15

SAFETY ISSUES IN BIOMEDICAL TELEMETRY

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15.1 INTRODUCTION

Achievements in wireless communications and microtechnologies combined with the growing need for advanced health care delivery systems have created a whole new field of interest in biomedicine. This includes the design of small biomedical devices with real-time biomedical telemetry functionalities for wearable, implantable, or ingestible applications. Wireless biomedical telemetry, performed by means of antennas, receives significant scientific interest. In the most complicated scenario, such devices not only communicate with a remote base station for telemetry purposes but also get powered wirelessly.

Even though biomedical telemetry is offering unique opportunities and enabling great advancements in prognosis, diagnosis, and treatment, there have been raised many questions regarding the safety of the aforementioned medical devices due to their proximity to the human body. Apart from all those risks and safety concerns that any medical device may have as a device that is responsible for the health of human beings, wireless medical devices have one further safety-related aspect that creates concerns to engineers and physicians. Since electromagnetic fields are used for communication with the exterior world, patients are exposed to electromagnetic energy.

Handbook of Biomedical Telemetry, First Edition. Edited by Konstantina S. Nikita.

In order for these devices to be marked as safe for use, special safety guidelines need to be followed.

This chapter analyzes all possible risks and safety concerns related to medical devices with biomedical telemetry functionalities. Apart from the usual operational and patient safety issues such as product hazard, device integrity and malfunction, side effects, human factors, and erroneous use, guidelines which need to be applied in order to ensure patient safety against electromagnetic field exposure are being extensively analyzed. Future research directions related to patient safety and the understanding of how electromagnetic fields interact with the human tissues are, finally, provided.

15.2 OPERATIONAL SAFETY

15.2.1 Electrical Hazards

Most of us have experienced some form of "electric shock," where electricity causes our body to experience pain or trauma. For a physiological effect to happen, the human body should, for some reason, become part of an electric circuit (Webster, 2009). The most basic and easy-to-understand effect of electricity on living tissues is when the current flows through the tissue, causing a dissipation of energy, usually in the form of heat. The effect is similar to that caused by an open flame to human tissues, except that the electricity also has the ability to further burn those tissues which are located well beneath the skin. Another effect of electricity on the human body, which can probably be considered as even more hazardous, is related to the electric stimulation of the excitable tissues, that is, nerves and muscles. Nerves all over the human body create a network of special cells called "nerve cells" or "neurons," which process and conduct those signals responsible for the regulation of several body functions (Brodal, 2010). Neurons communicate with each other by acting as "transducers" which create electrical signals (very small voltages and currents) in response to the input provided by certain chemical compounds, known as neurotransmitters. If electric current of sufficient magnitude is conducted to the living tissues, its effect will be to override the electric impulses generated by the neurons, overloading, in turn, the nervous system. Similar effects apply to muscle tissues, in which case current flow inside the human body may result in loss of full control of the muscular activity.

Figure 15.1 shows the magnitude of the current required to cause a number of physiological effects on the human body. A current with a frequency of 60 Hz is considered to be applied on a 70-kg human body for a time period ranging from 1 to 3 sec. The frequency of the current as well as the duration of the exposure and the weight of the individual are only indicated here as a reference. The threshold at which all the aforementioned effects happen is determined by the "let-go current," which is indicated in Figure 15.1 and defined as the maximum current at which a subject (e.g., a human) can withdraw voluntarily.

In the field of biomedical telemetry, use of all kinds of available equipment to-date in a way which deviates from the designer-set specifications may cause either

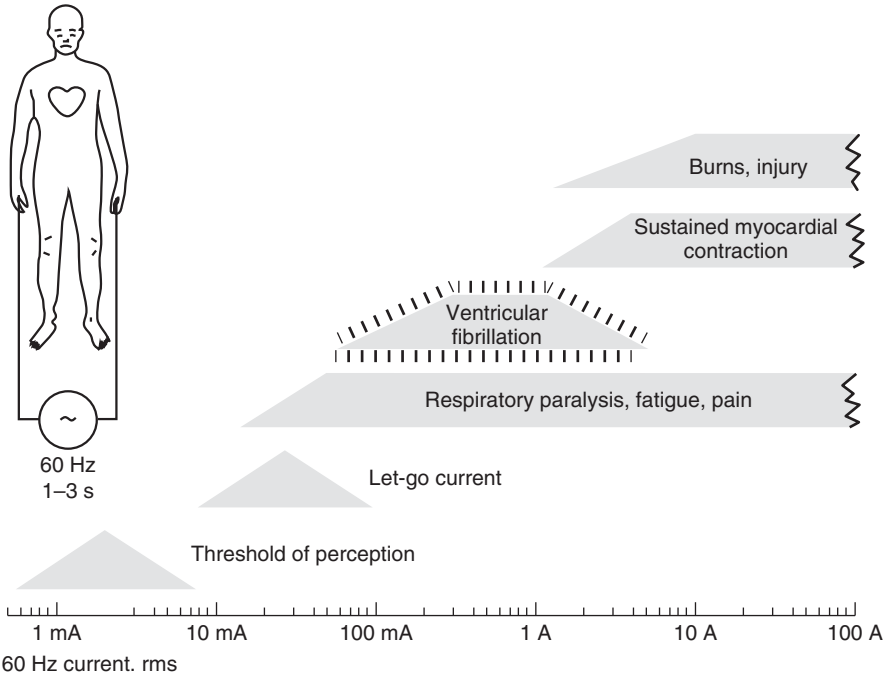

Figure 15.1 Physiological effects of electricity. Estimated thresholds are given for each effect. The current applied has a frequency of 60 Hz and is assumed to be applied on a 70-kg human for 1–3 sec via copper wires grasped by the hands (Webster, 2009).

macro- or microshocks. Macroshocks refer to those shocks which occur when the human body becomes a conductor of electric current without, however, the functions of the human's heart being affected. During a macroshock, current travels between two different areas of the skin. (Jacobson and Murray, 2007). For example, macroshock hazards may happen when on-body electrodes used to measure some physiological parameters induce a leakage current inside the human body as attributed to a malfunction or a failure (Anandanatarajan, 2011). On the other hand, microshocks are related to electric currents which are directly applied to the humans heart (Chan, 2008; Nokes et al., 1995) and could, for example, be a hazard in patients with intracardiac electrical conductors. Despite the fact that advanced medical devices are designed to prevent such phenomena by limiting any circuit currents to safe levels, microshocks continue to be a concern in cases where conductors are introduced into the human body and placed in close proximity to the heart.

To summarize, the physiological effects of electricity could be hazardous to patients' health. In the field of biomedical telemetry and in cases of biomedical devices which require electricity to operate, such hazards need to be addressed. Furthermore, due to the latest advances in biomedical telemetry, invasive devices that are either implanted or ingested inside the human body are used, making such hazards more apparent and crucial than ever before. Careful approaches on the

design and completion of devices and systems used in biomedical telemetry are thus required in order to end up with medical equipment which minimizes the risks related to current induction inside human tissues.

15.2.2 Heat-Related Risks

Operation of medical devices placed on or inside the human body raises several questions regarding the amounts of heat produced. Causes of temperature rise can be associated with several operations of the medical device, such as the stimulation and sensing functions, the power requirements of the electronics, and the communication functionalities (Lazzi, 2005). A device with limited electronics and communication functionalities which operates on demand can rarely be a problem from a thermal point of view. However, recent advances in microelectronics and antenna design provide the ground toward designing more sophisticated devices that can stimulate the human body and its neural tissues, allow contiguous communication with the exterior world, and provide vital physiological information 24 hr per day (Akay, 2008; Beach et al., 2005; Karacolak et al., 2008). Under these circumstances, heat generated by the device could be significant and should be carefully taken into account during the design process.

Figure 15.2 summarizes the potential causes of temperature increase in the surrounding human tissues produced by the operation of an invasive biomedical device. As mentioned earlier, several parameters can be the cause of temperature increase. If, for example, the invasive device uses a transceiver for exchanging data with the exterior world and/or uses an advanced wireless power system, then electromagnetic

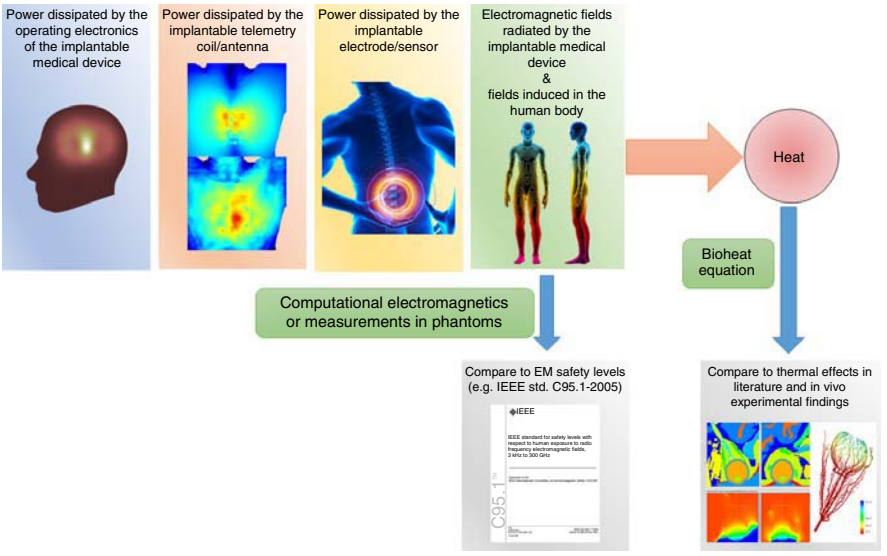

Figure 15.2 Schematic of potential causes of temperature increase in human body associated with operation of invasive devices. (*See insert for color representation of the figure*.)

power will be absorbed by the surrounding tissues and will in turn cause the temperature to increase. The aforementioned phenomenon can be quantified in terms of the specific absorption rate (SAR), which is expressed in watts per kilogram. SAR describes, in essence, the power induced per unit mass of tissue and is mathematically expressed as

$$\mathrm{SAR}\,(x, y, z) = \frac{\sigma(x, y, z)E^2(x, y, z)}{2\rho(x, y, z)} \tag{15.1}$$

where ρ is the tissue density (in kg/m^3), σ is the conductivity (S/m), and E is the electric field amplitude (V/m) at the point of coordinates x, y, and z.

Apart from the temperature increase caused by the electromagnetic fields (EMFs) induced in the human body, temperature can also be raised due to the contiguous operation of the electronics of the invasive device. Contiguous use of batteries to power the device can further increase the temperature locally. To quantify the thermal impact of the operation of the device, the bioheat equation can be used and adjusted to include all the aforementioned effects (Lazzi, 2005):

$$C\rho\frac{\partial T}{dt} = \nabla \cdot (K \nabla \mathrm{T}) + A_0 - B_0(T - T_B) + \rho SAR + P^{\mathrm{Density}}_{\mathrm{Electronics}} \qquad (\mathrm{W}/\mathrm{m}^3) \tag{15.2}$$

where T is the temperature (°C), C is the specific heat [J/(kg °C)], ρ is the tissue density (kg/m^3), K is the thermal conductivity [J/(m s °C)], A_0 is the basic metabolic rate [J / (m^3 s)], B_0 is the blood perfusion coefficient [J / (m^3 s °C)], T_B is the temperature of blood (°C), and $P^{\mathrm{Density}}_{\mathrm{Electronics}}$ is the power dissipated by the implanted electronics (W/m^3). In the bioheat equation, the left side of the equation represents the temperature elevation. The right side consists of all possible reasons that can cause this temperature elevation, including thermal spatial diffusion, tissue metabolism, blood perfusion, and external heat sources.

15.2.3 Failure/Malfunction of Devices

Due to the fact that electronic equipment comes with a constant failure rate most of the time, there is a common belief that medical devices used in biomedical telemetry fail independent of their age (Dhillon, 2000; Fries, 2005). However, this assumption has been criticized as inaccurate, especially when it comes to invasive medical devices. This is attributed to the fact that invasive medical devices and their reliability and failure patterns could be seriously affected by external factors that are mostly random and cannot be easily predicted or categorized during the design and development stages (Taghipour et al., 2011). Therefore, in 1990, the U.S. Congress enacted the Safe Medical Devices Act (SMDA), which aims to increase the amount of information that the Food and Drug Administration (FDA) and the manufacturers receive about serious problems related to medical devices.

A failure or malfunction takes place when a medical device does not meet its performance specifications. The causes of failure can vary, including electrical, mechanical, thermal, software or materials problems (Fig. 15.3). Analyzing and understanding

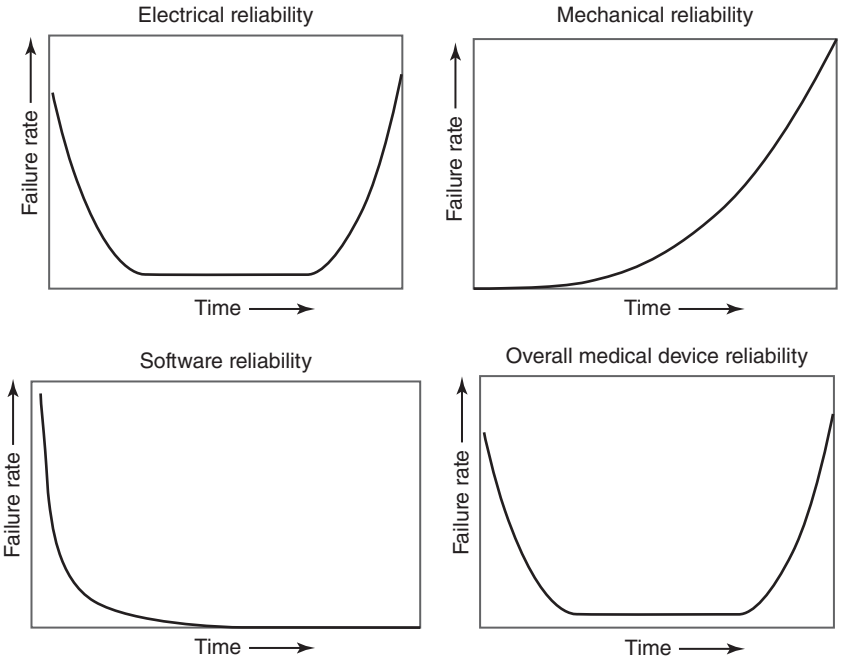

Figure 15.3 Reliability issues on medical devices, divided and analyzed by category.

the actual causes of malfunctions or failures of medical devices are considered crucial, because they can provide significant feedback to the designers, thus resulting in more fail-safe and advanced devices.

Due to their significant impact on human lives, medical devices used for biomedical telemetry must be evaluated in terms of reliability. Every aspect of their development—from early stages that cover design and prototyping through manufacture, distribution, and disposal—must adhere to quality standards that are well documented to specific functional and safety requirements set by the applications' standards. The standards should apply not only to manufacturers but also to all others involved in product development and distribution in order to ensure the quality of the devices and the indispensable safety and reliability. The process of identifying, analyzing, and eliminating or controlling the risks associated with medical devices is known as risk management and should address potential risks throughout the entire lifecycle of such products.

15.3 PRODUCT AND DEVICE HAZARDS

15.3.1 Adverse Tissue Reaction and Immune System Rejection Risks

Adverse reaction means a noxious and unintended response to any medical device that is implanted inside or ingested by the human body which in turn triggers the response

of the human immune system. This type of reaction is well known and widely studied in the field of metal-on-metal hip implants. Such implants are used to relieve arthritis pain or fix severe physical joint damage as part of a hip fracture treatment. Similar effects can take place with any invasive medical device which gets implanted inside the human tissues or ingested by the human body for diagnosis or treatment purposes. Adverse reactions can be mild, such as a simple rash, or more severe and even life threatening. They can occur immediately or develop over time. During an adverse reaction, the human immune system "identifies" the invasive device as a threat to the organism. In such a case, the defensive mechanisms would subsequently turn against the implant and probably cause a rejection of the device. Adverse reaction could cause prolonged pain and discomfort to the patient. Furthermore, a possible rejection of the device will inevitably require the removal of the device by means of another, most likely painful, surgery procedure.

A solution to the possible rejection of a medical device by the human immune system lies in the use of biomaterials, that is, materials which have the ability to coexist with the tissues of the human body without causing any nonacceptable harm (Onuki et al., 2008). Biocompatibility is, thus, becoming a critical factor toward the development of medical devices for biomedical applications such as tissue engineering, invasive monitoring, drug delivery, and gene transfection. There are several ways in which materials and tissues can be brought together. The search for biomaterials which guarantee the optimum performance of such devices has been based upon the understanding of the interactions between these materials and human tissues, as studied in the literature during the last century (Thull, 2002). Nowadays, biocompatible materials or encapsulation layers are used to ensure the biocompatibility of invasive devices used in biomedical telemetry (Prodromakis et al., 2009; Silay et al., 2010; Soontornpipit et al., 2005).

15.3.2 Migration

Migration occurs when an implantable device tunnels through the flesh to a different part of the body than its original implanted location. Implantable device migration is a serious ongoing problem for animals with implants, where microchips are implanted in pets for identification purposes, but it could be generalized to any application of implantable devices. Despite the use of a special coating designed to anchor the implant to the original implanted location, migration still occurs in many cases. The migration issues get more imminent when it comes to nerve stimulators or other devices intended to interact with the muscles of the human body. In these cases, the position of the device is crucial to its functionality and a small migration could cause a failure of the system.

15.3.3 Security Risks

Apart from the well-known questions regarding computer security, concerns also extend to medical devices with biomedical telemetry functionalities. Since microprocessors are used as part of these devices to perform a number of tasks, questions

related to security issues are coming up. Despite the recent advances in medical devices and technologies, security and privacy have not been in the top priorities during the design process. Security of medical devices should ensure reliable, secure data transmission and contiguous functionality, while, at the same time, preserving the patients' safety, confidentiality, and data integrity. For example, a recent research work has demonstrated that wireless connectivity can be exploited to gain access to confidential data transmitted by implantable medical devices (IMDs) or to send unauthorized commands to the IMDs—even commands that can cause the device to deliver an electric shock to the patient (Gollakota et al., 2011). As medical devices continue to evolve, balancing security and privacy with safety and efficacy will be one of the major challenges.

Adding a cryptography layer to existing medical devices in an attempt to solve the problem of security is difficult and ineffective (Gollakota et al., 2011). In terms of inalterability, many medical devices are already in use by humans serving several purposes. This issue becomes even more crucial in the case of invasive devices, where replacement with other devices which are enhanced with cryptographic abilities would require a surgery with all the risks, complications, and patient discomfort that this may cause. Overall, replacement of medical devices, except for the operational cost, also carries many risks that could directly affect the health of the patients. Another concern lies in the accessibility of the device. Adding a security cryptographic layer to a medical device could result in limited accessibility of the device in terms of communication. For example, if the device can be used only with proper credentials, then those credentials may not be available in specific scenarios, such as when the patient is unconscious or is examined by another doctor in another hospital. Last but not least, cryptography should enclose a software layer in the medical device that would manage the whole process. This software layer could be proved problematic due to possible software bugs. In this case, security of the device would be in question; in addition, the device could end up being inaccessible or nonfunctional.

Given the aforementioned difficulties, other ways should be found to ensure the safety, security, and privacy of biomedical telemetry devices. Gollakota et al. (2011) have proposed an interesting and promising advanced technique to surpass the problems mentioned earlier. In their study, the authors suggest the use of an external device, called a shield, which is interposed between an implantable device and potential counter parties—worn on the body near an implantable device. The shield acts as a gateway that relays messages between the IMD and authorized endpoints. Even though the method is promising, there is still ground to cover in the years to come in order to solve the security problems which come up with the growing needs of biomedical telemetry.

15.3.4 Development of Cancer

Eleven journal articles published between 1990 and 2006 have mentioned tissue reactions because of devices implanted into laboratory animals and dogs. A brief summary of the results is presented in Table 15.1. As perceived from the table, in some of these articles, animals developed malignant tumors around or adjacent to the

TABLE 15.1 In Vivo Animal Studies in Which Microchip-Induced Cancer Was Found

Authors	Species	Number of Animals	Length of Exposure	Developed Cancer
Johnson et al., 1996	Mice	2000	2 years	~1%
Tillmann et al., 1997	Mice	4279	Lifespan	0.8%
Palmer, et al., 1998	Mice	800	2 years	2.0%
Blanchard et al., 1999	Mice	177	6 months	10.2%
Elcock et al., 2001	Rats	1040	2 years	0.8%
Vascellari et al., 2004	Dog	N/A	18 months (at age 11)	1 dog
Vascellari et al., 2006	Dog	N/A	7 months (at age 9)	1 dog
Le Calvez et al., 2006	Mice	1260	2 years	4.1%

implanted devices. The percentage of the development was between 0.8 and 10.2% depending on the research. The devices used in at least 10 of those 11 studies were industry-standardized, passive implantable RF identification (RFID) transponders encapsulated in medical-grade glass and coated in an antimigration polymer sheath. Possible explanations behind the induced tumors have been proposed in these studies, which are summarized as follows:

- Foreign-body tumor genesis
- Postinjection sarcoma
- Possible genotoxic properties of the implant
- RF energy emissions

Even though malignant tumors were found to be developed in animals, the results cannot be generalized to humans, and scientists need to be really careful in criticizing the results. What happened to dogs and mice in response to an implantable device does not mean that it will be the same in the case of human beings. The human organism has a more advanced recovery and immune system and it can possibly assimilate the implant. It is important to highlight that, apart from the studies which are summarized in Table 15.1, there are a number of similar studies where no induced cancer effects were reported (Ball et al., 1991; Murasugi et al., 2003; Rao and Edmondson, 1990).

Furthermore, several medical devices, such as pacemakers, are already currently in use by humans and significantly enhance the quality of their lives without creating such phenomena. So, even though there is evidence about possible carcinogenetic reactions to animals, these results should be analyzed and criticized properly in order to get accurate results which could lead to a further improvement of the design of implantable medical devices.

15.3.5 Magnetic Resonance Imaging Incompatibility

Magnetic resonance imaging (MRI) is nowadays used to obtain highly detailed images of organs and tissues throughout the body without the need for x-rays or

"ionizing" radiation. MRI uses rapidly changing magnetic fields to create images which indicate the existence of an injury, disease process, or another abnormal condition. The major advantage of MRI over the other traditional methods of diagnosis is that it can characterize and discriminate among tissues by making use of their physical and biochemical properties. Moreover, its ability to obtain images in multiple planes adds to its versatility and diagnostic utility. Among all other capabilities, MRI can be used to image the cardiac anatomy and function, study the rest and stress myocardial perfusion, perform contrast-enhanced angiograms, and assess and quantify regurgitant lesions and intracardiac shunts.

MRI is, thus, a great diagnostic tool in modern medicine and is used in several ways to obtain useful medical information from patients. Given the powerful magnetic fields which are required for the operation of MRI, great care should be given to ensure that objects such as ferromagnetic materials are not brought into the MRI system. If a patient with implantable or ingestible devices in his or her body needs, for some reason, to be examined in an MRI system, then problems multiply. Invasive biomedical telemetry devices use materials that can generally interact with the magnetic fields produced by the MRI systems. Magnetic fields may cause traumas to the patient by pulling on the devices or may induce electric currents to the implantable devices which could, in turn, cause electric shocks. Moreover, a metallic implant or other object may cause signal loss or distort the MRI images. In other words, there exists an incompatibility between MRI and invasive devices used in biomedical telemetry that forbids the use of MRI systems to patients with such devices in their body.

Several studies have tried to suggest solutions to the aforementioned problem. In 1999, Schueler et al. proposed a testing protocol for the evaluation of the compatibility of the magnetic fields produced by MRI systems with implantable devices. In 2007, Buchler et al. studied and proposed a numerical analysis methodology to evaluate the MRI safety of active medical implants. At the same time, industry is trying to provide implantable devices that use some kind of coating which can ensure their compatibility with MRI systems. Even though there is a significant ongoing work, there is still much ground to cover in order to deal with the incompatibilities between MRI systems and invasive devices used in biomedical telemetry.

15.4 PATIENT AND CLINICAL SAFETY

15.4.1 Patient Safety

"Freedom from accidental injury" is the definition of patient safety used by the Institute of Medicine in its landmark 1999 publication, "To Err is Human: Building a Safer Health System" (Kohn et al., 2000). The authors estimated that as many as 44,000–98,000 people die in U.S. hospitals each year as a result of lapses in patient safety. The study characterizes medical errors as the eighth leading cause of death, more frequent than motor vehicle accidents (43,458), breast cancer (42,458), and AIDS (16,516). Recent studies in an increasing number of countries of the European

Union show that health care errors occur in around 10% of the hospitalizations, while adverse events may take place in all settings where health care can be delivered. In the field of biomedical telemetry, where several sophisticated medical devices and equipment are used for a number of medical applications, from diagnosis to targeted treatment or drug delivery, patient safety could be severely threatened without proper consideration.

Broadly speaking, according to Health EU (2005), patient safety is defined as the freedom of a patient from unnecessary harm or potential harm associated with health care. Errors that may threaten patient safety can be summarized in the following two basic categories:

- Medical complexity
- System failures

As far as medical complexity is concerned, and especially in the field of biomedical telemetry, errors and problems may occur due to the advanced technologies used or the intensive care provided. Moreover, other complicated technologies, powerful drugs, or even prolonged hospital stays could further result in several issues associated with patient safety. Regarding system failures, several issues associated with patient safety could occur. Some of these problems have been discussed earlier as part of operational or devices hazards. Apart from these, poor communication throughout the health care system, devices and systems that are not properly interconnected, and infrastructure failure issues could also threaten patient safety.

Patient safety can only be considered in relative terms [World Health Organization] (WHO), 2003]. Similar to any electronic device, medical devices carry a certain degree of risk and could cause problems under specific circumstances. Apart from device failure, part of a device or a component can also fail in an unpredictable or random way, thus resulting in a possible threat to human health. The current approach to medical device safety is to estimate the potential of a device to become a hazard that could result in safety issues. This estimate is often referred to as risk assessment (Wilkins and Holley, 1998). Risk is a measure of the combination of

- the hazard,
- the likelihood of occurrence of the adverse event, and
- the severity or overall impact.

In general, risk assessment significantly depends on experience, evidence, computation, or even guesswork. In practice, risk assessment of medical devices is based on the experience of the health care professionals and the degree of device safety as provided by engineers.

One response to the concern for patient safety has been an effort to improve the systems which report medical errors by including those errors which could have caused injuries or death due to malfunctions or other reasons but, fortunately, did not (Hughes, 2008). The philosophy behind this idea is to take advantage of the non-hazardous events and failures and use this knowledge to find ways to prevent specific

errors from recurring. This approach can be associated with safety design engineering which comes from the health care professionals under realistic conditions.

Another recent approach for securing patient safety has been the identification of existing knowledge and resources which come from nonrelated scientific fields, that is, lying outside the health care delivery system, and which may be applied to the problem under consideration. An example is the use of the extensive knowledge that industry has gained in the last 50 years regarding microelectronics devices in developing biomedical telemetry devices used for diagnosis and treatment. This approach can give a significant boost to patient safety.

World Health Organization The WHO was established on April 7, 1948, with headquarters in Geneva, Switzerland, and is a member of the United Nations Development Group. The constitution of WHO had been signed by all 61 countries of the United Nations (Burci and Vignes, 2004; Lee, 2008). The WHO's constitution states that its objective "is the attainment by all people of the highest possible level of health" (WHO, 2006). In October 2004, WHO launched a patient safety program in response to a World Health Assembly Resolution (2002) urging WHO and member states to pay the closest possible attention to the problem of patient safety (WHO, 2004). The mission of the WHO Patient Safety Program is to coordinate, facilitate, and accelerate patient safety improvements around the world by:

- Being a leader and advocating for change
- Generating and sharing knowledge and expertise
- Supporting member states in their implementation of patient safety actions

All these years, WHO, in participation with other organizations, has contributed to many projects related to public health and patient safety.

15.4.2 Clinical Safety

In general, pursuing safety is broader in scope than eliminating a risk. However, minimizing clinical risks that are closely related to applications of biomedical telemetry under specific circumstances and personnel will always be part of a clinical safety program. A rather practical and realistic definition of clinical risk is the avoidable increase in the likelihood of loss, damage, complaint, or harm to a patient, family member, staff member, or a member of the public during the treatment process in a clinical environment (e.g., a hospital). Clinical risks may result in harm, loss, or damage or they may lead to near-miss incidents that could have, but fortunately did not, threaten patient health or safety. Even though clinical risks may exist for some time without causing any harm or damage, that does not mean that the clinical risk does not exist or is insignificant. Clinical risk management tries to improve the quality and safety of health care by identifying the causes which may put patients at risk of harm and taking action to prevent or control those risks (Anderson, 2003). Clinical risk management is a continuous process as shown in Figure 15.4. The goals of risk management can be summarized as follows:

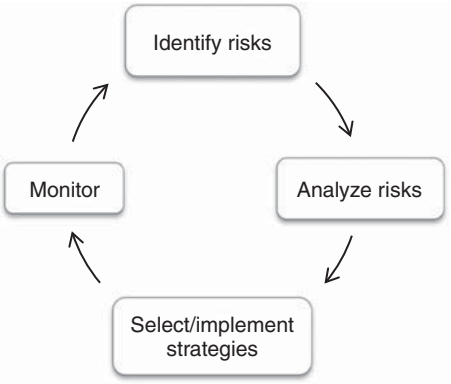

Figure 15.4 Clinical risk management process that ensures safety of medical devices in clinical environment.

- Identification of possible risks
- Prevention of harm, injury, and loss
- Control of systems and processes in a way to avoid possible risks

As shown in Figure 15.4, risk management does not stop after the identification, analysis, and control of possible risks. It is crucial to monitor the whole process for possible future risks or risks that could not be identified or solved in the first place.

In biomedical telemetry, where several medical devices are used for different reasons, for example, diagnosis, monitoring, and treatment, clinical risks are becoming more feasible. Implantable or ingestible devices which are placed inside the human body as well as simplified wearable devices can be used for monitoring and transmitting physiological parameters and vital data to other devices. Medical devices can interact, interfere, or malfunction, and the possibility of such effects further increases inside a clinical environment where several other electronic devices and equipment are being used at the same time. This means that clinical safety should be evaluated with a serious perspective while designing such systems in a way to prevent, minimize, or even eliminate clinical risks that can lead to threats for patient health and safety.

Some examples of harm related to clinical safety in biomedical telemetry are given below.

- The patient does not receive the right dose of a drug due to malfunction of implanted drug delivery system or due to problems of the telemetry link and/or remote control.
- Invasive diagnostic medical devices miss or cannot identify a possible threat to human health.
- Treatment devices or drug delivery systems deliver, by mistake, a medication that the patient does not need, thus resulting in adverse drug reaction.

- Operational device problems or malfunctions could result to incorrect or misleading diagnosis. An erroneous diagnosis could lead to mistakenly prescribing medication that either does not treat the disease or aggravates the disease symptoms.
- Interference issues could cause a medical device to operate in an improper way and cause several adverse reactions to patient health and safety.

15.4.3 Establishing Clinical Safety

Kohn et al. (2000) characterized medical errors as responsible for a higher number of annual deaths as compared to those caused by breast cancer, HIV, and road traffic accidents combined. Moreover, Nash (2012) shows that only a small fraction (less than 10%) of physicians are providing the best possible health care conditions for their patients in hospitals. Given the significance of clinical safety and its impact on patient health, as well as the growing need for more advanced medical devices that can be placed even inside the human body, ensuring clinical safety and avoiding clinical risks become more vital than ever before. In the same study, a robust, comprehensive, and integrated data infrastructure is proposed to continuously track the quality-of-care metrics and clinical safety issues in an attempt to minimize the clinical risks and the problems related to them (Nash, 2012). Web-based tools, rather than traditional methods, are suggested for real-time data collection, aggregation, statistical analysis, and report/graph generation, giving a significant boost to the effectiveness of current systems. Systems proposed try to deal with critical elements highlighted by the Institute of Medicine (IOM) (Kohn et al., 2000).

15.5 HUMAN FACTOR AND USE ISSUES

Human factor is a discipline that focuses on all those variables that affect the performance, reliability, and effectiveness of a medical device in terms of its interaction with the end user (Carayon, 2011). Errors in the use of medical devices are often attributed to the design of the user interface of the device or to the lack of knowledge regarding its proper use or some of its functionalities. Errors taking place while the medical device is operating could, in some cases, lead to injury or even death. Such errors may cause erroneous diagnosis, misleading monitoring, or ineffective patient treatment. Therefore, it becomes obvious that medical devices should be designed by taking into account the impact of the design in terms of safe use.

Use-related hazards are best identified and addressed by human factors engineering (HFE) (Lin et al., 1996). The ultimate goal of HFE is to minimize, ideally eliminate, any use-related hazards and assure that users are able to use the medical devices safely and effectively, as intended, throughout the product life cycle (FDA, 2000). Considering how and by whom a medical device will be used is highly significant in addressing use-related hazards. Substantial components of such considerations include:

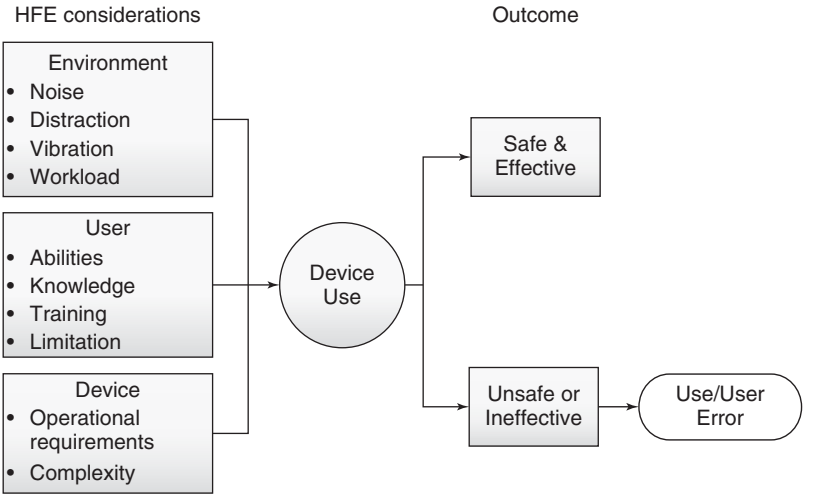

Figure 15.5 Interaction of HFE considerations could result in either safe and effective use or use error.

- User profile (e.g., patient, family member, qualified users)
- Typical and atypical uses of the device
- Device characteristics and particularities
- Environmental use characteristics
- Interaction between users, medical device, and use environment

In Figure 15.5, all the aforementioned components of HFE and the possible outcome of the interaction of the user with the medical device are being presented. The ineffective or unsafe use of the device could cause a use/user error, possibly affecting the patient's health or treatment process.

Most commonly, analysis and testing of prototype devices are carried out with actual users in an attempt to identify and investigate all possible usage scenarios that may lead to unanticipated hazards. This step is highly important because it is extremely difficult to identify and foresee all possible use-related problems in advance. After identifying any possible use-related hazards, hazards are mitigated or controlled by modifying the device–user interface or the abilities of potential users to use the specific device (e.g., training users, limiting use to qualified users).

15.5.1 Use-Related Hazards

Evidence from researchers suggests that the frequency and consequences of hazards resulting from medical device use might, by far, exceed those arising from device failures. A report by the IOM released in November 1999 estimated that as many as 98,000 people die every year from medical errors that occur in hospitals, a number

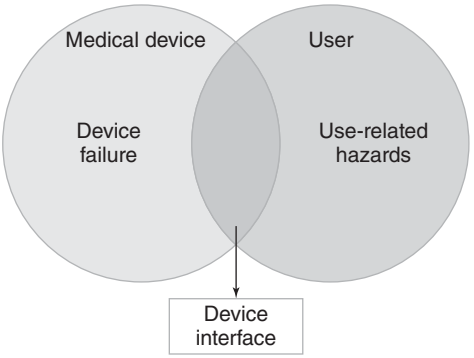

Figure 15.6 Medical device–interface–end user: How use-related hazards can affect device use and cause failure.

which is much higher than the number of people who die from vehicle accidents, breast cancer, or AIDS.

A medical device can be used safely and effectively if the device features, the operating environment, and the user capabilities are considered by the manufacturer as parameters during the design process. Operational hazards may cause a medical device to fail or malfunction and, thus, threaten the patient's health. Apart from operational safety or device failure, an erroneous user interaction with the device can also cause the device to fail. Use-related hazards and device failure hazards are connected as shown in Figure 15.6.

Use-related hazards can occur for one or more of the following reasons:

- Devices are used in ways that were not anticipated by the designer.
- Devices are used in ways that were anticipated but inadequately controlled for.
- Device use requires physical, perceptual, or cognitive abilities that exceed those of the user.
- Device use is inconsistent with the user's expectations or intuition about the operation of the device.
- The use environment affects device operation and this effect is not understood by the user (patient or qualified user).
- The user's physical, perceptual, or cognitive capacities are exceeded when using the medical device in a particular environment.

Use-related issues can become hazards or threats for human health under specific circumstances. For example, a user could calibrate a medical device intended for home use in a wrong way, use the device, and then act on the results that the device provides. In this case, inaccurate results are obtained because the device was not properly calibrated, and decisions involving a patient's health are made on these inaccurate results.

As home health care is becoming increasingly common due to the superior advantages (great improvement in quality of life, minimizing costs) and the unique challenges and opportunities it provides compared to traditional health care systems inside hospitals, use-related issues in home health care should be considered so that human health and safety are secured. Home health care has been enabled by the use of medical devices that can remotely connect to a hospital or a base station and transmit real-time physiological data. As a result, doctors are given the ability to diagnose or monitor diseases without the need of being physically close to the patient. In an environment where patients themselves rather than qualified users use the medical devices which are responsible for their disease monitoring or treatment, use-related hazards are becoming more apparent. Doctors should ensure that these devices are being used as intended by the patients or their family so that they can be sure about the validity of the results they get, remotely.

Due to the significance of home health care in modern medicine, in 2010 the FDA kicked off its Medical Device Home Use Initiative to assure the safety, quality, and usability of such medical devices (FDA, 2010). The Initiative's five actions can be summarized as follows:

- Developing formal guidance documents for home health care devices.
- Creating a labeling repository which provides online access for care recipients and caregivers on the proper use of these devices.
- Partnering with home health accrediting bodies to assess and provide training for home health care providers.
- Increasing postmarket surveillance of approved devices to understand their functionality and alert caregivers to specific risks identified by real-world usage
- Increasing public awareness on using the devices as directed

Apart from the aforementioned initiative, the FDA has also organized a Human Factors Program. In this program, the FDA works along with manufacturers to help ensure the application of human factors engineering to the design of new medical devices as well as to postmarket surveillance of currently marketed devices.

15.6 ELECTROMAGNETIC COMPATIBILITY AND INTERFERENCE ISSUES

The frequency bands which are of main interest to biomedical telemetry systems are the Medical Implant Communications Service (MICS) band and the industrial, scientific, and medical (ISM) bands. Each of these bands has advantages and disadvantages and is, thus, applicable to different medical scenarios.

The MICS band was adopted by the U.S. Federal Communications Commission (FCC) on October 10, 1999, and has been developed for use in medical implant communication systems [European Telecommunications Standards Institute (ETSI),

2002; FCC, 1999]. Example applications include heart pacemakers and defibrillators, while, in the future, wireless medical implant systems might include automated drug delivery devices and 24-hr real-time patient monitoring. The maximum available bandwidth of the MICS band has been set by the standard to 300 kHz. The MICS band uses the frequency range between 402 and 405 MHz and gives an implantable medical device the ability to be controlled and monitored from outside. Due to SAR limitations and interference issues, MICS band systems have an upper limit on the effective radiated power (ERP) that equals 25 μW. The MICS band enabled additional flexibility as compared to older inductive technologies by giving a range of a couple of meters in the communication link. However, due to the limited bandwidth available, MICS systems exhibit low bit rates as compared to systems using the higher frequency WiFi or Bluetooth technologies.

The ISM bands are portions of the radio spectrum which are internationally reserved for industrial, scientific, and medical purposes other than communications. In the early 1990s the FCC allowed the use of ISM bands for unlicensed communication equipment, which were defined in the following frequency ranges:

- 902–928 MHz
- 2400–2483.5 MHz
- 5725–5875 MHz

In the United States, use of these bands for communication purposes is regulated by part 15 of the FCC rules. The maximum output power fed into the transmitting antenna is defined as 30 dBm (1 W), while the maximum effective isotropic radiated power is set to 36 dBm (4 W). As compared to the MICS band, the ISM bands provide (a) easier antenna design due to the higher operation frequency and the expanded expertise obtained through the use of WiFi and Bluetooth systems in recent years, (b) better SAR distributions, and (c) wider bandwidth. However, signals at higher frequencies are attenuated considerably faster inside the human body, thus making the band difficult to adopt, especially for invasive (implantable and ingestible) devices.

In 1993, the International Electrotechnical Commission (IEC) published the first edition of the international electromagnetic compatibility standard for medical devices (60601-1-2) (IEC, 1993). Soon after, the European Committee for Standardization (CENELEC) adopted it as a European Norm (EN) standard with only minor changes. Electromagnetic compatibility (EMC) means that a device is compatible with its electromagnetic environment and does not emit EM energy of levels that could cause electromagnetic interference (EMI) to other devices in its close vicinity. EMC is a major concern in medical electronics and devices given the fact that functioning anomalies may be life threatening.

With all those medical devices used today, design approaches to face the EMC problems are straightforward and mainly include shielding and filtering techniques to protect the device. Pacemakers are typical examples of medical devices which are susceptible to EMC issues. However, pacemakers have greatly improved over the years with respect to compactness and immunity to RF interference so that current designs can foresee the electromagnetic environment where the device will be placed.

As a result, nowadays, pacemakers are very reliable to use and may only fail under extreme conditions.

EMI is defined as the disturbance that affects an electrical circuit as attributed to either electromagnetic induction or electromagnetic radiation emitted from an external source placed in the vicinity of the circuit. Problems caused by EMI can be minimized or eliminated by ensuring that all electronic equipment of the device is operated with a good electrical ground system. However, this can be hard to implement when it comes to invasive medical devices. Given the fact that the world's industrialized nations are becoming increasingly dependent upon the use of electrical and electronic equipment, EMI issues for medical devices are becoming more feasible than ever before.

EMI of devices can be classified under the two headings of "internal" and "external" EMI. Internal EMI is associated with the devices and components which are present within the device, such as resistors and transistors. External EMI is generated by sources outside the system and is normally the kind of EMI which causes most of the problems to medical devices. The effects of the EMI should be of great concern for designers/manufacturers of medical devices, qualified personnel, and end users of those devices.

For electromagnetic disturbances to cause interference, they must propagate in some way. The three main physical mechanisms of electromagnetic propagation are (Figure 15.7):

- Conduction Electromagnetic energy may be conducted in either the common mode or differential mode. This can be via power cables, earth conductors, signal cables, antenna feeders, or other low-impedance paths.
- Reactive Coupling Electromagnetic energy may also propagate by reactive coupling, either inductive or capacitive.
- Radiation For frequencies above approximately 30 MHz radiation tends to be the dominant propagation mechanism.

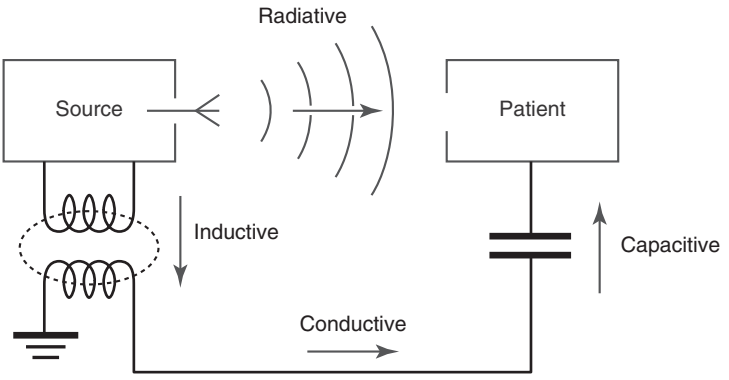

Figure 15.7 Schematic description of EMI coupling paths.

As in the case of EMC, EMI is a major concern for the design, fabrication, and testing of medical devices. Interference phenomena may cause operational problems, which can, in turn, result in patient life-threatening events.

It is important to highlight that interference issues are more intense in the ISM band, as more and more products use the 2.4-GHz portion of the radio spectrum. For example, interference issues are most commonly produced by WiFi networks or Bluetooth links which operate in the vicinity of the medical device under consideration. Due to its global availability, the ISM band constitutes a popular frequency band suitable to low-cost radios. New proposed solutions such as the Institute of Electrical and Electronics Engineers (IEEE) 802.15 technologies and Bluetooth as well as the IEEE 802.11 technologies and microwave ovens operate in the ISM band and are expected to cause interference issues to the medical devices since they operate in the same environment and frequency space. Designers should include all kind of interference right from the start and design the devices in a way to minimize or even eliminate the EMI effects.

At this point, it is worth noting that special mention is made on both IEEE and International Commission on Non-Ionizing Radiation Protection (ICNIRP) standards (see applicable guidelines for more info) concerning interference issues between mobile phones or any other electromagnetic device with pacemakers, a widely used medical device, which uses electrical impulses to regulate the beating of the heart. In the IEEE C95.1-2005 standard a suggestion of keeping a minimal separation distance between mobile phones and implantable cardiac devices of 15–22 cm is made, without though any specific restrictions or further recommendations (IEEE, 2005).

15.7 APPLICABLE GUIDELINES

The rapid development of technologies and systems that use RF EMFs to provide two-way radio communication between medical devices and exterior equipment poses several questions related to human exposure to EMFs.

The first standard of the American National Standards Institute (ANSI) that covered issues related to exposure to RF radiation was issued in 1966 and recommended that exposure should be limited to field levels no higher than 10 mW/cm^2 with a 0.1-hr (6-min) averaging time (ANSI, 1966). In 1982, IEEE developed the C95.1-1982 standard, which described the recommended limits for human exposure to RF fields (IEEE, 1982). Industry, engineers, and medical researchers contributed to the development of this standard as the first SAR-based human exposure standard in the world. It is noteworthy that the FCC wrote a set of regulations which asked RF services to comply with the limits proposed in C95.1-1982. Nine years later, in 1991, IEEE published a revised standard, C95.1-1991 (IEEE, 1991). The new standard decreased the maximum recommended RF exposure levels and extended the frequency range covered by the original standard. In 1996, upon the request of the U.S. Congress, a mandatory standard was adopted by the FCC for evaluating the radiation effects on human beings (FCC, 1996). Three years later, in 1999, the European Union Health Council, agreed on a similar recommendation for limiting exposure to

electromagnetic fields. The recommendation adopted was based on exposure limits that had been earlier proposed by the ICNIRP. At the same time a new revision of IEEE C95.1-1999 was introduced. The latest revised standard available is the IEEE C95.1-2005 (IEEE, 2005). Today, any of the standards which are adopted worldwide are based on the C95.1 standard developed by IEEE and the recommendations of ICNIRP, and quantify RF exposure in terms of the SAR.

15.7.1 Development of IEEE C95.1-1991 Standard

The C95.1-1991 standard was developed by the IEEE Standards Coordinating Committee 28, Non-Ionizing Radiation Hazards (SCC-28). The C95.1-1991 standard is so important because it was the first two-tiered standard. It was based on SAR values as this approach had already been incorporated into the previous ANSI C95.1-1982 standard and it was developed after an extensive and serious evaluation of all available scientific literature. At that time, SCC-28 consisted of researchers (in a percentage of about 70%) as well as people from various organizations and the industry. While developing the standard, SCC-28 considered a large number of input sources and research studies and evaluated them against several scientific criteria. After excluding papers that did not include measured EMF levels, SCC-28 gathered around 120 papers for consideration. Following an extensive analysis of the topics covered and the conclusions derived in these papers, SCC-28 reached a consensus that a standard for exposure could be set.

The SAR value of 4 W/kg, which is temporally and spatially averaged over the whole body mass, was the final threshold that was adopted by the committee. Several adverse biological effects were demonstrated above this threshold, such as disruption of work schedules in trained animals. For example, a monkey trained to push a button six times in order to get a banana decided that it did not want a banana when exposed to a 4-W/kg field. As soon as the field was removed, the monkey soon decided that it was hungry after all. The committee deems these results to be thermal effects of the application of electromagnetic fields. Recognizing and understanding the scientific uncertainty and the biological variability in the human population, the committee applied a safety factor of 10, setting a SAR value of 0.4 W/kg for controlled/occupational exposure and an additional safety factor of 5 for the general population, resulting in a total margin of 50 and a SAR value of 0.08 W/kg. Since, for a given exposure, the SAR distribution inside the human body can vary from point to point, a partial-body limit was also introduced. The local SAR limit in the IEEE C95.1-1991 standard was set to 1.6 W/kg for the uncontrolled environment in the body or 8 W/kg for the controlled environment and is averaged in any 1 g of tissue (defined as a tissue volume in the shape of a cube) (IEEE, 1991). Clearly, the C95.1-1991 standard provides recommendations in an attempt to prevent adverse thermal effects that could result in limited functionality of the human body. It is worth noting, however, that some scientists consider this whole topic as unfounded because the assessment criteria used in deriving the reports of biological effects did not take the mechanisms of interaction into account.

TABLE 15.2 MPE Limits for Uncontrolled Environments (IEEE C95.1-1991)

Frequency (MHz)	Power Density (W/m^2)
0.1–1.34	1000
1.34–30	$1800/f^2$
30–400	2.0
400–2000	$f/200$
2000–100,000	10
100,000–300,000	Increases from 10 to 100

TABLE 15.3 MPE Limits for Controlled Environments (IEEE C95.1-1991)

Frequency (MHz)	Power Density (W/m^2)
0.1–1	9000
1–30	$9000/f^2$
30–300	10
300–3000	$f/30$
3000–300,000	100

As mentioned in the previous paragraph, the IEEE standard sets exposure limits for electric fields and magnetic fields that refer to the whole body and are averaged over time. Limits can be expressed in terms of the maximum permissible exposure (MPE). The IEEE's MPE limits for both general public and occupational environment are shown in Tables 15.2 and 15.3. Limits indicated are spatially averaged over the whole body and time averaged over 6 and 30 min for controlled and uncontrolled environments, respectively.

15.7.2 International Commission on Non-Ionizing Radiation Protection and Its Role

The ICNIRP is an international commission specializing in the protection from nonionizing radiation and consists of an independent group of experts. The activities of the organization include:

- Responsibility to evaluate the current state of knowledge regarding the effects of nonionizing radiation (NIR) on humans
- Responsibility to provide science-based advice and recommendations related to human protection against the effects of nonionizing radiation

ICNIRP was founded in 1992 by the International Radiation Protection Association (IRPA), located in Geneva. It consists of a main commission with 14 members,

4 standing committees of 8 members, and a large group of consulting experts. The 4 standing committees are the following: (a) SCI on epidemiology, (b) SCII on biology and medicine, (c) SCIII on physics and engineering, and (d) SCIV on optical radiation. ICNIRP collaborates with a number of regional and international partners and organizations such as the WHO, the International Labor Organization (ILO), the European Council (EC), DG SANCO (Health), the European Society for Skin Cancer Illumination (CIE), and the International Commission for Occupational Hygiene (ICOH).

In order to fulfill its aim and provide information and advice on the potential health hazards due to EMF exposure, ICNIRP periodically publishes scientific reviews and reports and arranges relative meetings. The results combined with conclusions from studies carried out by other organizations form the ICNIRP guidelines. Examples are the guidelines for limiting exposure to EMF, lasers, and ultraviolet radiation.

Despite the wide use of the ICNIRP guidelines and guidance, the commission has already been criticized. The European Council has stated: "It is most curious, to say the least, that the applicable official threshold values for limiting the health impact of extremely low frequency electromagnetic fields and high frequency waves were drawn up and proposed to international political institutions (WHO, European Commission, governments) by the ICNIRP, an NGO [nongovernmental organization] whose origin and structure are none too clear and which is furthermore suspected of having rather close links with the industries whose expansion is shaped by recommendations for maximum threshold values for the different frequencies of electromagnetic fields" (Europe Council, 2011).

15.7.3 Issues on Developing Safety Standards

Developing a standard related to human health is of great importance due to the severity of the process itself and becomes even more crucial at a time when the actual interaction mechanisms between RF radiation and human tissues are still under consideration (Lin, 2000). There are two major issues related to the development of human exposure standards. The first issue is related to the procedure and process invoked to get the results and set the standards. The second issue has to do with the philosophy adopted in the process of developing the guideline or standard.

Typically, development of guidelines or standards should comprise (a) review of the available scientific literature, (b) accumulation of pertinent databases, and (c) identification of possible hazards. Following the considerations mentioned, the process continues to the drafting step, which often includes a review of the existing guidelines and standards. The process is completed when the exposure guideline have been finalized, published, and adopted by a recognized body. It is important to highlight that acceptance of the resulting standard is enhanced when the procedure invoked is as transparent as possible.

The identification of a hazard should be accompanied by a way or at least a philosophy of protection. This also applies to the possible hazards of EMF radiation on human health. The philosophical approaches to setting permissible exposure limits for RF radiation can be classified into the following categories (Lin, 2000):

- No demonstrable effect
- Observable effects with no known physiological consequence
- Minimal physiological consequence
- No adverse effect

It becomes obvious that the adoption of any no-effect philosophy would result in a non-wireless-technologies society, similar to the one of the nineteenth century. Given the aforementioned issues, it is apparent that setting, accepting the validity, and finally adopting a guideline or a standard could become really tricky.

15.7.4 Evolution and Comparison of Guidelines

Difficulties and different approaches in adopting the standards, combined with the publicly expressed lack of confidence pertaining to the maximum permissible MPE levels, have given rise to the development of two different sets of guidelines for limiting human exposure to RF radiation worldwide (Lin, 2003). IEEE and ICNIRP adopted different biological rationales to propose the RF exposure guidelines, resulting in two sets of distinct MPEs, which differ in terms of SAR levels and averaging tissue volume. Apart from the differentiation of standards across the two organizations, as already mentioned, there have been changes over time on the IEEE C95.1 standard to include available scientific data. Several scientific groups worldwide are trying to examine the existing guidelines or MPEs for human exposure in order to decide on the safety of the existing guidelines and come up with an explicit philosophy and procedure invoked in the process of setting the standards. The use of SAR was initiated as a recommendation of the National Council of Radiation Protection and Measurements (NCRP) and was adopted by the American National Standards Institute (ANSI) in 1982.

For example, the IEEE C95.1-1991 standard limited human exposure to RF radiation based on SAR dosimetric quantities and set the maximum SAR level to 1.6 W/kg averaged in 1 g of body tissue (IEEE, 1991). The guidelines proposed by ICNIRP restricted RF exposure by setting the maximum SAR level to 2 W/kg averaged in any 10 g of contiguous tissue (ICNIRP, 1998). For reference, both SAR levels mentioned earlier are referred to head tissues. Aside from the quantitative difference between the IEEE and ICNIRP standards (1.6 or 2 W/kg), there is also a difference in the definition of the tissue mass used to define the SAR standards (1 g for IEEE standard or 10 g for ICNIRP standard). This difference could have a great impact on the actual quantity of RF energy allowed to be deposited in human tissues. Due to the fact that the distribution of absorbed microwave energy varies from point to point inside the human body, a larger averaging mass (like the 10-g mass used in the ICNIRP standard) would tend to artificially smooth out the SAR distribution. Apart from the distribution smoothing of SAR, a larger averaging mass also tends to lower the value of the measured SAR by a factor of 2 or more (Lin, 2003). This means that the ICNIRP SAR limit of 2 W/kg averaged over 10 g of tissue could be equivalent to 4 W/kg or higher averaged over 1 g of tissue.

In many cases, such as in the example of the human eye mentioned in Lin (2003, 2006) or the muscle tissue, the 10-g tissue mass used to compute the average SAR distribution completely ignores the wide variation of SAR distribution and masks the intensity of the absorption of RF energy at the superficial layer of tissues. Another example of the distraction that a larger SAR averaging volume could cause is related to the anatomy of the human brain. Types and populations of cells and neurons inside the human brain are notably different even in 1 g of tissue. Absorption of RF radiation highly depends on the electric properties of the tissues involved, so that a larger averaging volume could mask the absorption of RF energy by neighbor cells or neurons inside the human brain.

As clearly seen by the examples mentioned above, SAR is a localized quantity and its value significantly depends on the averaging volume or mass. The larger the averaging volume or mass, the lower the resolution and sensitivity of SAR get, and the less useful the SAR becomes in terms of a metric which is used for quantifying the localized exposure to RF energy and the biological response to radiation.

As pointed out earlier, there are two different sets of standards worldwide for EM radiation safety. The first one has been developed, proposed, and published by IEEE and the second one by ICNIRP. Although in the past there were basic differences between the standards, most of them analyzed in the previous paragraphs, the latest revision of the IEEE standard (IEEE C.95.1-2005) is more similar than ever before with the ICNIRP standard, as indicated in Tables 15.4 and 15.5.

In Table 15.4 the whole-body average and localized SAR basic restrictions are presented according to the ICNIRP 1997 standard. There are two main parameters that should be well defined for these limits to get their actual meaning, the averaging time and the averaging tissue volume. All SAR values in Table 15.4 are to be averaged over any 6-min period. According to ICNIRP standards, the SAR averaging mass is defined as any 10 g of contiguous tissue without restrictions in terms of shape of the averaging mass.

In Table 15.5, the whole-body average and localized SAR basic restrictions are presented for the IEEE C95.1-2005 standard. Consistent with the approach used in the previous version of the IEEE C95.1 standard, a traditional safety factor of 10

TABLE 15.4 Basic Restrictions for Time-Varying Electric and Magnetic Fields for Frequencies from 100 kHz to 10 GHz According to the Latest ICNIRP Standards (1997)

Exposure Characteristics	Frequency Range	Whole-body Average SAR (W/kg)	Localized SAR (Head and Trunk) (W/kg)	Localized SAR (Limbs) (W/kg)
Occupational exposure	100 kHz–10 GHz	0.4	10	20
General public exposure	100 kHz–10 GHz	0.08	2	4

TABLE 15.5 Basic Restrictions for Time Varying Electric and Magnetic Fields for Frequencies from 100 kHz to 3 GHz According to Latest IEEE C95.1-2005 Standard

Exposure Characteristics	Frequency Range	Whole-body Average SAR (W/kg)	Localized SAR (Peak Spatial Average) (W/kg)	Localized SAR (Limbs) (W/kg)
Occupational exposure	100 kHz–10 GHz	0.4	10	20
General public exposure	100 kHz–10 GHz	0.08	2	4

has been applied to the established SAR threshold for such effects, yielding a SAR of 0.4 W/kg averaged over the whole body. As mentioned earlier, the averaging time and tissue volume should be defined. Contrary to the previous versions of IEEE C95.1, the averaging volume on the IEEE C95.1-2005 standard has been changed. The SAR is now averaged over any 10 g of tissue, defined as a tissue in the shape of a cube with volume of approximately 10 cm^3. In cases where the cubical volume rule cannot be satisfied (e.g., at the surface of the body), special rules apply for setting the SAR value in a given voxel. The averaging time for fields and power density are presented in Table 15.6. It is noteworthy that for the first time in its history the IEEE C95.1-2005 standard instituted exclusion for the pinnae or the external ears by relaxation of the above-mentioned basic SAR restriction from 2 to 4 W/kg. This relaxation by IEEE segregated the tissues of pinnae from all other of the human's head.

As clearly seen, the differences between the standards after the latest revision of IEEE C95.1 include the averaging tissue mass and the averaging time period that are being used for SAR calculation.

TABLE 15.6 Averaging Time of SAR Calculation for General Public in IEEE C95.1-2005 Standard

Frequency Range (MHz)	Averaging Time	
0.1–1.34	6	6
1.34–3	$f_M^2/0.3$	6
3–30	30	6
30–100	30	$0.0636 f_M^{1.337}$
100–400	30	30
400–2000	30	
2000–5000	30	
5000–30,000	$150/f_G$	
30,000–100,000	$25.24/f_G^{0.476}$	
100,000–300,000	$5048/[(9f_G-700)f_G^{0.476}]$	

Note: f_M is the frequency in MHz, f_G is the frequency in GHz.
Source: IEEE (2005).

TABLE 15.7 Ranges of Threshold Currents for General Public (ICNIRP, 1998)

	Threshold Current (mA)			
Effect	50/60 Hz	1 kHz	100 kHz	1 MHz
Touch perception	0.2–0.4	0.4–0.8	25–40	24–40
Pain on finger contact	0.9–1.8	1.6–3.3	33–55	28–50
Painful shock	8–16	12–24	112–224	
Severe shock	12–23	21–41	160–320	

Comparative evaluations of the IEEE C95.1-1999 and IEEE C95.1-2005 safety standards have been performed for implantable antennas (Kiourti and Nikita, 2012a, 2013). In these studies, numerical investigations were carried out for antennas implanted inside the skin tissue of the human head for applications such as intracranial pressure monitoring, stroke rehabilitation, brain wave sensing, and brain edema evolution monitoring. The IEEE C95.1-1999 standard was found to be much stricter, limiting the maximum allowable net input power to the antenna to more than six (Kiourti and Nikita, 2012a) and four (Kiourti and Nikita, 2013) times lower than that imposed by the IEEE C95.1-2005 standard. Furthermore, compliance with the recent IEEE C95.1-2005 standard was found to be almost insensitive to head properties (anatomical features and dielectric parameters), in contrast with the IEEE C95.1-1999 standard (Kiourti and Nikita, 2013).

Finally, it is worth noting that the new ICNIRP guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields have been developed to take into account safety issues regarding intrabody communications (currents propagating through the human body). Threshold currents that produce perception and pain or even shocks are presented in Table 15.7. It has been shown that threshold currents vary only a little over the frequency range of 100 kHz–1 MHz, while they are unlikely to vary significantly over the frequency range up to about 110 MHz.

15.8 OCCUPATIONAL SAFETY

Occupational safety for biomedical telemetry can be divided into two major categories: (a) safety that is related to patients who use wearable, implantable, or ingestible medical devices that could interact or interfere with other devices in the occupational environment of the patient and (b) safety that is related to the qualified users of the medical devices who are responsible for the patient monitoring and treatment. Either way, safety concerns arise for both patients who use a biomedical device to maintain their good health and qualified users who use medical equipment as part of their work.

As far as interaction or interference of the medical devices with their surrounding occupational environment is concerned, great progress has been made regarding the design of biomedical devices. Having in mind all those risks and possible interactions of the medical devices that have been analyzed and discussed earlier in this

chapter, designers try to foresee and solve/eliminate any problems that could become to hazards or life-threatening events. Gustrau et al. (2002) presented a study about the possible interference of low-frequency electric and magnetic fields with implanted cardiac pacemakers.

Safety of workers with biomedical devices is currently based on general and conservative estimations. These estimations introduce great uncertainties and raise many questions about the safety of workers. On the other hand, workers and their employers demand a more realistic estimation of the risks and related hazards.

In order to improve the assessment of the occupational risk for workers with medical devices, the Federal Institute of Occupational Safety and Health in Germany has launched two projects. The first project investigates the voltage induced in the medical device due to the electric and magnetic fields emanating from electrical devices in the workplace, whereas the second project investigates the immunity of medical devices to low-frequency electromagnetic fields. Combining the results of both projects will enable a more detailed analysis on how medical devices interact with occupational equipment and electromagnetic fields and will provide valuable information toward reducing the risks and hazardous events for workers with medical devices.

As long as workers and qualified users of biomedical equipment are concerned, safety issues are strongly related to the extensive exposure to electromagnetic fields generated for telemetry communication. Despite the fact that such fields are not so intense due to safety issues discussed earlier, workers are exposed to electromagnetic fields for a much longer period of time as compared to patients, so that specific guidelines and safety standards should apply to them.

15.9 FUTURE RESEARCH DIRECTIONS

Safety of medical devices with telemetry functionalities is a field of growing scientific interest. The field has attracted significant research efforts, especially during the last 10 years as attributed to the technology and microelectronics advances which have enabled the use of devices with telemetry abilities to be implanted or ingested within the human body for diagnosis and therapy applications. Implanted medical devices have been tested and are being used as diagnostic tools for heart or neural diseases. Proposed implanted systems for contiguous monitoring of physiological parameters are waiting for testing in real conditions. Ingested devices have already been used to investigate diseases and disorders of the small intestine where traditional methods failed to deliver reliable results. All those innovative medical devices have the potential to greatly improve the patient's quality of life. Despite the remarkable progress in the last years, there is still ground for research and several engineering problems to be solved.

As far as operational issues, product and device hazards, patient and clinical safety, and human factors are concerned, advanced design processes, engineering, experience, and user training are expected to minimize or even eliminate the possible hazards. It is important to highlight, however, that, regardless of the recent technological advances, some of these risks cannot be eliminated completely because of

their nature. Thanks to the experience gained and the statistical data collected by the current health care system and medical devices, safer devices are expected to be designed and be available in the market soon. In other words, engineers are expected to be able to design fail-safe devices based on the causes of failures or malfunction of the current devices. As a result, from an operational point of view, medical devices will be safer to use over time.

The real challenge, however, lies in the full understanding of the interaction of electromagnetic radiation with human tissues. Biological effects related to tissue exposure to repeated, prolonged, or lifelong RF energy emitted by low-power medical devices have only been very recently investigated. The existing scientific results are, therefore, equivocal and arguable in many respects, and scientists' understanding of biological effects of exposure to RF radiation is still evolving over time. As a result, as new research findings become available, it becomes necessary to periodically evaluate and possibly revise any criteria set forth for human safety due to exposure to RF radiation.

Last but not least, global harmonization of RF exposure standards would be a very desirable goal for consumers, manufacturers, and operators. At this time, two standards (IEEE C.95.1-2005 and ICNIRP) are available which are based on SAR limitations (ICNIRP, 1998; IEEE, 2005). However, the harmonization process should take place with respect to the overall improvement of the standards in terms of higher precision in the specification of the SAR, lower uncertainties in exposure assessment, more accurate biological results, and greater reliability in health status data. Advances and findings in bioelectromagnetics research will continue to facilitate this process. A global scientifically based and recognized exposure standard would help to address the existing widespread public concern related to the adequacy of the current guidelines.

15.10 CONCLUSION

In this chapter, a summary was provided regarding the safety issues encountered in biomedical telemetry. Safety issues related to device integrity, device use, clinical treatment, and RF exposure were presented. Compatibility and interference issues as well as applicable RF exposure guidelines were also discussed. Future research directions were finally proposed to improve safety in biomedical telemetry.

Regarding the device itself, operational and occupational safety, as well as user issues, human factors and device hazards were discussed. Due to the nature of biomedical devices used in biomedical telemetry, there exist several risks which could threaten the health of the patient during their operation. In addition, as for any electronic device, medical devices carry a risk of failure or malfunction. Moreover, due to human interaction with medical devices, user issues and additional hazards might appear. Finally, the clinical environment of the patient could result in a problematic operation of medical devices used for biomedical telemetry.

In addition to those common hazards, there are serious concerns related to the safety of patients exposed to repeated and prolonged exposure to RF energy. Different

approaches are followed for the derivation and adoption of standards, and different sets of guidelines are developed for limiting human exposure to RF radiation, so that public concern about their adequacy is, in turn, spreading. Two standards are currently in use [IEEE C.95.1-2005 and the ICNIRP standard (1998)] which use the SAR distribution to quantify and limit the RF exposure to human tissues. Their major differences are related to the tissue mass used for averaging and the average time period used in the SAR measurement.

Finally, an attempt was made in this chapter to provide some general directions for future research. For example, hazards related to the design of medical devices and their interaction with the end user (patient or qualified user) could be minimized by using the data obtained by medical devices which are currently in use. Furthermore, advanced scientific findings about the biological effects of RF radiation are expected to come over time, which should be used to develop global standards, that is, standards that would be adopted by every organization worldwide.

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