the models developed to predict thermal responses to RF radiation have ever been validated by experiments performed in human subjects or, more importantly, patients.

Several investigations conducted using human subjects have yielded extremely useful and important data with regard to thermoregulatory responses and other physiological reactions to RF radiation-induced heating during MR procedures. This article reviews and discuss these studies.

CHARACTERISTICS OF RF ENERGY-INDUCED HEATING

The physical dimensions and configurations of biological tissues in relation to the incident wavelength are important factors that determine the relative amount and pattern of RF energy absorbed during exposure to RF radiation (1–4). For example, if the tissue size is large in relation to the incident wavelength, RF energy is predominantly absorbed on the surface (1–4). If it is small relative to the wavelength, there is little absorption of RF power (1–4).

The most efficient absorption of RF energy occurs when the tissue is approximately 50% the size of the incident wavelength; this frequency of maximum absorption is known as the “resonant frequency.” Exposure to a resonant frequency of RF power is the most hazardous from a bioeffects standpoint because of deep and often uneven absorption patterns (1–4). Because of these factors, RF radiation-induced heating is considered to be a unique means of elevating the tissue temperature because of its ability to penetrate superficial tissues and directly heat internal sites of the body at certain wavelengths (2,3).

Tissue heating that results from the RF radiation used for MR procedures is primarily caused by magnetic induction, with a negligible contribution from the electric fields (11–20). Therefore, this ohmic heating of tissue during MR procedures is greatest at the surface or periphery and minimal at the center of the body of human subjects. Predictive calculations and measurements obtained in phantoms and in human subjects exposed to MRI support this pattern of temperature distribution (13).

The actual increase in tissue temperature caused by exposure to RF radiation is dependent on a variety of factors associated with the thermoregulatory system of the individual and the surrounding environment (2,3,14–18). In regard to the thermoregulatory system, when subjected to a thermal challenge, the human body loses heat by means of convection, conduction, radiation, and evaporation. Each of these mechanisms is responsible to a varying degree for heat dissipation, as the body attempts to maintain thermal homeostasis (2,3,25). If the thermoregulatory effectors are not capable of totally dissipating the heat load, then there is an accumulation or storage of heat along with an elevation in local and/or overall tissue temperatures (2,3,25).

As previously mentioned, various underlying health conditions may affect an individual’s ability to tolerate a thermal challenge. These conditions include cardiovascular disease, hypertension, diabetes, fever, old age, and obesity (29–35). Various medications (diuretics, beta-blockers, calcium blockers, amphetamines, muscle relaxers, sedatives, etc.) can also greatly alter thermoregulatory responses to a heat load. Notably, certain medications have a synergistic effect with respect to tissue heating if the heating is specifically caused by exposure to RF radiation (36).

The environmental conditions that exist in and around the MR system will also affect the tissue temperature changes associated with RF energy-induced heating. During an MR procedure, the amount of tissue heating that occurs and concomitant exposure to RF energy that is tolerable are dependent on environmental factors that include the ambient temperature, relative humidity, and air flow.

With respect to the environmental conditions of the MR setting, it has been proposed that, to counterbalance any excessive tissue heating that may occur during exposure to high levels of RF energy, patients should be “precooled” prior to performance of certain MR procedures. However, it should be noted that the subjective perception of human subjects to the environmental temperature depends on the gradient of temperature that is sensed by the peripheral thermoreceptors. Therefore, patients going from a cooler (ie, the “precooling” room) to a warmer environment (ie, the MR system) would probably be more uncomfortable. Preliminary data obtained during recently performed experiments support this contention (unpublished observations, 1994).

MR PROCEDURES AND THE SPECIFIC ABSORPTION RATE OF RF RADIATION

The thermoregulatory and other physiological changes that a human subject displays in response to exposure to RF radiation are dependent on the amount of energy that is absorbed. The dosimetric term used to describe the absorption of RF radiation is the specific absorption rate (SAR) (1–4). The SAR is the mass normalized rate at which RF power is coupled to biological tissue and is typically indicated in units of watts per kilogram (1–4). The relative amount of RF radiation that an individual encounters during an MR procedure is usually characterized with respect to the whole-body averaged and peak SAR levels (ie, the SAR averaged in 1 g of tissue).

Measurements or estimates of SAR are not trivial, particularly in human subjects. There are several methods of determining this parameter for the purpose of RF energy dosimetry in association with MR procedures (18–21). The SAR that is produced during an MR procedure is a complex function of numerous variables including the frequency (ie, determined by the strength of the static magnetic field of the MR system, with res-
onant frequencies producing the greatest effect), the type of RF pulse used (eg, 90° vs. 180° pulse), the repetition time, the type of RF coil used, the volume of tissue contained within the coil, the configuration of the anatomical region exposed, the orientation of the body to the field vectors, and other factors (18–21).

**ASSESSMENT OF THERMAL AND OTHER PHYSIOLOGICAL RESPONSES TO RF ENERGY-INDUCED HEATING**

Acquiring measurements of thermal and other physiological parameters in human subjects within the harsh electromagnetic environment of the MR system is not a simple task. The strength of the static magnetic field of the MR system can easily create missiles out of conventional monitoring devices because they usually contain ferromagnetic components (38–54). In addition, the static, gradient, and RF electromagnetic fields may adversely interfere with the proper operation of the monitor (38–41). In turn, the monitors themselves may produce subtle or significant imaging artifacts during operation by generating RF noise that can significantly distort the quality of the MR images (38–41).

Therefore, physiological monitors must be specially adapted or modified and then rigorously tested prior to use in the MR environment. Otherwise, the data pertaining to thermal and other physiological responses may be erroneous.

Currently, there are a variety of MR-compatible monitors, as well as other patient support devices that are commercially available for use in the MR environment (38–42). Every physiological parameter that is typically recorded in the critical care area or operating room setting may be obtained during an MR procedure, including heart rate, oxygen saturation, end-tidal carbon dioxide, respiratory rate, blood pressure, cutaneous blood flow, and, most importantly, body and skin temperatures (38–42).

For assessment of thermal responses during an MR procedure, volunteer subjects or patients have been continuously or semicontinuously monitored throughout the experimental procedures using several different types of devices. For example, sublingual pocket or tympanic membrane temperature (note that there is a good relationship between temperatures measured in the sublingual pocket or tympanic membrane and esophageal temperatures—an indicator of “deep body” or “core” temperature) has been obtained immediately before and after MR procedures using sensitive electronic thermometry or infrared devices (43–54). Skin temperatures have been measured immediately before and after MR procedures using highly sensitive and accurate infrared thermometry or thermographic equipment (43–53). Body and skin temperatures measured at multiple sites have been recorded before, during, and after MR procedures using a fluoroptic thermometry system that is unperturbed by electromagnetic radiation of all types, including static magnetic fields of up to 9.0 T (42). Heart rate, oxygen saturation, blood pressure, respiratory rate, and cutaneous blood flow, which are important physiological variables that can change in response to a thermal load, have been monitored before, during, and after MR procedures to assess the reaction of the thermoregulatory system of human subjects exposed to RF radiation-induced heating. All these parameters were obtained with MR-compatible devices that have been extensively tested and demonstrated to provide sensitive and accurate data (42–53).

**Thermal Responses to RF-Energy-Induced Heating**

As previously described, the increase in tissue temperature caused by exposure to RF energy during an MR procedure depends on multiple physiological, physical, and environmental factors. These include the status of the patient’s thermoregulatory system, the presence of an underlying health condition, the duration of exposure, the rate at which energy is deposited, and the ambient conditions within the MR system.

Although the primary cause of tissue heating during MR procedures is attributed solely to RF radiation, it should be noted that various reports have suggested that exposure to the powerful static magnetic fields used for MR procedures may also cause temperature changes (55,56). The mechanism(s) responsible for such an effect remains unclear. Nevertheless, the results of these previously published studies warranted the conduction of investigations in human subjects to determine the possible contribution of the static magnetic field to temperature changes that may be observed during an MR procedure.

Studies were performed in human subjects exposed to a 1.5 T static magnetic field to evaluate whether any thermal effect was produced on body and/or skin temperatures (57,58). The data revealed that there were no statistically significant alterations in any of the recorded tissue temperature or other physiological parameters (57,58). Furthermore, Tenforde (59) examined this phenomenon in laboratory rodents exposed to static magnetic fields of as high as 7.55 T and also reported no thermal effect. As far as the potential for production of heat by gradient magnetic fields is concerned, this is not believed to occur in association with conventional imaging parameters used for clinical MR procedures (15,19,20,22).

The first study of human thermal responses to RF radiation-induced heating during an MR procedure was conducted by Schaefer et al (60). Temperature changes and other physiological parameters were assessed in volunteer subjects exposed to relatively high, whole-body averaged SARs (approximately 4.0 W/kg). The data indicated that there were no excessive temperature elevations or other deleterious physiological consequences related to the exposure to RF radiation (60).

Several studies were subsequently conducted involving volunteer subjects and patients undergoing clinical MR procedures with the intent of obtaining information that would be applicable to the patient population typically encountered in the MR setting (43–50,52,54,61,62). The whole-body averaged SARs ranged from approximately 0.05 W/kg (ie, for MR procedures involving MR imaging using a transmit/receive head coil) to 4.0 W/kg (ie, for MR procedures involving the imaging of the spine or abdomen with a transmit/receive body coil)
(43–52, 54, 61, 62). These studies demonstrated that changes in body temperatures were relatively minor (ie, less than 0.6°C). While there was a tendency for statistically significant increases in skin temperatures to occur, these had no serious physiological consequence. Furthermore, there were no associated deleterious alterations in the hemodynamic parameters assessed during these investigations (ie, heart rate, blood pressure, and cutaneous blood flow).

Notably, studies have reported a poor correlation between body or skin temperature changes versus whole-body averaged SARs during clinical MR procedures. This finding is not unusual considering the myriad of variables that may alter thermal responses in a patient population. Therefore, the thermal reactions to a given SAR may be quite variable depending on the individual’s thermoregulatory system and the presence of one or more underlying condition(s) that can alter or impair the ability to dissipate heat.

An extensive research study was conducted in volunteer subjects exposed to an MR procedure with a whole-body averaged SAR of 6.0 W/kg (53). This investigation was performed in cool (22°C) and warm (33°C) environments to characterize thermal and other physiological responses to this high level of RF energy, since recently developed pulse sequences have very high SARs associated with their use (53). Notably, this is the highest level of RF energy that human subjects have ever been exposed to in association with an MR procedure.

The temperature of the tympanic membrane and six different skin temperatures were monitored along with heart rate, blood pressure, oxygen saturation, and skin blood flow (53). Measurements were obtained immediately before, during, and after exposure to RF energy. In the cool environment, there were statistically significant increases in the tympanic membrane, abdomen, upper arm, hand, and thigh temperatures as well as heart rate and skin blood flow. In the warm environment, there were statistically significant increases in tympanic membrane, hand, and chest temperatures as well as systolic blood pressure and heart rate. All the temperature increases recorded were within acceptable, safe levels. Of critical note is that these data indicated that an MR procedure performed at a whole-body averaged SAR of 6.0 W/kg can be physiologically tolerated by an individual with normal thermoregulatory function (53).

### RF ENERGY-INDUCED HEATING AND TEMPERATURE-SENSITIVE ORGANS

The testis and eye of human subjects have reduced capabilities for heat dissipation and may be injured by elevated temperatures (6, 7). Therefore, the testis and eye are primary sites of potentially harmful effects if exposure to RF radiation during an MR procedure is excessive (6, 7, 11–15, 17, 18).

Laboratory investigations have demonstrated that RF energy-induced heating may have detrimental effects on testicular function (eg, a reduction or cessation of spermatogenesis, impaired sperm motility, degeneration of seminiferous tubules, etc.) if the exposure level increases scrotal and/or testicular tissue temperatures between 38°C to 42°C (7). Scrotal skin temperatures (which are an index of intratesticular temperature (63)) were measured in volunteer subjects undergoing MR procedures at a whole-body averaged SAR of 1.1 W/kg (48). The largest change in scrotal skin temperature was 2.1°C, and the highest scrotal skin temperature recorded was 34.2°C (48). These temperature alterations were below the threshold known to impair testicular function (7, 48).

Excessive heating of the scrotum during an MR procedure could exacerbate a preexisting disorder associated with increased testicular temperature (eg, febrile illnesses, varicocelectomy, etc.) in patients who are already oligospermic, leading to temporary or permanent sterility. Therefore, additional studies designed to investigate these particular issues are warranted, particularly if patients are subjected to MR procedures using RF energy levels (ie, SARs) that are higher than those previously evaluated. This scenario is entirely possible considering the widespread clinical use of fast spine-echo pulse sequences that inherently have associated higher SARs compared with conventional spin-echo imaging techniques.

Dissipation of heat from the eye is a slow and inefficient process due to its relative lack of vascularization (6). Acute, near-field exposures of RF radiation to the eyes or heads of laboratory animals have been shown to be potentially cataractogenic as a result of the thermal disruption of ocular tissue (6).

An investigation conducted by Sacks et al (64) revealed that there were no discernible effects on the eyes of rats caused by MR procedures performed at RF energy levels that far exceeded typical levels used in the clinical setting. However, as previously indicated, it may not be acceptable to extrapolate data from laboratory animals to human subjects. For example, the coupling of RF radiation to the eye of a laboratory rat is obviously quite different from that for the eye of a human subject (ie, considering the size, shape, and tissue volume of each eye).

Corneal temperatures [corneal temperature is a representative site of the average temperature of the human eye (65)] have been measured in patients undergoing MR imaging of the brain using a transmit/receive head coil at peak SARs ranging up to 3.1 W/kg (46). The largest corneal temperature change was 1.8°C, and the highest temperature measured was 34.4°C. Another study examined corneal temperatures in patients with suspected ocular pathology who underwent MR imaging using the body coil to transmit RF energy and a special eye coil for RF reception (49). Peak SARs ranged from 3.3 to 8.4 W/kg. The highest corneal temperature measured in this investigation was 35.1°C (49).

Because the temperature threshold for RF radiation-induced cataractogenesis in animal models has been reported to be between 41 and 55°C for acute, near-field exposures (6), it does not appear that clinical MR procedures have the potential to cause thermal damage to ocular tissue. However, the effect of MR procedures on ocular tissue under conditions whereby higher SARs may be used remains to be determined.
MR PROCEDURES AND RF ENERGY-INDUCED "HOT SPOTS"

Theoretically, during the exposure to RF energy, “hot spots” (ie, excessive concentration of RF energy) may develop due to uneven distribution of RF power in association with restrictive conductive patterns (12,21,44,54). Under certain conditions, RF energy-induced “hot spots” may occur during an MR procedure that, in turn, generate thermal “hot spots.”

Because RF radiation is mainly absorbed by peripheral tissues, surface thermography has been used to study the heating pattern associated with MR procedures performed using relatively high whole-body averaged SARs (44,54). Fortunately, the findings of this research demonstrated that there was no evidence of surface thermal “hot spots” related to the use of MR procedures in human subjects (44,54). Apparently, the thermoregulatory system responds to the thermal load induced by RF energy by evenly distributing the heat where RF radiation-induced “hot spots” may occur (44,54).

However, there is a possibility that internal thermal “hot spots” may develop during an MR procedure. This issue needs to be thoroughly examined in human subjects undergoing MR procedures.

Shuman et al (66) reported that significant temperature increases occur in internal organs of laboratory dogs produced during MR imaging performed using relatively high SARs. Therefore, these findings suggest that internal thermal “hot spots” may occur in association with MR procedures. The investigation by Shuman et al (66) was conducted using anesthetized animals and, as such, is unlikely to pertain to conscious, adult human subjects because of the previously discussed factors related to the physical dimensions of the animals and the fact that an anesthetic agent was used, which may significantly effect thermoregulation. Additionally, the thermoregulatory systems of these two species is quite dissimilar. Nevertheless, data obtained by Shuman et al (68) may have important implications for the use of MR procedures in pediatric patients because this patient population is typically sedated or anesthetized for MR examinations and the physical dimensions of the laboratory dog are comparable to those of the pediatric population. Obviously, additional research is required to examine this issue further.

HEATING OF METALLIC IMPLANTS BY RF ENERGY AND OTHER MECHANISMS

The MR procedure-related heating of implants, materials, devices, and objects of a variety of sizes, shapes, and metallic compositions have been studied using ex vivo testing techniques (67–85). In general, these data indicated that only minor temperature changes occurred in association with MR procedures involving metallic objects (67–85). Notably, there has never been a report of a patient being seriously injured as a result of excessive heat developing in a metallic, implanted device. However, additional investigations are warranted to examine the effect of RF energy-induced heating for MR systems operating at ultra-high field strengths (>2.0 T; see below).

First-, second-, or third-degree burns have occurred in association with devices, mainly monitoring systems, that were not used according to manufacturers’ recommendations (68,83,84). The actual physical factors responsible for these particular hazards have not been identified or well characterized (ie, the imaging parameters, specific gradient field effects, size of the loop associated with excessive heating, etc.).

FUTURE STUDIES

Several of the newer pulse sequences and imaging techniques that have been developed use relatively high levels of RF energy during their implementation (86–88). For example, using fast spin-echo (FSE) and magnetization transfer contrast (MTC) pulse sequences on high-field-strength MR systems may require levels of RF energy that easily exceed whole-body averaged SARs ranging between 4.0 to 8.0 W/kg (ie, higher than the level currently recommended by the United States Food and Drug Administration).

In general, FSE pulse sequences are hybrids of rapid acquisition relaxation enhanced (RARE) pulse sequences and use higher amounts of RF energy compared with conventional spin-echo sequences (86,88). This is primarily due to the high density of 180° refocusing pulses used for these pulse sequences (86). MTC pulse sequences involve selective and continuous saturation of macromolecular protons by applying off-resonance RF pulses during the implementation of the technique (87). Again, the RF power deposition is of considerable concern when MTC is performed using a high-field-strength MR system (87). This is particularly a problem during MR imaging of large body parts that require the transmission of RF energy using the body coil. Because both the FSE and MTC pulse sequences appear to offer important clinical advantages over conventional pulse sequences, studies are currently examining the human thermoregulatory responses to SARs that are higher than those that have been evaluated in recent years.

Other MR procedures in which RF radiation-induced heating may cause appreciable increases in tissue include H-1 decoupling, Overhauser enhancement, and burst sequences used in MR spectroscopy (16). Again, these techniques are particular problematical using high-field-strength MR systems. Therefore, MR procedures that utilize these techniques will need to be carefully evaluated in the future to determine the relative safety of these applications in patient populations.

There are now several MR systems operating with static magnetic field strengths of 3.0 and 4.0 T (89–90). Notably, there is also an 8.0 T MR system in existence, which is the most powerful whole-body scanner in the world (91,92). These specialized MR systems are used to perform imaging procedures, functional studies, and spectroscopy applications in human subjects (89–91).

For a given application, the ultra-high-field MR systems are capable of generating RF power depositions that greatly exceed those associated with a 1.5 T MR system. Therefore, investigations are needed to evaluate thermal responses in human subjects to assess...
potential thermogenic hazards for these powerful MR devices. Finally, additional studies are required to evaluate patients with conditions that impair heat dissipation. An on-going effort is needed to characterize thermal and other physiological responses for various patient groups to ensure the safe use of MR procedures that use high levels of RF energy.

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