Safety of Fetal MRI Scanning

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Contents

Abstract

› MRI uses a variety of different magnetic fields to produce images. These all interact with the body in some way. This chapter considers how they interact with the fetus in particular, and whether they pose any risk to the fetus. It also considers practical aspects of MR scanning that can cause problems for the mother or fetus.

1 Introduction

This book demonstrates that fetal magnetic resonance imaging (MRI) can provide major benefits in the management of pregnancy and fetal development. However, given that many MRI developments are relatively recent, it remains important to balance these benefits against any possible risks that MRI may pose to the fetus. As for all subjects being scanned with MRI, there are three areas of concern with regard to safety of the fetus and indeed that of the mother and the MR worker. These are the static field used to polarize the nuclear magnetization and provide high signal-to-noise ratio in the MR data, the time-varying (approximately kilo Hertz) magnetic fields arising from the switched magnetic field gradients used for image encoding, and the radiofrequency (RF) fields used to excite the nuclear spin signal to obtain a signal. Each

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of these fields will be considered in turn in terms of the possible risks to the health of the fetus. Following that, reviews of studies into outcomes of children scanned as fetuses will be presented. Finally, some other factors that could affect the well-being of the fetus will be discussed.

2 Static Field

In the MR safety literature, the term "projectile effect" is often used to describe the acceleration of ferromagnetic materials within the vicinity of the stray field of the magnet, and it is unquestionably the case that this effect is the primary danger associated with MRI. Accelerated metal objects can obviously cause serious injury and this risk is likely to be somewhat increased when scanning pregnant women because it is likely that other healthcare professionals and partners may accompany the subject to the scan and even into the scan room. However, this risk should be mitigated by careful staff training, scanner room layout, and adherence to appropriate local working rules (Kanal et al. 2002, 2004).

Associated with this is the risk of torques or translational forces on metal objects in the body, or the risks to the functioning of medical implants. With some exceptions (body piercing), these risks are less likely to be an issue in young pregnant subjects than in older patients, but nonetheless all subjects must be carefully screened to determine whether they have any foreign objects in their body.

Large (>2 T) static magnetic fields (or movements in such fields) are known to affect sensory organs, leading to a perception of vertigo, a metallic taste in the mouth and in some instances phosphenes, although these effects are apparently transient and not associated with any risks to health (Glover et al. 2007). These effects are most pronounced when moving rapidly through a spatially varying magnetic field, and so as the mother is likely to be moving slowly when climbing onto the bed these effects are unlikely to be a problem for a pregnant woman at normal clinical field strengths. At very high fields (>16 T) it is possible that the force on a blood (a conducting fluid) moving in a magnetic field (the magnetohydrodynamic effect), might become significant, initially leading to compensatory changes in blood pressure in the adult, but there is no consistent evidence that any clinically significant change can be detected at the field strengths currently used (Kinouchi et al. 1996). Therefore, this will also not be a problem for the fetus at the field strengths currently used, though on going to higher field strength it should be noted that the fetus may be more sensitive to this effect than the adult for a number of reasons. First, the fetus can be lying randomly orientated with respect to the direction of the static field, and hence, unlike the adult in most current scanner configurations, it could be aligned in such a way that the direction of flow is perpendicular to the magnetic field (which is the worst-case scenario that was assumed in the study by Kinouchi et al.) Furthermore, the fetus has a similar aortic blood flow velocity to the adult (Marsal et al. 1984), which will determine the force on the blood, but has a somewhat lower blood pressure so any compensatory action may need to be relatively greater.

There have been a number of reviews of the effects of static fields on embryo development over the last few years. There is evidence that magnetic fields can alter the early division of the frog embryo probably due to variations in the magnetic susceptibility of the different components of a cell involved in division, but this effect does not persist to impede later development (Denegre et al. 1998). There have been a number of studies suggesting that magnetic fields can interfere with the chick embryo development, but these effects are less consistently reported in mammals (HPA 2008; ICNIRP 2009a, b). Overall, it is concluded that no adverse effects have been consistently demonstrated but that more studies are required particularly at fields about 1 T.

There is no consistent evidence that magnetic fields are mutagenic, although there are a few studies suggesting that magnetic fields may act synergistically with other mutagenic agents such as x-rays (Nakahara et al. 2002) or chemicals. The mechanism for such an interaction has not been elucidated but could be related to altered DNA repair mechanisms in a strong magnetic field.

3 Gradients

The gradients used in MRI are varied with time during the scanning session, and hence induce electric currents within the human body, which vary at approximately 1 kHz. It is well known that rapid changes or large field gradients can cause peripheral nerve stimulation (PNS) in adults, and this occurs well below the threshold at which cardiac defibrillation occurs. The PNS thresholds for a scanner are generally determined empirically in adults, and there is a possibility that the different geometry of a pregnant woman could lead to an increased risk of PNS in certain circumstances, although this would be unpleasant rather than risky at the levels obtained on a clinical scanner, and extremely unlikely if the scanner is run in the international electrotechnical commission (IEC) Normal exposure Level. The fetus is contained within the body where the induced currents will be lower. Nonetheless, it is sensible to restrict scanning to the Normal level to reduce the risk of PNS in the mother.

However, a more significant concern is that the gradients are also responsible for the loud acoustic noise associated with MRI that can reach 120 dB_A. Because of this high noise level, all subjects should be advised to wear ear protection while being scanned, but there is a concern whether the sound intensity level could be damaging to the fetal ear. There are two routes for noise transmission to the fetus, airborne noise transmitted through the maternal body wall, and mechanical vibrations transmitted to the fetal ear because the mother is lying in contact with (is mechanically coupled to) the scanner bed. However, the noise level reaching the fetal cochlear is significantly reduced because the fetus is insulated by the mother's abdominal wall and amniotic fluid which attenuate the noise in a frequency-dependent manner (higher frequencies are attenuated, lower frequencies can be somewhat amplified) and because the fetal ear is filled with amniotic fluid preventing the normal amplification of sound by the ear (Glover et al. 1995; Richards et al. 1992). Furthermore, the sound exposure is relatively brief compared to typical occupational sound exposures. Therefore, it is not expected that acoustic noise will be a significant problem for fetal hearing. It should be noted that the noise levels involved certainly exceed noise levels that, if applied persistently through pregnancy, can lead to poor pregnancy outcome, presumably due to maternal stress (Etzel et al. 1997).

To reduce fetal and maternal noise exposure, the mother should be given adequate hearing protection herself and should be mechanically isolated from the bed by using dense mattresses, and loud pulse sequences should be avoided if alternatives exist. The acoustic noise is expected to increase with magnetic field strength, although in practice it is also significantly affected by the design of the scanner and couch and also by the design of the scanner hall.

4 Radiofrequency (RF) Fields

The established risk associated with RF fields is that of heat deposition, both global heat load and focal heating potentially leading to local burns. Heating is a particular concern for fetuses since temperature rises are known to be teratogenic (Edwards 2006). There have been a few experimental studies of MRI heating of the fetus, for instance measuring the temperature rise in the uterus of a pregnant pig. These studies found no change in temperature for the sequences used at the time (Levine et al. 2001).

It should be noted that the most significant source of RF burns in the adult is due to contact with extraneous electrical conductors (including metal implants, ECG leads, and RF coils leads), close contact with the RF coils, and conduction loops setup through the skin (e.g., by allowing skin of the shins or thighs to touch). None of these sources of localized burning are likely to be a problem for the fetuses.

The models of RF deposition used to control the RF output of the scanners are generally based on models of the nonpregnant adult, and so recently there have been a number of studies aimed at modeling typical RF deposition (Specific Absorption Rate, SAR) within the fetuses and pregnant mother from MR scanners (Hand et al. 2006; Shamsi et al. 2006). These studies generally agree that the highest local peak of SAR is to be found in the mother with the ratio of fetal peak SAR to maternal peak SAR increasing with field strength and that maternal local SAR limits will be exceeded if the scanner is only set to limit whole body exposure. However, SAR is not really the parameter of interest; the biologically important parameter is temperature rise.

It is difficult to predict the fetal temperature rise for a given SAR from the standard models applied to adults since the fetal and maternal circulations are independent of each other. Adult limits to RF power deposition assume that there are good routes for heat loss via the skin (that the scanner bore temperature is less than 24°C, that the humidity is less than 60%, and that the subject is not covered with blankets) whereas this route is impaired for the fetus since it is contained within the mother's abdomen which is at 37°C. This means that the only route for heat loss from the fetus is across the placenta, and to a lesser extent by conduction through the amniotic fluid (Gowland and De Wilde 2008). Fortunately, Hand et al. (2010) have recently attempted to account for this by modeling the temperature rise in the fetus due to RF exposure, and their results suggest that if the scanner is operated in the IEC normal mode (<2 W/kg whole body exposure) then the fetal SAR and temperature rises will be within international safety limits, but in case of a whole body SAR exposure of 2 W/kg for periods of 7.5 min, the fetal temperature may rise above 38°C. Therefore, it would seem unwise to scan fetuses above the Normal SAR level until further information becomes available. It would also be sensible to design fetal imaging protocols to limit fetal temperature rise by interleaving the higher SAR sequences (e.g., HASTE) with lower SAR sequences (e.g., EPI).

Unfortunately, rapid imaging sequences are required to reduce the impact of fetal motion on image quality, such as half fourier acquisition single shot turbo spin echo (HASTE) and even balanced turbo field echo (bTFE) tend to be high SAR sequences, although with more rapid acceleration factors becoming available with 32 channel abdominal or pelvic coils, this may become less of a problem. In our lab as a precautionary measure, we never exceed the first controlled level of RF exposure when scanning fetuses. A practical consequence of this is that we have only scanned at 1.5 T and not attempted to scan at 3 T since our experience suggests that this will only be achieved successfully with our current hardware by going to the first controlled level.

5 Outcome Studies

There are disappointingly few of studies following up fetuses exposed to MRI in utero. There have been a number of studies of fetal well-being during MRI procedures, monitored using MR compatible cardiotocograph (CTG) systems. These studies showed no evidence that MRI changed the fetal heart rate or fetal movements (Poutamo et al. 1998; Vadeyar et al. 2000; Michel et al. 2003). A study of the birth weight of infants scanned with echo planar MRI at 0.5 T (which therefore had relatively low RF exposure but relatively high noise level exposure) showed that there was no evidence of MRI causing reduced fetal growth; there was some evidence of earlier delivery for the fetuses scanned with MRI, but this was attributed to increased intervention in the group of subjects who were scanned (Myers et al. 1998). When the same infants were followed up at 9 months, the only differences found compared to the control group were a small decrease in length and a small increase in gross motor function (Clements et al. 2000). A separate group of fetuses who had similar exposures were followed up at 3 years, and found no effects of MR exposure (Baker et al. 1994). In a study of children aged up to 9 years old who had been scanned as fetuses, no adverse effects of MRI scanning could be observed (Kok et al. 2004). There have been few studies of the pregnancy outcomes of MR workers, although an early study found no major reproductive hazard associated with MRI work (Kanal et al. 1993).

One common question is how early in gestation can the fetus safely be scanned? There is no data on the risks of exposure during the first trimester though it is probably sensible to avoid scanning in that period since the fetus is more vulnerable to teratogenic insults during that period. Furthermore, heat loss may be even more compromised before placental blood flow becomes properly established.

6 Other Issues Related to MR Scanning and the Well-being of the Fetus

Finally, it is not only the magnetic fields of an MR scanner that will impact on the well-being of the fetus and mother during an MR scan. Obviously, it is important to avoid any unnecessary stress for the mother of undergoing a fetal MRI scan, and as with all clinical procedures, this can be mitigated by careful subject handling (Duncan et al. 1996).

It is also important to bear in mind the relatively high risk of aortocaval compression if the mother lies flat on her back when heavily pregnant. Aortocaval compression causes hypotension to the mother and makes her feel unwell and nauseous and also leads to reduced uteroplacental blood flow. Ideally, subjects should be scanned in the left lateral position, but this is rarely feasible. However, simply elevating the right hip by 15–20 cm generally eliminates the problem. Unfortunately, for most scanner designs this lifts the mother away from the RF coil. The mother must be closely monitored during scanning (via the intercom) to ensure she is not experiencing this symptom.

There is some evidence that some MR contrast agents can cross the human placenta and reach the fetus (Brunelli et al. 2008). In the light of the recent evidence that MR contrast agents are associated with nephrogenic systemic fibrosis (NSF) it would seem prudent to apply the utmost caution before using MR contrast agents in pregnancy, considering in particular the stability of the chelate. Toxicity tests in embryos must consider the biological half-life of the contrast agent in the human amniotic sac.

In conclusion, there have been a number of recent reviews of the effects of MRI and its associated fields on fetal development, which have concluded that there is no apparent risk to human fetal development (Juutilainen 2005). Although it is important to be extremely careful when undertaking any procedure on a fetus, there are no apparent risks associated with fetal MRI, and this procedure must be balanced against the potential advantages of undertaking the scan.

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