Chapter 8
Static Magnetic Fields on Human Bodies

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Abstract With the development of modern technologies, people have increased exposure to various types of electromagnetic fields, including static magnetic field (SMF). Accordingly, World Health Organization and international commission on non-ionizing radiation protection have also publish guidelines for the safety application of magnetic fields on human bodies. This chapter summarizes the study results of SMF effect on human bodies, as well as some magnetic field applications in medicine (magnetomedicine). It not only includes some commonly seen SMFs, such as the weak Earth magnetic field that we are all exposed to, but also moderate to ultra-high field generated by magnetic resonance imaging scanners in the hospitals. Magnetic surgery, magnetoencephalography, and magnetocardiogram, which have been used in clinics, are also briefly introduced. SMF-based magnetic therapies are also discussed, which have a long-debated history and still lack of systematic mechanics investigations and sufficient double-blinded, randomized and placebo-controlled human studies. Based on the research progresses in the last few decades, we predict that magnetomedicine will have a great potential in the near future.

Keywords Magnetic field (MF) · Static magnetic field (SMF) · Earth magnetic field · Geomagnetic field (GMF) · Magnetic resonance imaging (MRI) · Magnetic therapy

8.1 Introduction

From a simplified view, the human body is mainly composed of weak diamagnetic materials, including water, most proteins, and lipids. The term diamagnetic means that the substance repels with the externally applied magnetic field (MF). In an

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externally applied magnetic field, the electron motions in diamagnetic molecules make small changes, which generate weak magnetic fields in the opposite direction to the external MFs. Although the diamagnetic properties of most living organisms are very weak, since the repulsive force is proportional to the product of the MF intensity and the field gradient, the forces can be amplified by ultra-strong magnetic field. For example, the most famous case is the “flying frogs” a few decades years ago. People put small diamagnetic objects such as water drops, flowers, grasshoppers, and small frogs in the 16 T ultra-strong static magnetic field (SMF) produced by a vertical electromagnet and levitated those small objects. Theoretically, the human body could also be levitated if we have a vertically oriented, large-sized high-field magnet.

Due to the fast development of technologies, people have increased exposure to different kinds of electromagnetic fields (EMFs) nowadays. Most EMFs are time-varying magnetic fields (also called dynamic magnetic fields), such as 50–60 Hz power line EMFs as well as radiofrequency EMFs emitted by cell phones and microwaves. Therefore, these EMFs have attracted paramount interests. There are many reviews and books about this topic and we will not discuss about the details here. The focus of our book is SMFs, which have non-changing magnetic fields over a certain period of time (0 Hz). The most common SMFs that people are exposed include the weak but ubiquitous Earth magnetic field/geomagnetic field (GMF) (~0.5 Gauss, ~50 μT). In the meantime, people can also be exposed to magnetic resonance in imaging (MRI) scanners in the hospitals (most of them are between 0.5 and 3 T), as well as permanent magnets of various magnetic intensities that some people may use as alternative medicine for some chronic medical conditions such as chronic pain relief, as well as small magnets that are frequently used in household items such as refrigerators, toys, and accessories. Moreover, with the development of ultra-high field MRI machines, people have increasing exposure to high SMFs, which unsurprisingly raised new concerns. Therefore, the effects of SMFs and their effects on human bodies certainly require more research to get a better understanding.

From the safety point of view, since the public are always concerned about various EMFs, (World Health Organization) WHO initiated the International EMF project to assess health and environmental effects of exposure to static and time-varying electric and MFs. More information can be found at the WHO website: https://www.who.int/health-topics/electromagnetic-fields, or the international commission on non-ionizing radiation protection (ICNIRP) website: https://www.icnirp.org/. It should be mentioned that the ICNIRP updates their guidelines for radiofrequency magnetic fields from 100 kHz to 300 GHz (https://www.icnirp.org/en/frequencies/radiofrequency) very frequently, about every 2 years. As for now, Aug 2022, the last updated radiofrequency magnetic fields guideline was in 2020. In contrast, the most updated guideline for SMFs was published in 2009 and has not been updated since then (https://www.icnirp.org/en/frequencies/static-magnetic-fields-0-hz). One of the most important reasons for this is that SMFs are much safer than EMFs.

Table 8.1 Limits of exposure to SMF set by ICNIRP (international commission on non-ionizing radiation protection)

	Exposure characteristics	Magnetic flux density
Occupational[a]	Exposure of head and of trunk	2 T
	Exposure of limbs[b]	8 T
General public[c]	Exposure of any part of the body	400 mT

ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits

[a]For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects

[b]Not enough information is available on which to base exposure limits beyond 8 T

[c]Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material, and dangers from flying objects, which can lead to much lower restriction levels such as 0.5 mT. This table and its annotation are from the ICNIRP guideline for SMF (Ziegelberger and International Commission on Non-Ionizing Radiation Protection 2009)

WHO and ICNIRP have set the upper limit for SMF exposures for both public and occupational exposures. According to the last guideline published by ICNIRP in 2009, the upper limit for the public exposure is 400 mT and occupational exposure is 2 T/8 T (Table 8.1). The limit of exposure for general public of 400 mT was calculated by applying a reduction factor of 5–2 T, which has been proved to have no demonstrated robust effect on animals (Gaffey and Tenforde 1983; Tenforde 2005) or humans. The exposure of SMFs above 8 T requires approval of the research protocol by an Institutional Review Board as well as the informed consent of the subjects.

Although there are also some countries that have a stricter standard, such as Bahrain, Republic of Korea, and Iran, the ICNIRP guideline published in 2019 is still the basis for most countries to set their standards, especially for the occupational exposure, as shown on the WHO website (Table 8.2).

8.2 Earth Magnetic Field/Geomagnetic Field (GMF)

As mentioned above, the most common SMF that all people are exposed to is the Earth magnetic field/GMF, which is around 0.5 Gauss/50 μT (0.3–0.6 Gauss, depending on locations). GMF is much weaker compared to other types of SMF exposure but it is present everywhere and is exceptionally important to the living organism on Earth. It is now known that the Earth can create a region around the planet, called the magnetosphere. It is believed that planets without an intact global magnetic field are subject to atmospheric stripping by the solar wind. For example, people think that Mars does not have a global magnetic field so that the solar wind has contributed to the loss of water and the erosion of Mars' atmosphere. In contrast, the Earth has its magnetic field (magnetosphere), which protects our whole planet

Table 8.2 Exposure limits of SMF in different countries

Country	Magnetic flux density	
	Public	Workers
Bahrain	40 mT	0.2 T
Republic of Korea		
Iran		0.2 T/2 T/5 T
Denmark		2 T
Hungary		
Israel		
Switzerland		
Austria		2 T/8 T
Cyprus		
Greece		
Finland		
Sweden		
United Kingdom of Great Britain and Northern Ireland		
Netherlands	400 mT/0.5 mT	
Croatia	400 mT	2 T
Singapore		
New Zealand		2 T/8 T
Norway		
Germany	400 mT/500 mT	
Argentina	N/A	2 T/60 mT
Belgium		2 T/8 T
Bulgaria		
France		
Ireland		
Italy		
USA		

Information is from WHO website, which was last updated on June 20, 2018. For more detailed information, please check out at: https://www.who.int/data/gho/data/indicators/indicator-details/GHO/magnetic-flux-density-(microt)

N/A not applicable

from harmful solar and cosmic particle radiation, as well as erosion of the atmosphere by the solar wind (Fig. 8.1). More information about the magnetosphere can be found at the NASA website (https://www.nasa.gov/magnetosphere).

It is well known that birds, bees, turtles, and some other animals are shown to sense GMF for direction during migration and there are many studies about GMF and animal magnetoception. There are also some other animal behaviors that were reported to be correlated to GMF. For example, people found some interesting but enigmatic phenomena that dogs like to align their bodies along the Earth magnetic field when they excrete (defecation and urination) (Hart et al. 2013). More information about the SMF effects on microorganisms, plants, and animals will be discussed

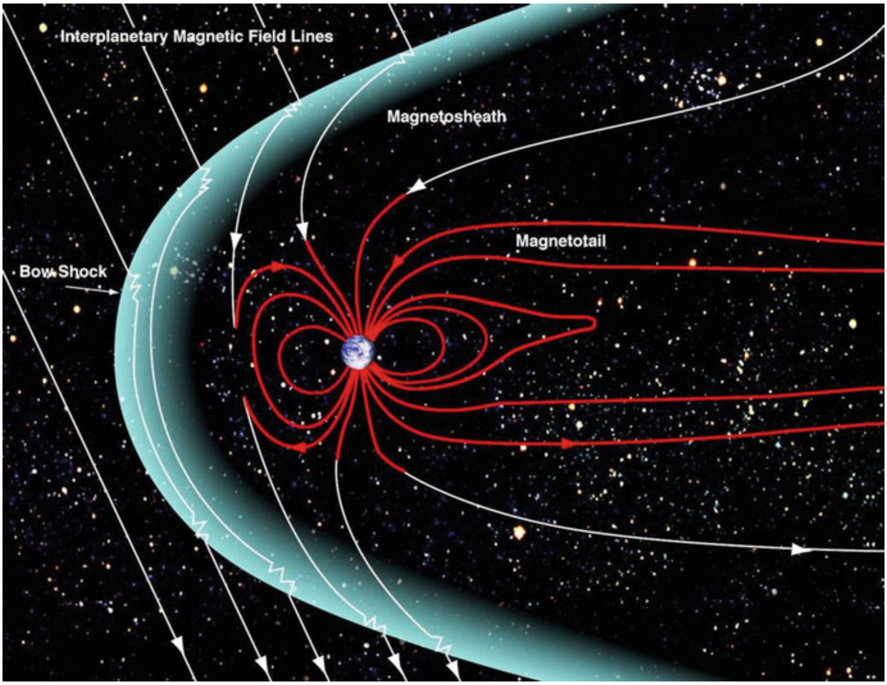

Fig. 8.1 Earth's magnetosphere. The shape of the Earth's magnetosphere is directly affected by solar wind (the sun is on the left). The image was from the NASA website (https://www.nasa.gov/mission_pages/sunearth/multimedia/magnetosphere.html). [Credit: NASA/Goddard/Aaron Kaase. Therefore, for a longer period of time, the Earth magnetic field/GMF is not strictly static, or as static as permanent magnets]

in Chaps. 7 and 13. Although the progress in this particular field is vast in the past few years, more efforts are still needed to unravel the exact and detailed mechanisms to explain various animal behaviors in SMFs, especially the weak GMF.

Whether humans can sense GMF has always been debated. It is interesting that there are a few new studies in recent few years indicating that humans can sense Earth MF (Chae et al. 2019, 2022; Wang et al. 2019). In 2019, Wang et al. reported that the Earth-strength MFs can produce strong, specific, and repeatable effects on human brainwave activity in the electroencephalography (EEG) alpha-band (8–13 Hz), and they propose the mechanism to be related to ferromagnetic transduction element, such as biologically precipitated crystals of magnetite (Fe_3O_4) (Wang et al. 2019). On the other hand, Chae et al. also studied human magnetoreception and stated that starved men have better magnetoreception ability than women (Chae et al. 2019). Recently, they indicated that a magnetic field resonance mechanism mediates light-dependent magnetic orientation in men (Chae et al. 2022). Apparently, this field still remains blurred and we are still far away from understanding the nature of it.

In the meantime, there are multiple studies indicating that GMF could affect other aspects of human. For example, Thoss and Bartsch indicated that the GMF could actually affect human visual system (Thoss and Bartsch 2003, 2007) although the mechanism is not completely understood. Burch et al. indicated that the GMF can affect melatonin secretion (Burch et al. 2008), which is a possible mechanism for the neurological and cardiovascular effects of altered GMF. In addition, Lipnicki et al. showed that there may even be some association between GMF activity with dream bizarreness (Lipnicki 2009). However, there are also some reports that reported negative results. For example, in 2002, Sastre et al. examined the effects of controlled changes in the GMF on 50 human volunteers for electroencephalogram (EEG) and did not find any obvious correlation (Sastre et al. 2002). Since different aspects were measured in these individual studies, they are not exactly comparable.

On the other hand, there are also some evidences showing that in the absence of GMF, frequently referred to hypomagnetic field (HMF), the gene expression, cell proliferation, migration, and adhesion of some human cancer cells could all be affected (Martino and Castello 2011; Mo et al. 2013, 2014, 2016). For example, Mo et al. did multiple studies about the effects of HMF on human SH-SY5Y neuroblastoma cells. In 2013, they showed that continuous HMF exposure significantly increases the proliferation of human SH-SY5Y neuroblastoma cells by promoting cell cycle progression (Mo et al. 2013); in 2014, they compared the transcriptome profiles of SH-SY5Y cells exposed to either the HMF or the GMF and found multiple genes are differentially expressed, including MAPK1 and CRY2 (Mo et al. 2014). In 2016, they found that in HMF, SH-SY5Y cells have reduced F-actin cytoskeleton as well as reduced adhesion and migration (Mo et al. 2016). In addition, HMF was also found to reduce the reactive oxygen species (ROS) level in human pancreatic AsPC-1 cancer cell line and bovine pulmonary artery endothelial cells (PAEC) (Martino and Castello 2011), which is consistent with some studies reporting that SMFs could increase ROS in some cancer cells. In addition, they also did some studies in *Xenopus laevis* (African clawed frog) and found that HMF could cause a decrease in horizontal third cleavage furrows and abnormal morphogenesis in Xenopus embryos (Mo et al. 2012). Their results indicate that a 2-h brief exposure to HMF is sufficient to interfere with the development of Xenopus embryos at cleavage stages. Although this study was done in frogs, the impact of HMF on mitotic spindle and cell division could also be potentially comparable in other organisms, including humans.

In fact, to make things even more complicated, we need to keep in mind that the GMF is not strictly static. It is part of a dynamic, interconnected system that responds to solar, planetary, and interstellar conditions. Therefore, it is not surprising that the GMF around us would have slight fluctuations during day vs. night, winter vs. summer, and also depend on whether there are sporadically occurred solar winds. In fact, it has been reported that the GMF disturbances and/or solar radiation are correlated with suicide/depression in Japan, Taiwan, Finland, and Australia (Partonen et al. 2004; Berk et al. 2006; Tada et al. 2014; Nishimura et al. 2020). Therefore, no matter whether or not humans can sense the GMF for direction like some migrating or homing animals do, current available evidences indicate that our bodies are indeed affected, or more accurately, protected by the Earth magnetic field. More investigations are encouraged to get a more comprehensive understanding on this topic.

8.3 Time-Varying Magnetic Fields and Their Clinical Applications

Although the focus of this book and this chapter are SMFs, here I want to briefly introduce the time-varying magnetic fields and their clinical applications because their successful development in clinics may shed light on the future progress of SMFs in clinics.

8.3.1 Magnetoencephalography and Magnetocardiogram

As mentioned in the beginning of this chapter, the human body is mainly composed of weak diamagnetic materials, such as water, proteins, and lipids. However, our bodies also generate currents that produce small magnetic fields (Cohen et al. 1980). Neurons in our brain, nerve cells, and muscle fibers are all excitable cells that can generate currents when they are activated. Consequently, relevant instruments were also developed to measure these electric activities. For example, electrocardiogram (ECG) measures the electrical activity of the heart, and electroencephalogram (EEG) measures the electrical activity of the brain, both of which have been widely used in clinic.

Magnetic fields produced by the human body have been measured, which are actually very weak (10^{-10} to 10^{-5} gauss). It is well accepted that the human brain can be divided into multiple areas, and each of them is responsible for different aspects of behavior. The accurate and efficient connectivity between these areas is critical for normal function of a healthy brain. Although a single neuron could only produce very weak current, it can be amplified when the neurons are clustered and aligned together and excited simultaneously. In this case, the neurons can produce magnetic fields that are strong enough to be detected using superconducting quantum interference devices (SQUIDs) (Zimmerman et al. 1970; Hamalainen et al. 1993). Weak alternating magnetic fields outside the human scalp, produced by alpha-rhythm currents, were demonstrated. The fields near the scalp are about 1×10^{-9} gauss (peak to peak) (Cohen 1968). Magnetoencephalography (MEG) is a noninvasive sophisticated technique that captures the magnetic fields generated by synchronized intraneuronal electrical activity, which yields rich information on the spatial, spectral, and temporal signatures of human brain function. It is capable of imaging electrophysiological brain activity with good (~5 mm) spatial resolution and excellent (~1 ms) temporal resolution and provides significant value in elucidating the neural dynamics of the human connectome in health and disease (O'Neill et al. 2015). There are many very useful reviews and research articles for MEGs showing that neuroimaging methods like MEG represent an outstanding approach to better understand the mechanisms of both normal and abnormal brain functions (Brookes et al. 2011; He et al. 2011; Pizzella et al. 2014; Kida et al. 2015; O'Neill et al. 2015; Pang and Snead 2016; Stefan and Trinka 2017; Baillet 2017). Similarly, magnetocardiogram (MCG) measures the magnetic fields of the heart, which is a complementary or alternative tool for noninvasive detection of coronary artery disease (Kandori et al. 2010; Wu et al. 2013).

In addition, MEG appears to be more sensitive than EEG and can provide additional and different information compared to EEG (Cohen 1972). MEG is useful for functional neurosurgery and connectivity analyses. Since MEG could offer additional insights not possible by MRI when used to study complex network function, people are combining MEG (which has high temporal resolution) with functional MRI (fMRI), which has high spatial resolution, to provide more information on human brain function (Hall et al. 2014). In particular, MEG is most widely applied to the study of epilepsy, a brain disorder that causes people to have seizures (Kim et al. 2016; Pang and Snead 2016). In addition, simultaneous MEG/EEG recording and analysis could provide complimentary information and better detection sensitivity for tracing primary epileptic activity (Hunold et al. 2016; Stefan and Trinka 2017). Moreover, for chronic neurological disorders such as epilepsy, functional connectivity detected through hemodynamic and electromagnetic techniques help to identify the interactions between epileptic activity and physiological networks at different scales. fMRI and EEG/MEG functional connectivity can help in localizing important drivers of epileptic activity and can also help in predicting postsurgical outcome (Pittau and Vulliemoz 2015). In recent few years, with the help of quantum sensors, people are able to develop MEG into a helmet-like wearable device, which does not rely on superconducting technology and allows the free and natural movement of the subjects or patients during scanning (Boto et al. 2018).

8.3.2 Transcranial Magnetic Stimulation

First of all, the magnetic fields in transcranial magnetic stimulation (TMS) are pulsed magnetic fields, but not static magnetic field. TMS is an electromagnetic method that uses a “coil” placed near the head to stimulate small regions of the brain and is used to diagnose or treat multiple diseases such as stroke and depression. It is the best-known magnetic field-related therapeutical instrument that are applied in clinics world widely. In fact, TMS is currently covered by some health insurance in the United States to treat diseases like depression. Some of their applications may be inspirational for people to study SMFs, especially for their applications in the nervous system. There are many reviews that are helpful for people to get more information on this topic (Hallett 2007; Rossi et al. 2009; Pitcher et al. 2021).

8.4 Static Magnetic Fields and Their Clinical Applications

Besides the weak GMF of ~50 μT, nowadays people have more chances to get exposed to much stronger SMFs. On the one hand, MRI scanners are used in the hospitals all over the world, which is the best application of high magnetic field in human health. On the other hand, there are also some SMF-based magnetotherapy products that are available in many countries and mostly used by people by themselves, which will be discussed in more detail by Dr. Kevin Yarema in Chap. 15 of this book.

8.4.1 Magnetic Resonance Imaging (MRI)

MRI has a superior soft-tissue contrast compared to other radiological imaging methods, which makes it a powerful tool in many physiological and functional applications. Currently, the SMF of most MRI scanners in hospitals is 0.5–3 T, which is around 10,000–60,000 times higher than the GMF. This is exceptionally stronger than the GMF or other permanent magnets that people can easily get access to. However, MRI is considered to be a very safe diagnosis technique, as long as the operation follows the basic guidelines. For example, people with pacemakers should not use MRI because the pacemakers may be reprogrammed or turned off by the MFs of MRI. People with some other implants, such as ferrous intra-cranial vascular clips, should also avoid MRI because the strong SMF of MRI may cause possible movement of the implants. Cell phones and credit cards may be damaged by the MFs so that they should also be kept out of the MRI room. It is well recognized that for the regular exposure to the MRI, there are some commonly experienced symptoms including nausea and headaches, which are all reversible (Heilmaier et al. 2011). This will be discussed in more details in Chap. 13 of this book.

In the meantime, since high SMF field can help providing enhanced sensitivity, higher resolution as well as decreased acquisition time, MRI machines with higher magnetic field strength are already developed. For example, the 7 T MRI can obviously provide much more information than the 3 T or 1.5 T MRIs (Fig. 8.2). In the meanwhile, people are continuously investigating on building MRI machines with ultra-high magnetic fields. Beside the clinical studies on 9.4 T MRIs, the 10.5 T MRI was also tested on humans (Grant et al. 2020). This pilot study found that the subjects' cognitive performance was not compromised at isocenter while their eye movements increased. In addition, they experienced small changes in vital signs but no field-induced increase in blood pressure. None of the effects was identified as compromising subject safety. In the meantime, animal studies have been carried out on much higher field MRIs. For example, in 2010, Schepkin et al. tested mouse and rat brains using a 21.1 T MRI, the highest field MRI to date, at the National High Magnetic Field Laboratory (NHMFL) in the United States. They were able to achieve imaging resolution of 50 μM, which is much higher than the lower field

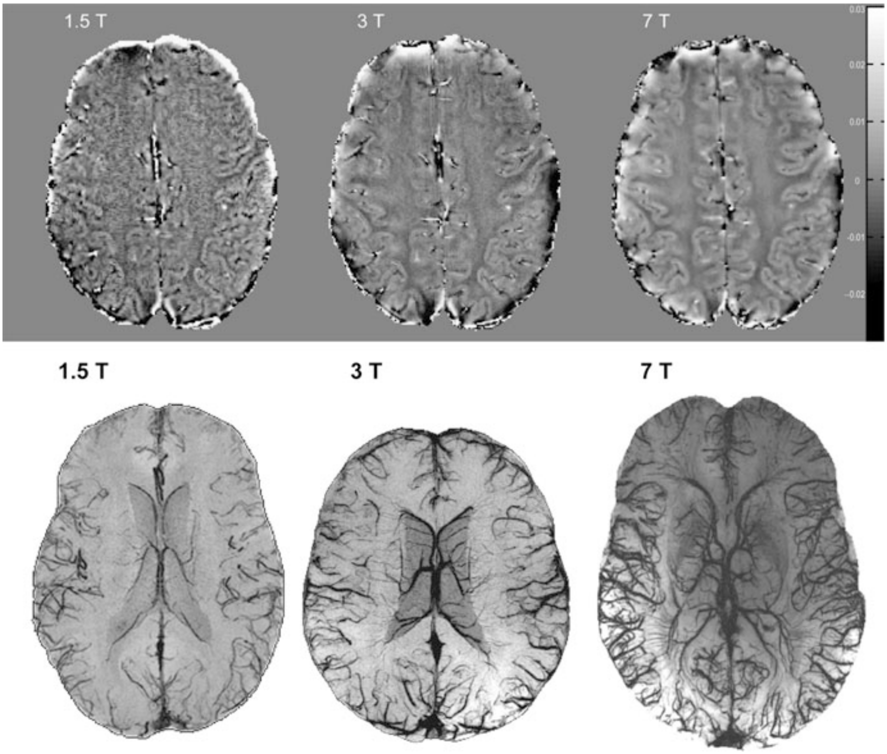

Fig. 8.2 Higher field MRIs have improved resolution. Up: Phase images at 1.5 T, 3 T, and 7 T normalized by field strength and echo time with an isotropic resolution of 0.8 mm. Reprinted with permission from (Zhong et al. 2008). Bottom: Three SWI minimum intensity projections (mIPs) at 1.5 T, 3 T, and 7 T with resolutions of 0.7 × 0.7 × 1.0 mm^3, 0.5 × 0.5 × 1.0 mm^3, and 0.5 × 0.5 × 0.5 mm^3 (Monti et al. 2017). [Reprinted with permission from (Ladd et al. 2018)]

MRIs. In addition, they also compared 21.1 T MRI to 9.4 MRI and found that the 21.1 T MRI can provide much more detailed features about the tissues and blood vessels in the rodent brain (Schepkin et al. 2010). This showed the promising future of developing similar MRI for human.

Since our knowledge of the biological effects of SMFs will guide us for future increase in field strength for MRI to benefit medical diagnosis, more studies are definitely needed to investigate the biological effects of ultra-high SMFs, which are necessary for the future application of ultra-high field MRI machines on humans. In recent few years, there are multiple studies that were performed on this purpose. For example, in 2021, Wang et al. reported a study to address the effects of 28-day long-term exposure to high SMFs of up to 12 T on healthy male C57BL/6 mice (Wang et al. 2021). They found some alterations in the Mg, Fe, Zn, Ca, and Cu content in mice, but did not reveal any detrimental effects. In addition, our group has performed a series of animal studies to investigate the safety issues of SMFs above 20 T (Tian et al. 2018, 2019, 2021; Lv et al. 2022; Khan et al. 2022). In 2018, we first reported a pilot study of 3.7–24.5 T SMFs 9-h exposure on tumor-bearing nude mice and found overall good biosafety on except for some moderate liver impairment (Tian et al. 2018). Then we reduced the exposure time to 1–2 h and used healthy C57BL/6 mice for our next few studies. We found that 3.5–23.0 T SMF exposure for 2 h did not show obvious harmful effects on healthy mice, including food and water consumption, blood glucose levels, blood routine, blood biochemistry, as well as organ weight and HE stains (Tian et al. 2019). In a later study, we further increased the field to 33.0 T and reduced the exposure time to 1 h, which is closer to the clinical MRI exposure time, and did not show significant changes for most physiological indicators in the healthy C57BL/6 mice (Tian et al. 2021). In addition, behavior tests were also performed to examine the potential neurological effects of 3.5–33.0 T SMF treatment for 1–2 h on healthy C57BL/6 mice. Surprisingly, we found that this high-field SMF treatment could improve the mental state and spatial memory of these mice (Lv et al. 2022; Khan et al. 2022), which was further confirmed by physiological and behavior tests with CUS (chronic unpredictable stress) depression mice that were treated with 7 T SMF for 8 h (Lv et al. 2022). These preliminary studies not only provide useful safety information for the development of ultra-high MRI, but may also indicate that high SMFs have the potential to be developed as anti-depression treatment modalities in the future.

It should be noted that although current MRI machines in the hospitals are considered to be safe, the long-term consequences of repeated exposure and their potential beneficial effects on human bodies are still incomplete identified. In addition, obvious advantages of ultra-high field MRI machines encourage people to design ultra-high MRIs for technical benefits. This also calls for attention for necessary studies for the accompanied safety issues. More efforts are needed to help establish guidelines for occupational staff and patient exposures to higher field SMFs.

8.4.2 Magnetic Surgery

As early as in 1957, Equen et al. have reported the retrieval of foreign bodies in the esophagus, stomach, and duodenum by using magnets (Equen et al. 1957). However, the application of magnets in clinics were not much progressed, until in the past two decades, an increased amount of interests and progresses were made, especially in the GI (gastrointestinal) tract (Cantillon-Murphy et al. 2015). For now, magnetic surgery, which is to apply magnetic fields in surgical procedures, has been developed into multiple surgical areas, especially in gastrointestinal surgery, which provides a minimally invasive surgery choice that benefits various procedures (Diaz et al. 2019). Doctors in the field of magnetic surgery have reached some consensus, aiming to reduce surgical trauma, improve the exposure of the surgical field and the surgical operability (Lv et al. 2019; Bai et al. 2022).

For now, most magnetic surgery can also be called as magnet-assisted surgery, which uses permanent magnets to perform minimally invasive surgery (Fig. 8.3).

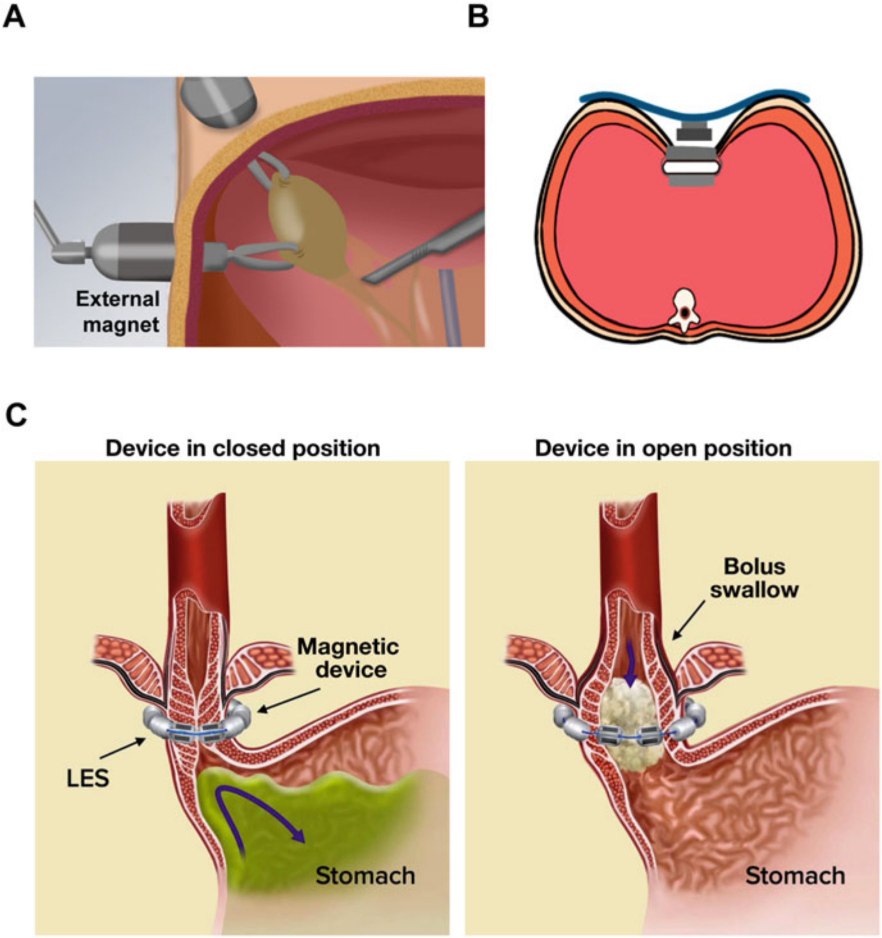

Fig. 8.3 Two types of magnetic surgery, one temporally uses magnets during the surgical procedure, and one places magnets in the human bodies for years. (**a**) Temporarily used magnets during the surgical procedures to provide better anchorage. (**b**) A novel minimally invasive magnetic procedure used to correct pectus excavatum. Both illustrations courtesy of Ding Joe Wang. (**c**) The magnetic sphincter augmentation for the treatment of gastroesophageal reflux disease, in which the magnetic rings can be placed in the patient's bodies for years. [Reprinted with permission from (Ganz et al. 2016)]

Magnets have been used for tissue retraction, anchoring, mobilization, and anastomosis. It should be noted that the progresses of magnetic surgery in the last few decades were mainly boosted by the development of magnetic materials, especially neodymium magnet, which can provide strong enough magnetic force to enable the doctors to design various novel surgical procedures. For example, there is already a magnetic surgical system that has been approved by Food and Drug Administration (FDA), called the Levita™ Magnetic Surgical System, to be used on laparoscopic cholecystectomy. It has been shown that routine use of this system may facilitate a reduction in the total number of laparoscopic trocars used, leading to less tissue trauma and improved cosmesis (Haskins et al. 2018). There was also a retrospective review of consecutive patients who underwent magnetic-assisted liver retraction during primary or revisional laparoscopic bariatric surgery at the Duke Center for Metabolic and Weight Loss Surgery between October 2016 and August 2017. It is clear that the magnetic-assisted liver retraction is a novel approach that allows a safe, reproducible, incision-less technique for unconstrained, port-less intra-abdominal mobilization, which enhances surgical exposure while decreasing the number of abdominal incisions (Davis et al. 2019). It has also been shown that magnetic liver retraction in bariatric surgery is associated with decreased postoperative pain scores, decreased hospital length of stay, and increased operating supply costs (Welsh et al. 2021).

Besides the magnets that are used temporally during the surgical procedure, there are also cases that the magnets are placed inside the human bodies for long term, to correct pectus excavatum (sunken chest) (Harrison et al. 2007, 2010, 2012; Jamshidi and Harrison 2007; Graves et al. 2017), or gastroesophageal reflux disease (GERD) (Bonavina et al. 2013; Lipham et al. 2015; Ganz et al. 2016). For example, magnetic sphincter augmentation (Fig. 8.3), an FDA-approved procedure that involves placing a magnetic device over the lower end of the esophagus, near the sphincter, has been proved to be an effective and safe surgical method for the treatment of GERD (Bonavina et al. 2013; Lipham et al. 2015; Ganz et al. 2016). Ganz et al. performed a prospective study of the safety and efficacy of a magnetic sphincter augmentation device in 100 adults with GERD for 6 months or more, at 14 centers in the United States and the Netherlands. Eighty-five subjects were followed up for 5 years. They found that augmentation of the lower esophageal sphincter with a magnetic sphincter provides significant and sustained control of reflux, with minimal side effects or complications, which validate the long-term safety and efficacy of the magnetic sphincter augmentation device for patients with GERD (Ganz et al. 2016).

8.4.3 Magnetic Therapy Using SMFs

Looking back into history, magnetic therapy has been debated for thousands of years and there were multiple rounds of up and downs (Basford 2001). It is interesting that the lack of solid scientific explanation for the working mechanism of magnetic field on human bodies does not really prevent people from using magnets at their own wish. Although it is never a mainline medicine, there are still many people currently using magnetic therapy as an alternative and complementary treatment for some chronic diseases, such as arthritis, wound healing, and analgesic therapy (pain relief). Every year, the magnetic therapy products have billions of dollars in sales worldwide. In fact, this is mostly because many people using magnetic therapy do find themselves benefiting from them. For example, there are some magnetic therapy products on amazon.com. Some of these products have thousands of positive

Table 8.3 Moderate static magnetic fields reduced pain level in post-polio patients

Pretreatment and posttreatment pain scores

	Active magnetic device ($n = 29$)	Inactive device ($n = 21$)	Significance
Pretreatment pain score	9.6 ± 0.7	9.5 ± 0.8	ns
Posttreatment pain score	4.4 ± 3.1	8.4 ± 1.8	$p < 0.0001$
Change in score	5.2 ± 3.2	1.1 ± 1.6	$p < 0.0001$

Proportion of subjects reporting pain improvement by magnetic activity of the treatment device

	Active magnetic device	Inactive device
Pain improved	$n = 22$ (76%)	$n = 4$ (19%)
Pain not improved	$n = 7$ (24%)	$n = 17$ (81%)

The top table shows that the pain score is efficiently reduced by active magnetic device. The bottom table shows that the % of patients that have effective pain relief is much higher in the active magnetic device group. Both tables were based on results from reference (Vallbona et al. 1997)
NS no significance

comments claiming that they could alleviate the pain and discomfort, especially the magnet bracelets that have some relatively stronger magnets embedded. By browsing the magnetic therapy products on the market, it is not surprising that the magnetic bracelets that received good reviews usually have their magnetic flux densities clearly labeled and most of them are within the range of hundreds to thousands of gausses (0.01–1 T).

Despite the fact that magnetic therapy has a long history, it is still not well accepted by the mainstream medicine. In some cases, it is even considered to be pseudoscience. The doubts are mainly due to the lack of consistency and scientific explanations (as discussed in Chap. 1). There are many efforts that have been devoted to trying to resolve this issue and some of them did provide positive results. For example, in 1997, Vallbona et al. conducted a well-controlled study on 50 post-polio patients and found that the 300–500 Gauss (0.03–0.05 T) SMFs (active magnetic device) significantly reduced the patient pain level from 9.6 to 4.4 ($p < 0.0001$) on a 10-point scale (Vallbona et al. 1997) (Table 8.3, top). It is interesting that the sham-exposure system that maximally mimics the magnetic device (inactive device) also had some placebo effects and reduced the patient pain level from 9.5 to 8.4. However, it is obvious that the pain level change in the SMF-treated group is fivefold more efficient than the placebo-device group (5.2 vs. 1.1, $p < 0.0001$). In addition, 76% of the patients in the active magnetic device group reported much reduced pain while the placebo-device group only have 19% patient (Vallbona et al. 1997) (Table 8.3, bottom). This study was done with proper controls, which provided people with convinced evidences that SMFs could indeed have beneficial effects on pain relief.

Another two scientifical studies in the field of magnetic therapy were performed by Alfano et al. and Juhasz et al. In 2001, Alfano et al. did a randomized, placebo-controlled, 6-month trial conducted from 1997 through 1998 on people with fibromyalgia (Alfano et al. 2001). In addition to sham controls, they compared a group of people that were exposed to sleep pads with magnets that provided low uniform SMF of negative polarity (Functional Pad A) with a group exposed to sleep pads with magnets that varied both spatially and in polarity (Functional Pad B). In fact, they did find that the Functional Pad A had the most significant effects and both Functional Pad A and B groups showed improvements in functional status, pain intensity level, tender point count, and tender point intensity after 6 months of treatment, but they did not differ significantly from changes in the control groups (Alfano et al. 2001). Therefore, although this study showed that the magnetic sleep pads had the potential to work, the effects were not statistically significant. I think the major reason for the lack of efficiency in their study might be the magnetic field strength, which is too low (below 1 mT). Increasing the magnetic field strength to hundred to thousand gauss might work. However, scientific studies are needed to be done to prove this. Moreover, in 2014, Juhász et al. did a randomized, self- and placebo-controlled, double-blind, pilot study included 16 patients diagnosed with erosive gastritis. They used inhomogeneous SMF-exposure intervention at the lower sternal region over the stomach with peak-to-peak magnetic induction of 3 mT and 30 mT/m gradient at the target site. They did find clinically and statistically significant beneficial effect of the SMF- over sham-exposure on the erosive gastritis symptoms. The average effect of inhibition was 56% ($p = 0.001$). This indicates that inhomogeneous SMF could be a potential alternative or complementary method for erosive gastritis (Juhasz et al. 2014). It is interesting that their magnetic field intensity seems much lower than most other studies that have positive results.

Current evidences show that magnetic field strength is a key issue for potential magnetic therapy applications. Overall, it is believed that magnetic fields with too weak strength are not enough to produce enough energy. As mentioned above, the permanent magnets most people used for magnetic therapy have been proved to be effective ranging from hundreds to thousands of gausses. For example, in 2002, Brown et al. showed that 0.05 T SMF for 4 weeks could reduce chronic pelvic pain in patients (Brown et al. 2002). In 2011, Kovacs-Balint et al. did a research on 15 young healthy human volunteers and found that an inhomogeneous 0.33 T (Bmax) SMF exposure for 30 min could increase the thermal pain threshold (TPT) (Kovacs-Balint et al. 2011). However, it is possible, and very likely, that different symptoms have different requirements for the magnetic field intensity, as well as other magnetic field parameters.

For example, Richmond et al. compared a magnetic wrist strap with (1502–2365 gauss), a demagnetized (<20 gauss) wrist strap, an attenuated (250–350 gauss) magnetic wrist strap, and a copper bracelet. Their results show that wearing a magnetic wrist strap or a copper bracelet did not appear to have any meaningful therapeutic effect, beyond that of a placebo, for alleviating symptoms and combating disease activity in rheumatoid arthritis (Richmond et al. 2013). For now, we are not sure about the reason for this lack of efficacy, however, as mentioned in Chap. 1, magnetic field parameters and multiple other factors have led to the large variations in the clinical or research work about the SMFs. For example, although lacking scientific mechanistic foundations so far, it is interesting that there are multiple

Table 8.4 The north and south magnetic poles are claimed to have different "healing effects" by some magnetic therapy manufactures and therapists

North pole-"negative"	South pole-"positive"
Inhibits relieves pain	Excites increases pain
Reduces inflammation	Increases inflammation
Produces an alkaline effect	Produces an acid effect
Reduces symptoms	Intensifies symptoms
Fights infections	Promotes microorganisms
Supports healing	Inhibits healing
Reduces fluid retention	Increases fluid retention
Increases cellular oxygen	Decreases tissue oxygen
Encourages deep restorative sleep	Stimulates wakefulness
Produces a bright mental effect	Has an over productive effect
Reduces fatty deposits	Encourages fatty deposits
Establishes healing polarity	Polarity of an injury site
Stimulates melatonin production	Stimulates body function
Normalizes natural alkaline pH	

It is still not very clear whether these are real, but different magnetic field directions DO generate some differences. Although from the scientific point of view, there is no explanation for this yet, I do not exclude the possibility that these claims, or at least some of them, might be true. More scientific studies are strongly encouraged to explore this question

claims about the differential effects of the two different magnetic poles on human bodies (Table 8.4). In fact, there are two recent papers observed differential effects of different magnetic field directions (De Luka et al. 2016; Milovanovich et al. 2016). Although more research is strongly needed to confirm their results, I think people should pay attention to the magnetic poles or directions when they investigate the biological effects of magnet fields in the laboratory, or simply want to try some magnetic therapy products.

The differential effects of the magnetic field direction and north/south poles need to be further confirmed by more scientific researches and ultimately to provide clear scientific explanations. For now, I myself are not clear why two different poles can make any differences because there is no physical difference between the north and south pole of the magnet, at least from our current scientific knowledge. However, it is possible that some unknown mechanism indeed exists to explain these observations. Moreover, since it has already been shown that magnet could levitate single cells when the magnetic field is upward to balance the gravity (Durmus et al. 2015), it makes more sense to me if it is the magnetic field direction that makes the differences that people observed. More interestingly, Durmus et al. demonstrated that each cell type (i.e., cancer, blood, bacteria, and yeast) has a characteristic levitation profile, and they have identified unique differences in levitation and density blueprints between breast, esophageal, colorectal, and non-small cell lung cancer cell lines, as well as heterogeneity within these seemingly homogenous cell populations (Durmus et al. 2015). This indicates that various cell types in the human body might respond totally differently to the magnetic fields. More researches are needed to confirm this.

8.5 Discussion

It is worth to mention that currently many researches related to magnetic therapy as well as the biological effect studies about magnetic fields are not well described or properly controlled. In 2008 and 2009, Colbert et al. wrote two important and comprehensive reviews (Colbert et al. 2008, 2009), which stated that *"Complete descriptions of the SMF dose that was applied to human participants are notably lacking in the majority of SMF therapy studies published to date. Without knowing the SMF dose that was delivered to the target tissue, we cannot draw meaningful inferences from clinical trial results. As research on SMF therapy progresses, engineers, physicists and clinicians need to continue to work together to optimize SMF dosage and treatment parameters for each clinical condition. Future publication of SMF studies should include an explicit assessment of the SMF dosage and treatment parameters outlined in this review, so as to be able to replicate previous studies, validly assess outcomes and make objective, scientific comparisons between studies."* The parameters they outlined include the magnet materials, magnet dimensions, pole configuration, magnetic flux density, frequency of application, duration of application, site of application, magnet support device, target tissue, distance from magnet surface, which all have great potential to directly affect the outcomes (Colbert et al. 2008, 2009) (Table 8.5). Many related researches need replication and we hope we can make great advancement after we have the proper knowledge of the magnetic field and biological systems, which will not only be helpful for WHO to assess any possible health consequences, but also improve the current status of magnetic therapy, which definitely needs much more rigorous experimentation. In fact, FDA has already approved the use of TTF (tumor treating fields), which

Table 8.5 10 essential static magnetic field dosing parameters

	Static magnetic field dosing parameters
1	Target tissue(s)
2	Site of magnet application
3	Distance of magnet surface from target tissue(s)
4	Magnetic field strength
5	Material composition of permanent magnet
6	Magnet dimensions: size, shape, and volume
7	Magnet polar configuration
8	Magnet support device
9	Frequency of magnet application
10	Duration of magnet application

Adapted from reference (Colbert et al. 2008). We recommend that people should all follow these standards when reporting their results delivers low-intensity, intermediate-frequency (100–300 kHz), alternating electric fields to treat newly diagnosed and recurrent glioblastoma, which works by disrupting cancer cell division, with no significant damage to normal non-dividing cells (Kirson et al. 2004; Pless and Weinberg 2011; Davies et al. 2013). Although TTF is a type of electromagnetic field therapy using low-intensity electrical fields, not SMFs, it may shed light on the SMF investigations for their potential clinical usage.

8.6 Conclusion

Since human body itself is an electromagnetic object, it is not surprising that the magnetic fields can produce some effects on us. However, the electrochemical processes within the human bodies are very complicated and still remain incompletely understood. Therefore, the actual physical effects of magnetic fields on human bodies will still need continuous efforts to achieve a complete understanding. In the meantime, magnetic therapy may be an alternative or complementary method in the clinical use, especially in cases when conventional therapy options are unavailable. In addition, whether the magnetic therapy works does not depend on our understanding for its underlying biological mechanisms. As Dr. Basford said in his review (Basford 2001) *"An electric or magnetic therapy is first discovered by the populace, resisted by the medical establishment, and then discarded—only to arise again in the future in a slightly different form. Although sophistication has increased, this pattern is likely to continue into the future until clear treatment benefits and, one hopes, a convincing mechanism of action are established."* Currently, what we should do is to try our best to unravel the mysteries so that we can maximize the benefit we can get from these nature powers. In the meantime, we should alert people that there are numerous unreliable websites or products about magnetic therapy. We believe that with the increasing efforts to use legitimate and scientifically backed methods in the field of magnetic field research, we will gain more mechanistic insights to facilitate the clinical application of SMFs and make magnetic therapy scientifically respectable.

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