Exposure of an individual working in the MRI environment

P&S: MAGNETIC FIELDS IN DAILY LIFE

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1 Introduction

The goal of this report is to examine the exposure of individuals working in the MRI environment as well as finding out whether such a surrounding poses any serious health risks.

However, before elaborating on our results, we first want to stress why we decided to sign up for this class and consequently why we wanted to broaden our knowledge about magnetic fields. For us, the primary source of motivation was to better understand everyday life. Magnetic fields are pretty much everywhere around us[1] and more often than not we do not give much thought to them, simply because they have become an integrated part of our lifestyles. While it is out of doubt that such sources (e.g. smartphones, kitchen appliances, transformer stations etc.) are essential to our lifestyles, we rarely ask ourselves what price we are paying for these amenities. So, our initial motivation for measuring magnetic fields was to determine their magnitude in different objects and eventually find out whether the obtained values imposed any health risks.

Yet, over the course of the first couple of classes, we decided to shift our focus a little bit. As we have noticed, previous student groups have already thoroughly investigated magnetic fields in connection to household devices which made us realize that we would prefer to take a path less travelled. This got us thinking about where potential health risks due to magnetic field exposure would have the most severe consequences. And the answer to that was quite simple: the hospital. When being seriously ill, practically all patients receive supportive medical equipment which runs on electricity and therefore, as already stated, magnetic fields can be measured. Since these people's immune system is already drastically weakened, an additional health risk due to very high exposure would be fatal. Unfortunately, we were not granted permission to investigate this question. However, we were reluctant to give up on the idea of conducting our measurements at the hospital, because we felt that gathering our data in this environment could provide us with valuable insights. And then we suddenly came up with a new idea. What if we could make our measurements at the MRI - Centre at the University of Zurich? This way we would be able to follow our core interest, while still respecting the hospital's guidelines. However, since we could only measure the static magnetic field, we restricted ourselves to examining the exposure of an individual working in this environment rather than focusing on patients since they are exposed to two additional components which will be discussed in more detail in the third chapter.

The second chapter serves as an introduction to the physics behind an MRI-scan, as well as presenting the setup and procedure of our measurements. In the third chapter we want to give an overview of our results as well as establishing a link to potential health problems which is then followed by a short summary of our work.

[1] Precisely speaking, it is electromagnetic fields to which we are constantly exposed to, since where there is electricity, electric and magnetic fields go hand in hand. However, in this report we shall focus solely only the magnetic field.

2 Theory & Setup

2.1 Exposure Limit Values

The exposure limit values specified in the Ordinance on Protection against Non Ionizing Radiation (ONIR) protect the population against scientifically established acute effects of strong electric and magnetic fields. For the public electricity supply, these are 5 kV/m for the electric field and 100 µT (1 Gs) for the magnetic flux density. The installation limit value for the magnetic flux density is 1 µT (0.01 Gs) at full load. The occupational exposure limit value for low-frequency magnetic fields is 500 µT (5 Gs) and thus complies with the recommendations of the ICNIRP. [11][16]

2.2 Working Principle of MRI

Magnetic resonance imaging (MRI) is an imaging technique used to create pictures of the anatomy of a patient. It is a medical application of nuclear magnetic resonance (NMR). [1]

To perform a measurement, the MRI scanner forms a strong magnetic field around the area to be imaged. First, energy from an oscillating magnetic field is temporarily applied to the body of the patient at the right resonance frequency. The excited hydrogen atoms emit a radio frequency signal, which is measured by a receiving coil. This radio signal may be made to encode position information by varying the main magnetic field using gradient coils. These coils are rapidly switched on and off and create the characteristic repetitive noise. The radio signal has a frequency range from 5 to 350 MHz, which depends on the magnetic field. Radio frequencies of 64 MHz for 1.5 T and 128 MHz for 3 T are widely used. [2][3]

The main components of an MRI scanner are:

- the main magnet, which polarizes the sample
- the shim coils for correcting shifts in the homogeneity of the main magnetic field
- the gradient system which allows to localize the MR signal
- the RF system, which stimulates the sample and receives the resulting NMR signal.

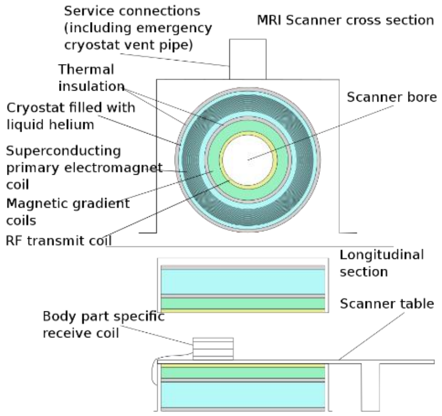

Figure 1: Schematic of construction of a MR scanner [3]

MRI is in general a safe technique. As MRIs use powerful magnets, it can cause magnetic materials to move at great speeds. Contraindications include most cochlear implants and cardiac pacemakers, shrapnel, and metallic foreign bodies in the eyes. [2]

2.3 Source of Static Magnetic Field

In this project, we focus on the main magnet, which is the largest and most expensive component of the scanner. The field strength of the magnet is measured in tesla (T). Clinical magnets generally have a field strength in the range of 0.1 T to 3.0 T and the majority operate at 1.5 T. There are research systems available up to 9.4 T for human use and 21 T for animal systems. [2][3]

MRI requires a magnetic field that is both uniform and strong. The straightness of the magnetic lines within the centre of the magnet needs to be near-perfect. Inhomogeneities in the field strength should be less than 3 ppm in the scan region. The magnetic field is very similar to a cylindrical coil with its axis of symmetry through the centre. Most clinical magnets are superconducting magnets, which require liquid helium to be cooled to 4 K (-269 °C). The construction is extremely costly, and the cryogenic helium is expensive and difficult to handle. [2][3]

The magnetic field strength is an important factor for the image quality. Higher magnetic fields permit higher resolution or faster scanning as they increase signal-to-noise ration. A field strength of 1.5 T is a good compromise between cost, safety and performance for image resolution. [2][3]

2.4 Measurement Setup

The Magnetic Resonance (MR) User Lab provides access to MR scanners to institutions and research groups of the University Zurich and ETH Zurich, the University Hospital Zurich and external groups. The MR User Lab offers access to three human MRI scanners.

One laboratory is equipped with a Philips Achieva 7T. This is a State-of-the-art MRI scanner with ultra-high magnetic field strength (7 tesla) for increased image quality, contrast and resolution. Coils are available for brain, knee, muscle and cardiac applications. [4] It is located at the MR Centre South of the University Hospital Zurich.

The area within the shielding has a surface of approx. 40 square metres. The shielding is made from 400 t iron. [5] The magnetic space is surrounded by a current-carrying grounded Faraday cage that blocks high-frequency electromagnetic signals.

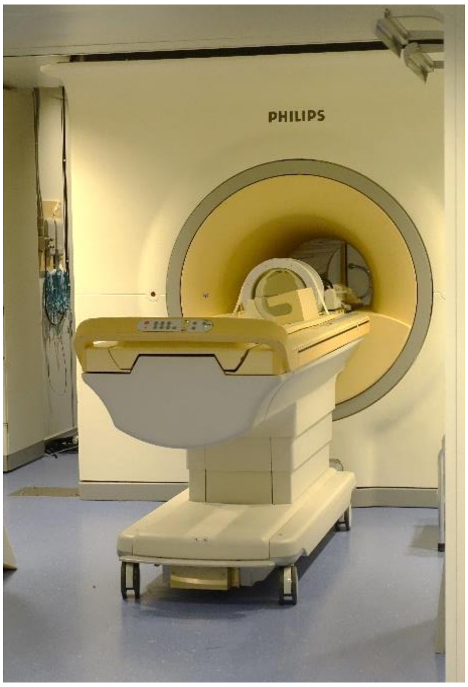

Figure 1: Philips Achieva 7T

2.5 Measurement Procedure

The MRI Philips Achieva 7T with a static magnetic field of 7 T was selected as the measurement object. The measurements were carried out with the ExpoM magnetometer from Fields at Work. This small device allows to track personal exposure to extremely low frequency magnetic fields. It provides an integrated data logger and a smartphone app with real-time data streaming.

In order to generate a spatial image of the magnetic field, a measuring-grid on the floor was created. Adhesive tape was used to mark points at a distance of 61.5 cm in both the examination- and the preparation-room. The magnetic field is assumed to be symmetrical so that only one side of the surrounding area is considered. The measuring points are located at zones where the use of the measuring device is permitted and reasonable.

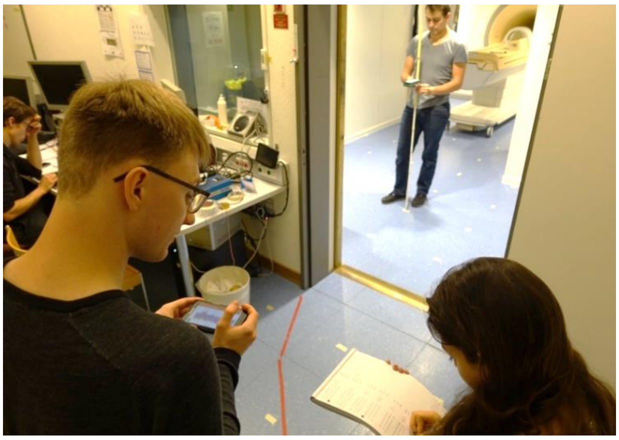
Figure 2: Measurement set-up

This means that the minimum distance was determined by two factors. The ExpoM measuring device must not be attracted to the static field. In addition, the built-in sensors should not reach saturation, which is the case at 45 mT.

In the vertical direction, measurements were taken at distances of 80 cm, 120 cm and 160 cm from the ground. The height of 120 cm corresponds exactly to the centre of the MRI. The height of 80 cm was not fallen below, because there are fields created by the shielding, which could destroy the magnetometer.

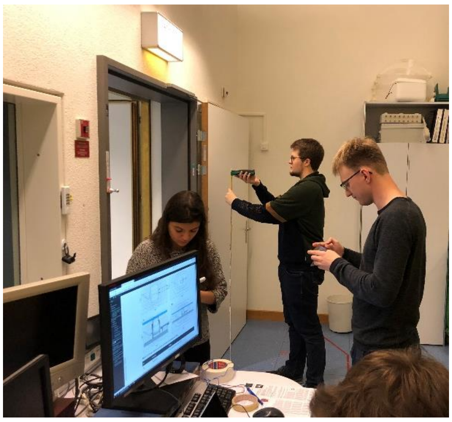

Figure 3: Measurement set-up

Since electronic devices such as computers, smartphones and cameras could be damaged by the strong magnetic field of the MRI [6], the measurements were triggered via the smartphone and its WLAN connection to the magnetometer. This allowed a direct control whether the measurement had been taken correctly. At least two measurements were carried out for each height position, so that the average can be determined during the evaluation.

2.6 Mu-Metal-Box

In some cases, certain areas or equipment in the immediate vicinity of a strong field source may be affected or even harmed by the field. [7] If it is not possible to change the location, a shielding must be used.

Mu-metal is a nickel-iron soft ferromagnetic alloy with very high permeability, which is used for shielding sensitive electronic equipment against static or low-frequency magnetic fields. Magnetic shielding made with high-permeability alloys works not by blocking magnetic fields but by providing a path for the magnetic field lines around the shielded area. The best shape for shields is a closed container surrounding the shielded space.

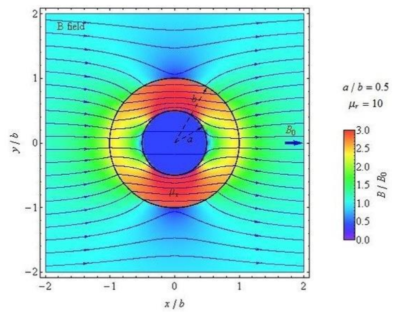

Figure 4: Mu-Metal generic field map

Mu-metal typically has relative permeability values of 80’000-100’000 compared to several thousand of ordinary steel. It requires heat treatment after it has its final form – annealing in a magnetic field in hydrogen atmosphere increases the magnetic permeability about 40 times. The annealing alters the material’s crystal structure, aligning the grains and removing some impurities. Bending or mechanical shock after annealing may change the material’s grain alignment and its permeability.

The effectiveness of mu-metal shielding drops off at both low field strengths and, due to saturation, at high field strengths. To avoid this, mu-metal shields are often made of multiple enclosures one inside the other, each of which successively reduces the field inside it. [15]

The measurements with the mu-metal-box were carried out in the preparation room at approx. 9 m from the MRI so that it is not attracted by the field. Two series of measurements, one without cover and one completely closed, were carried out at all three heights.

3 Results

The first step was to copy the measurements from the magnetometer to the computer using the ExpoM utility and validate them according to the frequency spectrum. Some measurements did not capture the static field, but the pumping process of helium, which results in different peaks in the frequency domain.

To analyse the data, the measured values (in µT) were transferred to an excel-file. Since the static field was considered, only the DC component is important for the analysis. For each coordinate point, several measured values were collected so that the average field strength per component (x, y, z) and the absolute value were calculated. In order to visualize the exposure in the vicinity of an MRI, the data has now been processed to plots using MATLAB.

3.1 Overview Measurements

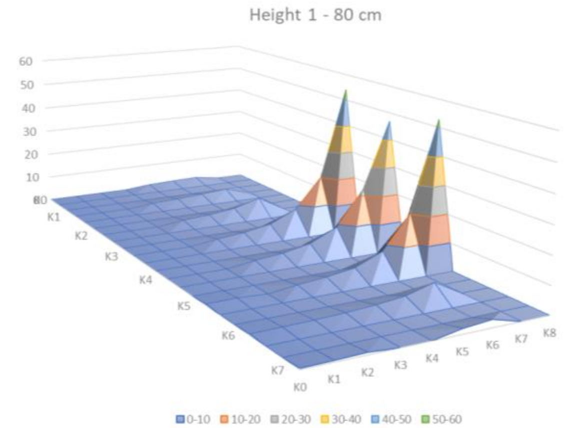

Figure 5: Field strength of MRI

The plot on the left shows the field strength as an absolute value of all three components for the height 80 cm. We see that the field drops very rapidly. The points on the centre axis tend to be smaller than the others. We have a maximal field strength of up to 541 Gs (54.1 mT). This is measured at a distance of approx. 4.2 m from the centre of the MRI.

3.2 Plan View

First, the field coursey in the vicinity of the MRI was evaluated. The field strength is given as the absolute value of all three components. Two different plots were made for each measuring height. It should be noted that the magnetometer is theoretically limited to 45 mT (450 Gs) by saturation. This saturation is reached at a distance of approx. 4 m from the centre of the MRI. The first plot shows a more detailed plan view up to the 50 Gs line. The second plot shows the whole measuring range including the 5 Gs line.

Plan view of magnetic field lines at a height of 80 cm

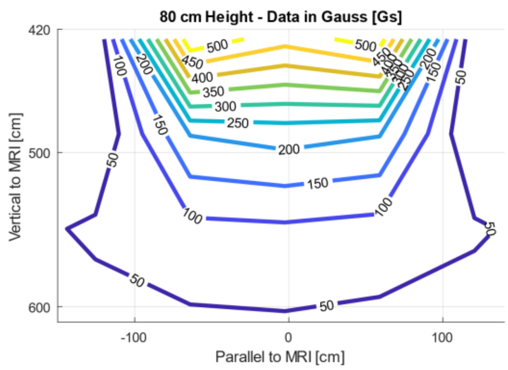

Figure 6: MRI field map at height of 80 cm 50 Gauss upwards

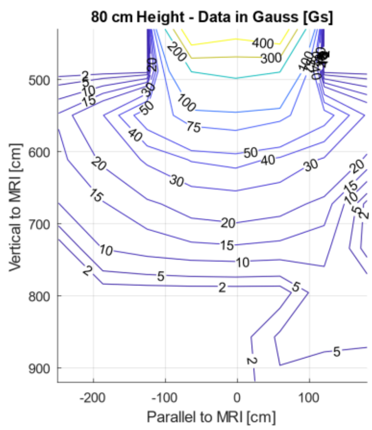

Figure 7: MRI field map at height of 80 cm

Plan view of magnetic field lines at a height of 120 cm

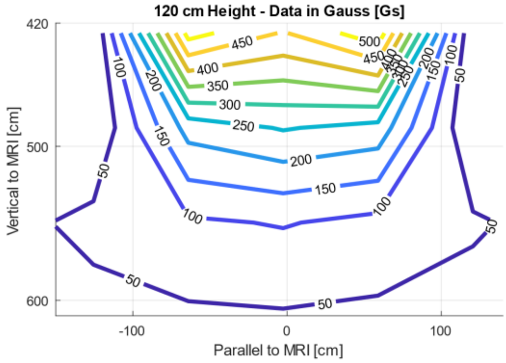

Figure 8: MRI field map at height of 120 cm
50 Gauss upwards

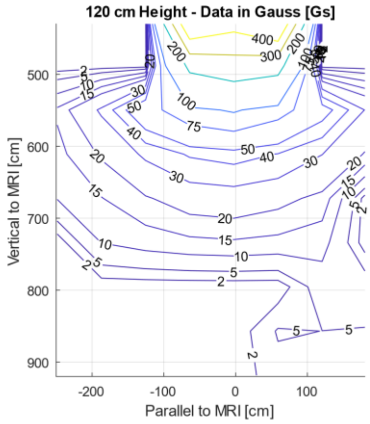

Figure 9: MRI field map at height of 120 cm

Plan view of magnetic field lines at a height of 160 cm

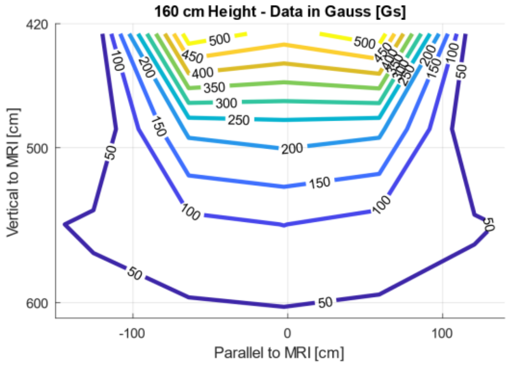

Figure 10: MRI field map at height of 160 cm
50 Gauss upwards

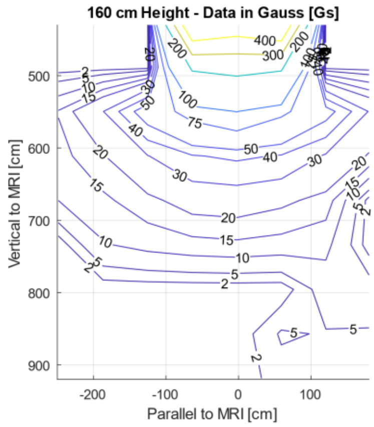

Figure 11: MRI field map at height of 160 cm

The plots show a very similar field line course for all three measurement heights. It can be observed that the field strength decreases very quickly with growing distance. It is symmetrical to the centre axis of the MRI. The highest field strength of up to 541 Gs (54.1 mT) is measured at points at a distance of approx. 4.2 m from the centre of the MRI. One can see that the shape of the field corresponds to a coil, because the points left and right to the centre axis have a higher field strength than the centre ones.

The 50 Gs (5 mT) has a distance of about 6.2 m to the MRI. The 5 Gs (0.5 mT) has a distance of about 9.2 m. The plots show that the actual measured distances correspond to the simulated distances marked in the blueprint.

In Switzerland, SUVA guidelines based on ICNIRP recommendations apply to workplace exposure to electromagnetic fields. The ICNIRP recommendations allow exposure of head and torso to static magnetic fields up to 2 T and of extremities up to 8 T. In controlled environments, such as an MRI device, the head and torso may also be exposed to up to 8 T, provided employees are encouraged to move as slowly as possible. [11][16]

The limit value for the static magnetic field to which a part of the body of a pregnant woman may be exposed is 400 Gs (40 mT). If pregnant women nevertheless have to enter the magnetic zone of an MRI, the 200 Gs (20 mT) line must be marked on the floor. This line must not be crossed. In order to ensure that the hands of pregnant women are not even exposed to the 400 Gs (40 mT) fields, the 200 Gs (20 mT) line runs with a safety distance.

With the values measured here, the 400 Gs (40 mT) line must be drawn at a distance of 4.5 m and the 200 Gs (20 mT) must be drawn at 5 m. As far as the exposure of researchers is concerned, it can be shown that the field strength at the control console (distance approx. 9 m) lies between 2 Gs (0.2 mT) and 5 Gs (0.5 mT). This field strength is therefore just below the occupational exposure limit value of 5 Gs, but clearly above the ONIR value of 1 Gs and the installation limit at full load. [16]

One sees that for this kind of representation one can do without a measurement of three different heights. The resolution of the plot would be improved if the measuring-grid was denser and more expanded in distance, so if more measurement points were considered closer together. This is especially true for the points very near to the MRI, where the field strength decays very fast.

3.3 Cut perpendicular to MRI

Second, three cuts perpendicular to the MRI were plotted. They help to illustrate how the field propagates in 3D. The averaged x- and z-components were used for the visualizations. Plots at three different distances at 4.2 m, 5.4 m and 6.6 m have been made.

Cut perpendicular to MRI at a distance of 4.2 m

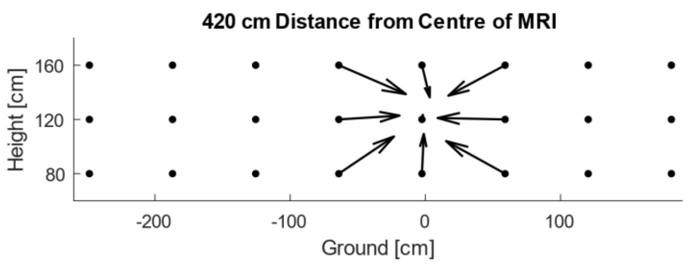

Figure 12: Field strength of MRI at 420 cm distance from MRI

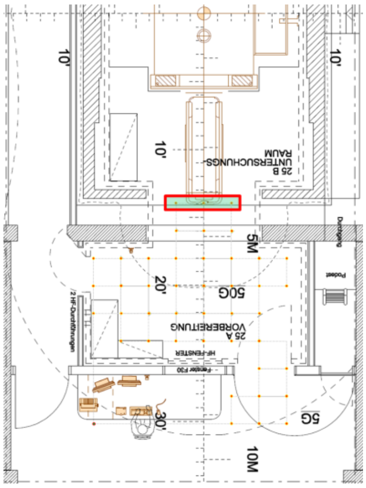

Figure 13: measurement locations

Cut perpendicular to MRI at a distance of 5.4 m

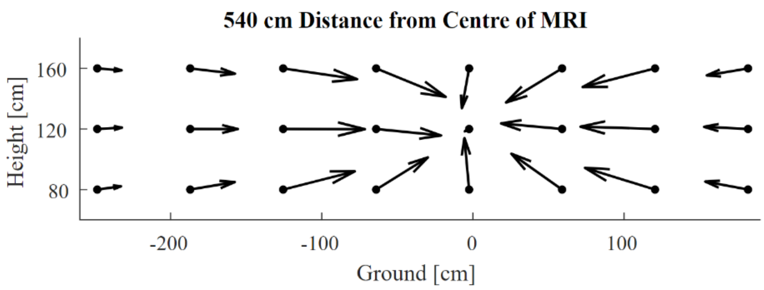

Figure 14: Field strength of MRI at 540 cm distance from MRI

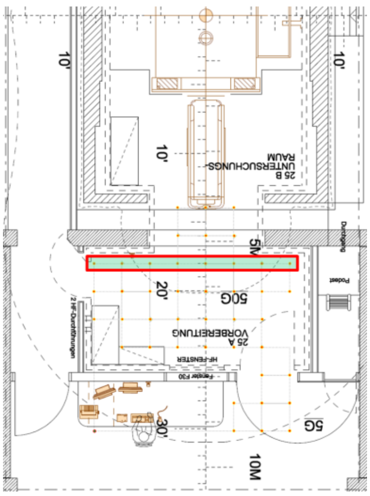

Figure 15: measurement locations

Cut perpendicular to MRI at a distance of 6.6 m

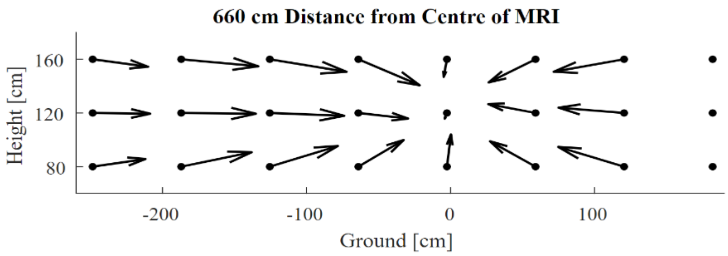

Figure 16: Field strength of MRI at 660 cm distance from MRI

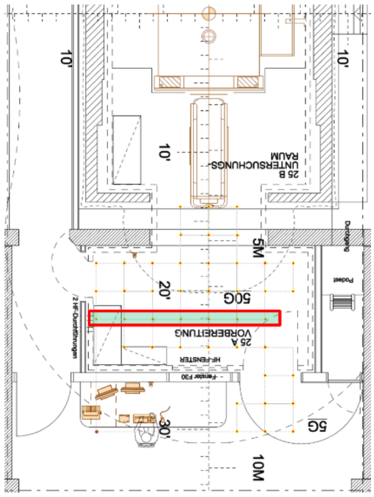

Figure 17: measurement locations

As we know from the theory of MRI, a horizontal magnetic field is formed in relation to the vertical current, since the two directions of current flow and magnetic field are perpendicular to each other. The static field with which the MRI works, runs directly from head to toe through the body when a patient "lies in the tube".

It can be seen from the directions of the arrows, which all point from the outside inwards to a centre point, that the plots represent cuts viewed from the foot of the MRI or the opening where the patient is pushed into the device. As it is showed in the illustration on the right, the field is running from north to south.

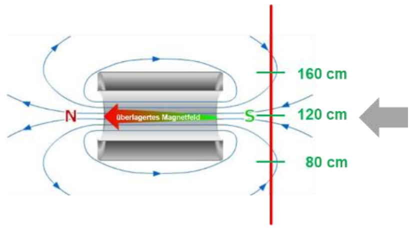

Figure 18: Side cut of MRI-field

The resolution of the plot could be improved if the measuring-grid was denser and more heights were considered.

3.4 Shielding with mu-metal-Box

We have investigated how a small cylinder made of mu-metal behaves in the static field of the MRI at a distance of about 9 m. Measurements were made at the measuring point at three heights without the shielding, with mu-metal box without cover and with completely closed mu-metal box. The field strength is given as the absolute value of all three components. The measuring device is completely encased by the cylinder.

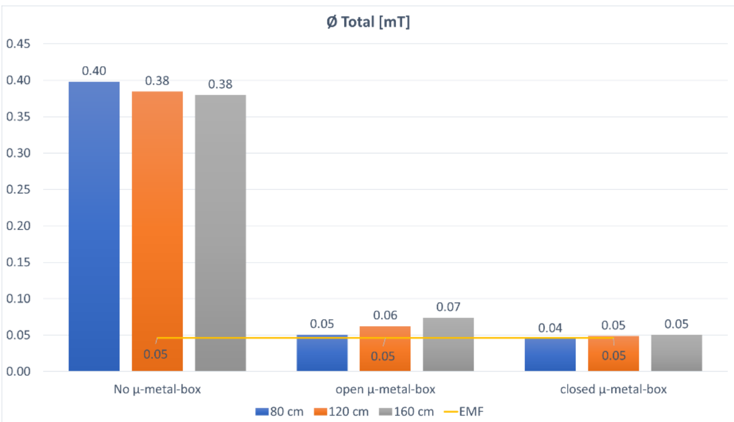

Figure 19: Measurements of Mu-Metal experiment

As can be seen from the diagram, the field strength at 9 m is around 0.40 mT without shielding. The differences between the three heights are small. As a reference, the strength of the Earth's magnetic field in Zurich is shown, which is 0.05 mT.

A clear shielding effect can be seen with the mu-metal box. The difference between the box without cover and the completely closed box is very small at this location. The field strength could be reduced to 0.07 mT. This is a reduction by a factor of 5 to 6.

3.5 Magnetic field at large distance

In order to see how the magnetic field of the MRI spreads over long distances in space, the field strength was measured at interesting locations and represented as points on the construction plan. The field strength is given as the absolute value of all three components.

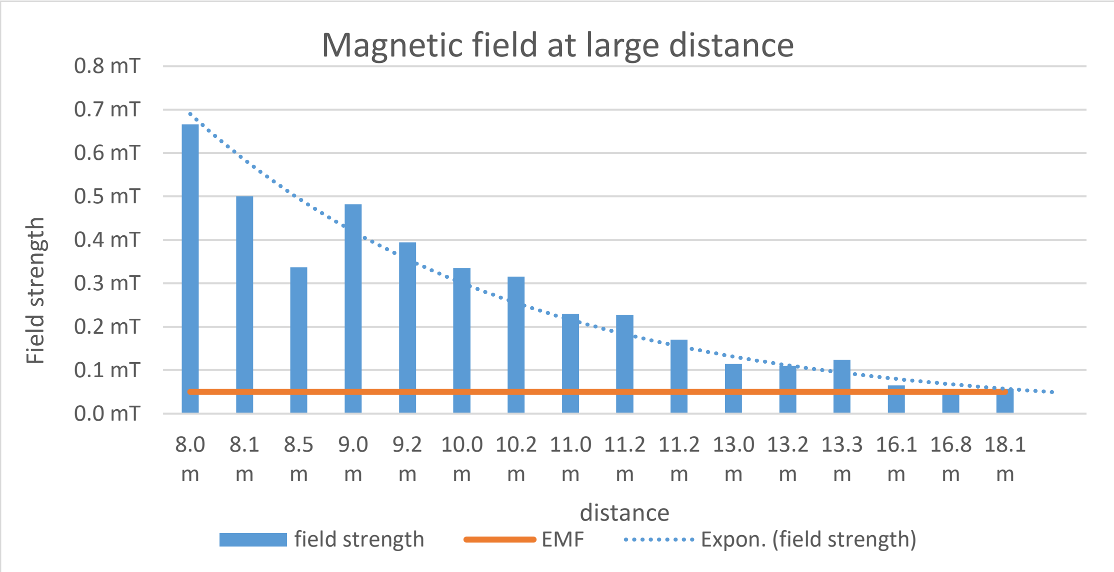

Figure 20: Magnetic field at large distance from MRI

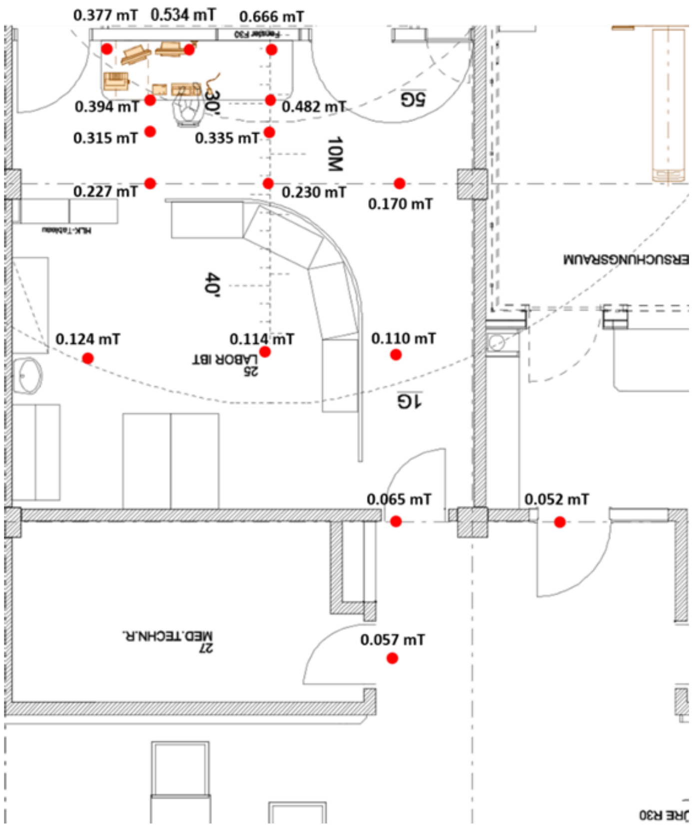

Figure 21: Measurement points in anteroom of MRI

3.6 Health effects of static magnetic fields

First of all, it should be stated that magnetic resonance imaging is a very safe method to obtain detailed images of soft tissue. Especially when comparing MRI to other imaging techniques such as computer tomography or x-rays where in both cases ionized radiation comes into play [8], it performs significantly better health-wise. Nevertheless, certain health hazards may occur and shall be investigated in greater depth in the following subsection. For the purpose of our main research interest, the discussion below will focus on health effects caused solely by the static magnetic field. The reason for this is that we gathered our data while no image was being taken, which means that only the static magnetic field was present. Otherwise we would have had two additional components, namely the time-varying magnetic field and radiofrequency energy, that each bring about another set of potential health effects. [9]

3.6.1 Long-term effects

When examining long-term effects of exposure to strong magnetic fields of up to 8 Tesla, main concerns are an increased risk of cancer and a decrease in fertility. However, both outcomes could not yet be scientifically proven leading to the consensus that current studies do not have sufficient evidence to support the statements mentioned above. [10]

3.6.2 Acute effects

When it comes to acute effects, the topic becomes less debatable. There are very clearly stated symptoms that can arise:

- Increase in blood pressure
  However, it only increases by 4 percent which is considered to be minor and therefore not clinically significant [11]
- Metallic taste sensation
  This is amongst the most common immediate effects and increases with increased rate of movement. It is practically non-existent during head-nodding, but very well so during horizontal head shakes. Interestingly, the sensation is perceived stronger when the mouth is kept closed. [12]
- Dizziness
  It has long been thought that quick movement within strong static magnetic fields is the primary reason for dizziness. And while it is true that movement does play a role in the perception of vertigo, recent studies have shown that even when lying still a person can experience dizziness. Therefore, another factor was needed to describe this phenomenon. As it turns out, the magnetic field interacts with spontaneous currents flowing in the liquid of our inner ear resulting in induced Lorentz forces. These forces are so strong that they interfere with the vestibular system which eventually leads to the feeling of vertigo. [13]
- Phosphenes
  In common parlance this is known as “seeing stars”. It essentially describes the sensation of seeing light even though none of it is actually entering the eye. [14] Such effects can be experienced when the magnetic field exceeds a threshold of 2 Tesla and the reason for this is a movement induced electric field in the head. [11]
- Nausea
  When provoked due to MRI exposure this is regarded as a very strong response and occurs significantly less often than the other symptoms listed

4 Summary

Concluding, we want to stress that these acute effects do not necessarily have to occur. Reactions differ greatly between individuals meaning that there are also many people working in MRI who hardly or very rarely experience the described symptoms. Nevertheless, these sensations can arise and therefore it is important that individuals who are regularly around MRI-scanners, such as researchers, take this into account when doing their work. Additionally, they should be equipped with a profound knowledge of how to behave in such an environment, such as restraining from fast movement and avoiding making abrupt direction changes.

In the process of making our measurements we came to the realization that there are certain tradeoffs one must accept in order to achieve a greater goal. Thanks to the technology behind MRI-Scans millions of people can receive treatment early enough and thus lives are being saved or at least prolonged. Sure, there are certain side effects linked to magnetic resonance imaging, but we think it is safe to say that considering the enormous positive impact this technology brings about, feeling a little dizzy is a price one can pay. Yes, it is true that the symptoms we have discussed in section 3.6.2 are unpleasant, but that is already about it. They are unpleasant for a short period of time and then they pass just as quickly as they have arisen.

In our case, it is rather difficult to draw consequences since the affected people cannot really change their behavior in order to decrease their exposure. Also, the technology cannot get rid of the magnetic field, because that is precisely what makes the entire imaging technique possible. And as hard as that is to admit for us as engineering students, we think that in this specific case, we just have to accept things the way they already are.

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6 Appendix A

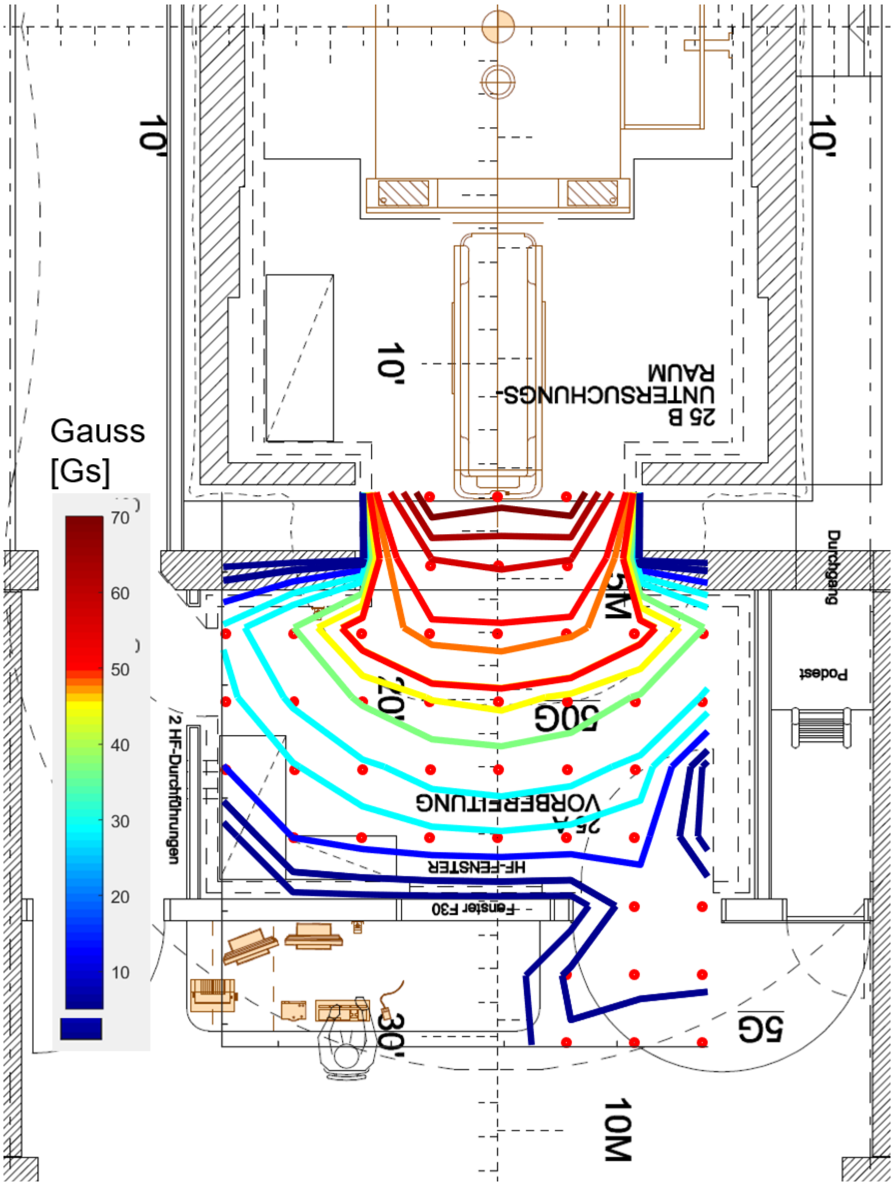

Figure 22: Top-Down-View up to 5 Gauss Line

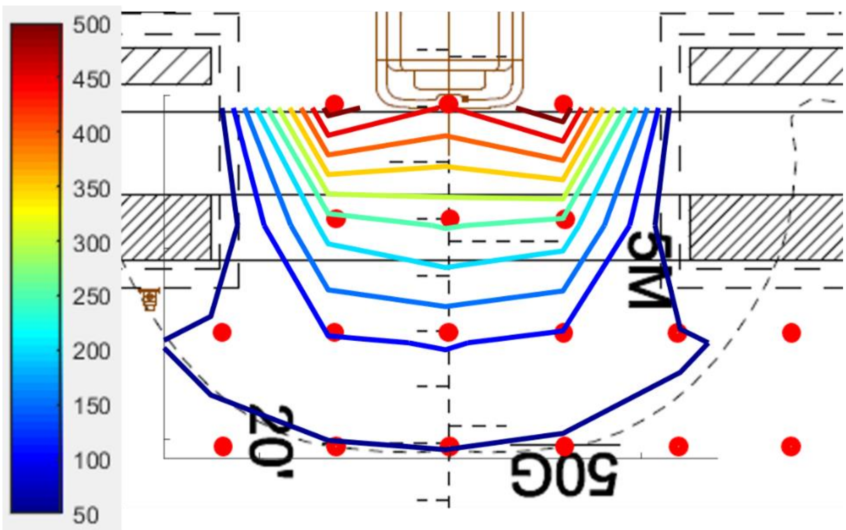

Figure 23:Top-Down-View up to 50 Gauss Line