Guest Editorial for the Special Issue on Wireless Real-time Health Monitoring Technology for Personalized Medicine

I. Scope of the Special Issue

RECENT global focus on healthcare has stimulated research and development of innovative technologies which address many sustainability issues of the current healthcare provision models. Rapid advances in mobile, wireless, and sensing technologies have enabled new opportunities in healthcare, enabling cost-effective and efficient healthcare delivery in home, hospital, assisted living, and nursing home settings [1]. Remote diagnosis, patient and elderly monitoring, sensing of vital parameters of people suffering from chronic diseases such as asthma, diabetes, neurodegenerative and cardiovascular diseases, are just a few examples.

Medical care is moving toward "personalized medicine," where therapy will be specific for a person, in a specific environment, and with a unique history of epigenetic influences. This type of healthcare will be more cost effective than our current system which is based on validating therapy on the basis of population testing because there will be increased accuracy. Wireless monitoring will be vital for providing the information needed to tailor therapy to a person.

However, these modern healthcare systems have additional critical requirements and challenges compared to traditional wireless networks [1], [2]. These include: timely and reliable access to diagnostic information in many acute care settings, energy-efficient biosensor design, biocompatibility and "chronic implantability," system integration, sensor miniaturization, patient safety, emergency response and detection.

Groundbreaking technological developments in the field of wireless healthcare biotechnology can address the aforementioned challenges and revolutionize healthcare delivery and wellness management through the development of novel on-/in-body biosensors, radio frequency (RF) medical devices, intrabody communication systems, and innovative imaging modalities.

Advances in enabling technology for implants (semiconductor industry, packaging, biocompatible materials, etc.) have played a significant role in rapidly expanding the development and adoption of medical implantable devices for sensing (brain implants, glucose monitors, etc.) and stimulation (pacemakers, defibrillators, etc.) [3]–[5]. Flexible materials such as conductive fabrics and polydimethylsiloxane (PDMS) substrate, liquid metal, and paper, along with additive technologies like inkjet printing have led to the development of conformal, flexible and robust antenna designs for use with everyday clothing, wearable sensors, biomedical wireless sensors and RF identification (RFID) systems [6]–[8].

Development of wireless implanted medical devices requires the implementation of efficient implantable antennas [4], [5], [9]–[11]. They are integrated within the implant and, depending on the application, may operate in subcutaneous [4], [5] and/or deep-tissue environments [9]–[11]. Accordingly, design of on-body antennas that are specifically optimized for biomedical telemetry with wireless implants, has attracted significant scientific interest. Additionally, on-body devices for direct monitoring and recording of major physiological parameters inside the body, and subsequently transmitting this information using low power consumption [12] have attracted significant scientific interest. Further, wearable devices able to provide wireless power to the human intranet comprising implantable and other body-worn devices [13] have become a critical enabling component, since implants must often be charged from devices outside the human body. Wireless Power Transfer (WPT) eliminates the need for implantable batteries or cabling requirements, and makes biomedical implants more practical [14], resulting in more applications rapidly emerging, thanks to the appeal of charging wirelessly and conveniently.

Since antenna structure is the key component for the wireless interconnection of in-body (implantable, ingestible) and on-body (wearable, epidermal) devices within the framework of Wireless Body Area Networks (WBANs), a new generation of research work has been fostered investigating wearable or implantable nodes and addressing challenges related to the development of electrically small and conformal antenna structures that maintain efficient performance in the presence of human body [15] or in the presence of body tissues for *in vivo* applications [16].

Reliability of the communication link in WBANs also plays a key role and is highly dependent on the antenna design, operation frequency selection, and characterization of the intrabody propagation channel. Different frequency bands have been investigated for in-body devices, the most commonly employed being the Medical Device Radio Communication Service (MedRadio) band of 403.5 MHz, and the Industrial, Scientific and Medical (ISM) band of 2.4 GHz. Ultrawideband (UWB) frequency offers several advantages, such as very low power consumption, smaller size of the antennas and higher data rate, which are important for applications such as wireless capsule endoscopy (WCE), as higher data rates allow the streaming transmission of high quality images or videos and enable the localization and tracking of the

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wireless capsule. The effect of other medical implants (that contain steel, titanium alloys, tungsten, and other highly conductive materials), or medical wires, staples, and bands, on the radio channel characteristics between the implant and the on-body device, have become important research topics [17]–[19], especially when UWB frequency band is considered for implanted device communication in WBANs, due to the frequency-dependent, high attenuation suffered by the transmitted signal propagating across the human tissues.

Disease detection and diagnosis through the use of portable imaging devices is also envisioned as a transformative approach to healthcare, addressing many unsustainabilities of the current healthcare provision models. Microwave technology offers an affordable and portable alternative for the early detection of cancerous tissues, hemorrhages, internal injuries and other characteristic changes inside human tissues and has gained increasing attention toward the development of electromagnetic imaging (EMI) systems due to reduced complexity and miniaturization advantages compared to other techniques [20]. Each EMI system is mainly comprised of an antenna element or array of antennas (radiation sources) and a diagnosis approach that analyzes the changes in the behavior of the reflected or transmitted signals. To obtain the required penetration inside human tissues, EMI systems generally operate at lower microwave frequencies, around 1 GHz. Recent research efforts in EMI systems focus on techniques to reduce the antenna size while maintaining the required penetration inside human tissues, and address limitations related to strong mutual coupling between antenna elements located at a close distance to each other.

This IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION Special Issue on Wireless Real-time Health Monitoring Technology for Personalized Medicine solicited papers addressing innovative research activities which reveal the rapidly changing face and context of patient monitoring and healthcare delivery facilitated by wireless communications and sensing technologies. Contributions were encouraged on novel implanted and wearable sensory and monitoring systems, EMI algorithms and devices, computational and experimental bioelectromagnetics, covering new research, applications and case studies, along with enabling technologies. The special issue presents current and emerging trends; highlights challenges related to design, evaluation, and usability; and identifies open issues and future steps that will advance the domain.

II. OVERVIEW OF THE SPECIAL ISSUE

The papers in this special issue demonstrate some of the most exciting developments in antenna design, development, and evaluation and investigate important propagation and communication issues related to wireless powering and data telemetry for medical devices and implants. Applications range from implantable, ingestible and wearable systems to microwave imaging (MI) systems and radar sensing for vital sign monitoring. Papers in this collection use computational methods, experiments in phantoms, and *in vivo* measurements to provide important insights to the investigated technologies.

All papers submitted in response to our call for papers went through a rigorous peer review process, and 16 papers were selected for inclusion in the special issue. The collection of papers in this issue nicely cover a broad range of enabling technologies for in-body and on-body medical devices, advanced sensing and novel imaging modalities. Eight of these papers refer to the design, operation, and performance of in-body medical devices, three papers deal with the development of antennas operating in close proximity to lossy media, either for on-body applications or for RFID tags mounted on blood bags, two papers explore sensing technologies, and three papers focus on imaging modalities. Papers in this issue have relevance for key disease detection and diagnosis, like atherosclerosis and neurodegenerative diseases, and address applications ranging from colonoscopy and WCE, to head and thorax imaging.

The first six papers deal with in-body devices focusing on antenna design and issues related to WPT and communication with external monitoring/control equipment.

Manoufali *et al.* ("Compact Implantable Antennas for the Cerebrospinal Fluid Monitoring") investigate the feasibility of an implantable antenna to concurrently operate as radiator in a biotelemetry system and sensor of the dielectric properties of cerebrospinal fluid (CSF). The ultimate goal is to detect changes in CSF glucose and protein concentration that can be utilized in the diagnosis of neurodegenerative diseases. Three implantable antennas were designed exploiting narrow slits and gaps as capacitors for sensing the permittivity of CSF. *In vitro* measurements of CSF from pigs with different ages in the sub-1 GHz band (0.1–1 GHz) showed that the dielectric properties of the CSF do not reflect age-dependence and thus, sensing sensitivity is implicitly not affected by age. Finally, the implantable antennas were fabricated and tested inside a piglet's head and CSF simulants, exhibiting a shift in resonance frequency ranging from 31 MHz to 40 MHz for a permittivity increase by 14% at 400 MHz with a relative resonance sensitivity of 6%–8%.

Guardiola *et al.* ("Design and Evaluation of an Antenna Applicator for a Microwave Colonoscopy System") present the design of an antenna applicator for a microwave colonoscopy system. The applicator is designed as a compact cylindrical array of eight antennas attached at the tip of a conventional colonoscope. The presented design is composed by one transmitting and one receiving cavity backed U-shaped slot antenna elements fed by an L-shaped microstrip line. The antennas are low profile and present high isolation at 8 GHz. The applicator performance is assessed by means of simulations and experiments using a phantom composed by different liquids. High accuracy is reported in detecting flat and protruded lesions, 20 mm and 10 mm in diameter, respectively. The authors suggest integration of MI through the proposed applicator with conventional colonoscopy in a multimodal approach, in an attempt to improve the detection of subtle/flat lesions and to provide differential diagnosis of benign and malignant polyps by exploiting the contrast mechanism offered by microwaves.

The knowledge of fundamental radiation limits for antennas implanted in a lossy medium are of key interest to the antenna designer, as they allow fast assessment of the feasibility of specific antenna requirements for implantable devices. Skrivervik *et al.* ("Fundamental Limits for Implanted Antennas: Maximum Power Density Reaching Free Space") explore these fundamental limits by considering the total radiated power reaching free space (out of the lossy host medium) and the maximum power density obtained at the surface of the lossy host medium as key performance indicators for assessing the quality of a specific antenna radiating into a lossy tissue medium. To this end, elementary radiating sources, a spherical model for the host body and a spherical expansion to describe the electromagnetic fields inside the structures, are used. The obtained results are quite universal and directly usable in practice for host bodies of noncanonical shapes, as the critical parameter for the obtained bounds is the depth of the implant and not the shape of the phantom.

Although implant communications has been a subject of recent intensive study, the impact of passive medical implants on the on-body radio channel characteristics is still a scarcely studied topic. A comprehensive study on the impact of sternotomy wires and a medical implant on the UWB channel characteristics is presented by Särestöniemi *et al.* ("Measurement Data Based Study on the Intrabody Propagation in the Presence of the Sternotomy Wires and Aortic Valve Implant"), by investigating intrabody propagation in the vicinity of on-body antennas. Propagation path calculations are verified against measurement data, taken from a volunteer that has sternotomy wires and an aortic valve implant, and from a reference volunteer without any implants. Finite integration technique simulations using a layered tissue model are also carried out. It is shown that additional signal peaks and variations of the channel impulse responses are observed for the medical implant case since both sternotomy wires and aortic valve implant contain highly conductive materials, which affect the channel characteristics. In the time domain simulation results, the difference between the channel strength of the cases under study (with and without sternotomy wires and implant) varies between 5 dB and 17 dB within the time range corresponding to the relevant propagation paths.

Wireless communication with implanted devices for, e.g., neural recording and stimulation, is particularly challenging, especially in cage environments, where many neuroscience experiments with freely behaving animals are conducted. The metal cage walls form a reverberant cavity with dense multipath. Sharma *et al.* ("Wideband UHF DQPSK Backscatter Communication in Reverberant Cavity Animal Cage Environments") demonstrate the reverberant cavity effect via measurement of the channel transfer function inside a metal cage used for nonhuman primate (NHP) research in the (902 to 928) MHz ultrahigh-frequency (UHF) ISM band. A ceramic patch antenna developed for the Neurochip neural recording and stimulation device was placed to a saline tissue proxy, while a commercial air-dielectric patch antenna was placed to the ceiling of the cage. Based on the performed measurements, a UHF-band, DQPSK monostatic backscatter data uplink was successfully designed and validated inside the cage, exhibiting 0% packet error rate for all but two of the measurement locations at a symbol rate of 3.125 MHz (i.e., a bit rate of 6.25 Mb/s). Simulations and experimental results show good agreement and reveal that wideband backscatter communication systems can perform well despite the significant multipath inside the reverberant cage environment.

In various applications of implantable devices powering through WPT, the implanted receiver must be small, often on the order of millimeter, a requirement that poses significant design challenges. Machnoor *et al.* ("Analysis and Design of a 3-Coil Wireless Power Transmission System for Biomedical Applications") present a modified three-coil system configuration to improve the performance of systems with size limited implanted receiver coil. In the proposed system, mutual coupling, mutual capacitance, and relative polarity can all be used, thereby introducing additional degrees of freedom on coil layouts. Performance is further enhanced by two additional techniques that maximize the reflected impedance between the receiver coils. Experiments demonstrate that the proposed three-coil design provides twice the efficiency of a conventional system for small receiver coils. The proposed system also achieves receiver designs with better insensitivity to load variation while also reducing the fields induced in the body due to secondary coil current. In addition, at the considered frequency, system performance is robust to the presence of human tissue.

The next two papers focus on UWB technology and the advantages it offers for high data rate transmission and localization in WCE.

Perez-Simbor *et al.* ("UWB Path Loss Models for Ingestible Devices") study the radio channel in a gastrointestinal scenario in the lower part of the UWB frequency band (from 3.1 GHz to 5.1 GHz), by using and comparing three methodologies, namely, software simulations and experimental measurements either in phantom or *in vivo* in animals. The path loss (PL) is studied in three setups intended to mimic the real WCE scenario, where the transmitting antenna is located inside the intestine and the receiving antenna is placed over the abdominal region of the human body. Results on heterogeneous accurate phantoms are compared with realistic *in vivo* experiments. PL models considering the three methodologies are given and compared.

Barbi *et al.* ("UWB RSS-Based Localization for Capsule Endoscopy Using a Multilayer Phantom and *In Vivo* Measurements") investigate the performance of an RSS-based localization technique, for in-body to on-body communications in the (3.1 to 5.1) GHz UWB frequency band, through experimental laboratory measurements and *in vivo* experiments. The 2-D localization is performed using experimental measurements conducted in a two-layer phantom based setup. In this case, an adaptive linearized method, considering different combinations of three receivers, is sufficient to estimate the in-body antenna coordinates. The 3-D localization is performed using data from a recently conducted *in vivo* experiment in a living pig. In this more realistic case, Least Square and Non Linear Least Square methods have been implemented for the estimation of the in-body antenna coordinates, due to the high dispersion of the PL values [with respect to the fitting model]. For both, 2-D and 3-D cases, localization accuracy using PL models, under the assumption of ideal and not ideal channel estimation, is analyzed. Results show that, under not ideal channel assumption, the relative localization error slightly increases for the 2-D case but not for the *in vivo* 3-D case. The impact of receivers' selection on the localization accuracy has also been investigated for both, 2-D and 3-D cases.

The next three papers focus on the design, development, and evaluation of two wearable antennas for on-body communication and an inkjet-printed dipole antenna for RFID dosimeter tags to be used in the context of next generation blood irradiation systems.

Bhattacharjee *et al.* ("A Compact Dual-Band Dual-Polarized Omnidirectional Antenna for On-Body Applications") present a compact dual band dual polarized wearable antenna for on-body communication in the 2.45 GHz and 5.8 GHz ISM bands. The antenna is linearly polarized (LP) at 2.45 GHz and circularly polarized (CP) with the conical pattern at 5.8 GHz, which is suitable for multi-sensor link networks. The resonance modes of the ground plane are computed initially by using the characteristic modal analysis technique. Application of the ground plane for generating dual band characteristics results into a compact antenna size. Four L-shaped open-ended slots are cut in the ground, which radiate in $\lambda/4$ resonant mode at 2.45 GHz and $3\lambda/4$ odd mode at 5.8 GHz band with horizontal polarization. CP is obtained in the higher band with the combination of horizontal polarizations generated by the L-shaped slots and vertical polarization generated by the top loaded patch antenna. Enhancement in axial ratio bandwidth is achieved with the addition of a dielectric superstrate over the feed layer. Bending sensitivity, transmission loss and specific absorption rate (SAR) are studied for on-body characterization. The level of detuning is assessed by evaluating the antenna performance on a single- as well as a multi-layer phantom model. Simulated and measured results are found to be in good agreement.

Blauert and Kiourti ("Bio-Matched Horn: A Novel 1–9 GHz On-Body Antenna for Low-Loss Biomedical Telemetry with Implants") introduce a novel on-body biomatched horn antenna, capable of low-loss biomedical telemetry with wireless implants across the entire (1 to 9) GHz bandwidth. To achieve this unique performance, the biomatched horn is composed of water-filled holes used to closely match the frequency-dependent permittivity of the underlying tissue over its entire bandwidth. The horn shape further allows the proposed antenna to communicate efficiently through biological tissue for both subcutaneous and deep-tissue wireless implants. With this uniquely engineered effective permittivity, the antenna was able to overcome conventional challenges of on-body antennas, such as mismatch vs. the high-permittivity biological tissue, varying tissue properties with frequency, and intersubject/environmental variances of biological tissues. Simulation and measurement results indicate that the biomatched horn offers versatile communication capabilities for both subcutaneous and deep-tissue implants. Measurement results at 2.4 GHz are in good agreement with simulations and show a remarkable improvement in the transmission loss versus the state-of-the-art for subcutaneous and deep-tissue telemetry, respectively. The antenna is also shown to be relatively robust to both rotational and positional misalignments and to conform to FCC SAR standards for input power levels as high as 8.57 dBm.

Sanusi *et al.* ("Development of 2.45 GHz Antenna for Flexible Compact Radiation Dosimeter Tags") present the design of a low-cost inkjet-printed dipole antenna on flexible Kapton substrate for a 2.45 GHz RFID dosimeter tag. The tag is to be mounted on blood bags used for transfusions, replacing standard visual indicators in an attempt to automate the process of blood irradiation with X-rays applied for safety concerns. The concept of artificial magnetic conductor (AMC) unit cells is investigated for best impedance and gain performance of the antenna operating in a lossy blood environment, which can severely affect its radiation performance. When integrated with a dipole radiator, the fabricated AMC-backed antenna maintains broadside radiation with gains of (4.1 to 4.8) dBi under planar and bending conditions, and on a lossy blood bag. In a rectenna configuration, the antenna can power sensors for ranges up to 1 m. Measured output dc voltages up to 1.7 V are achieved across a 25 kΩ resistor. The proposed antenna design is flexible, compact, efficient on lossy structures and suitable for direct integration with biomedical sensing chips.

The next two papers present innovative technologies for vital signal sensing based on radar and Doppler principles.

Prat *et al.* ("Collimated Beam FMCW Radar for Vital Sign Patient Monitoring") introduce a noncontact and nonobstructive system for vital sign monitoring, using a 120 GHz FMCW radar. The proposed approach is advantageous since it does not require any contact with the patient. The system is based on a commercial radar chipset that includes its own antennas. The authors focus on the design, construction and testing of a specific reflector antenna for the system. The addressed challenge refers to the design, construction and testing of the optimum reflector in a cost effective way. The reflector has been 3-D printed and its performance has been assessed by implementing a near-field testing technique. The results show that the system is able to measure vital signs, such as breathing rhythm and heart beat rate, at distances beyond 1 m and can be used in a clinical scenario due to its immunity to unwanted reflections.

In the paper by Kamiya ("A Simple Concurrent Parameter Estimation Method Suitable for Noncontact Vital Sensing Using a Doppler Sensor"), a simple concurrent parameter estimation method for multiple periodic signals is proposed, suitable for vital sensing using a Doppler sensor. The main idea is to cope with multiple periodic signals to estimate the number of signals in addition to the period and the fundamental waveform, as well as the direction of each of the multiple signals. Simulation results demonstrate the proposed method's ability to estimate the directions of multiple targets even if the number of the targets exceeds the degree of freedom of receiver antennas. Additionally, direction estimation by the proposed method is shown to be robust against the coherence among the incoming signals.

The final three papers present novel EMI modalities for head and thorax imaging as well as a flexible 3 T MRI coil for carotid artery imaging.

Rokunuzzaman *et al.* ("Compact 3-D Antenna for Medical Diagnosis of the Human Head") report a probe fed 3-D folded cavity backed antenna for microwave medical diagnosis. The antenna is matched with an inhomogeneous human head allowing higher field penetration without the need of any coupling liquid. A rectangular cavity is used to minimize side and back lobe radiation and reduce interference from the surrounding environment. The cavity and folded antenna configuration achieves a highly directional radiation pattern toward the head with a front-to-back ratio of more than 17 dB. An operational frequency band from 1 GHz to 1.7 GHz is achieved with the antenna attached to the surface of a curved inhomogeneous human head phantom. The key design parameters and intersubject variability are examined through a detailed parametric study, while analysis of the SAR distribution over the operational frequency range is carried out. The salient characteristics of the proposed antenna make it a suitable candidate for near-field microwave diagnosis applications, including brain imaging, stroke detection, and tomography approaches.

Rezaesieh *et al.* ("Pattern Reconfigurable Wideband Loop Antenna for Thorax Imaging") developed a pattern reconfigurable square-loop antenna to address the multi-slice (level) scanning requirements of EMI systems for thorax imaging. To create a unidirectional radiation, the loop is loaded with capacitive gaps, which convert its radiation mechanism to that of two virtual dipole arrays with quadrature phase excitation. By changing the location of the gaps on the loop's structure, the radiation pattern is rotated on the azimuth plane, without physically moving the structure of the antenna. As a proof of concept, six gaps were created on the loop and each gap was loaded with a p–n diode to electronically switch between positions of the design gaps, thus enabling changing the radiation direction. The proposed antenna can achieve a compact size and a wide fractional bandwidth of 32% at (0.8 to 1.15) GHz, with a peak gain and front-to-back ratio of 2.1 dBi and 8 dB, respectively.

Zhang and Rahmat-Samii ("A Novel Flexible Electrotextile 3 T MRI RF Coil Array for Carotid Artery Imaging: Design, Characterization, and Prototyping") use computerized embroidery and laser cutting technology to address limitations for high quality MR imaging related to the signal-to-noise ratio (SNR) performance of the RF coils. The authors present a novel flexible electrotextile 3 T MRI RF coil array for carotid artery imaging. A roadmap to systematically design electrotextile RF coil arrays is proposed, achieving accurate resonant frequency, good impedance matching, and low mutual coupling. A method to characterize the performance of the electrotextile pattern is presented and used to assist the development and performance characterization. Magnetic field distribution, bending effects, and human body effects are also discussed. High resolution and high SNR images of various phantom kinds are obtained using the electrotextile coil array after its integration with a 3 T MRI scanner. Compared with the conventional surface coil, more than 10 and 3 dB SNR increase is observed at a depth of 0.5 cm and 3 cm, respectively.

III. Future Trends

This special issue presents significant research achievements in the field of wireless healthcare biotechnology and focuses on the development and optimization of medical devices, imaging modalities, sensing technologies and procedures regarding early disease detection, prevention, and continuous health monitoring. However, certain challenges are key to further advances in this emerging field, including the following.

A. Further Optimization of On-Body and In-Body Antenna Design

Biomedical applications require conformal antenna structures and designs that maintain efficient performance in the presence of human tissues [2], [9]. In the field of on-body antennas, further research is essential toward ensuring proper operation and resonance within in short distances from the human body [22]. In addition, advanced technologies to further reduce power absorption by the human tissues and improve efficiency are necessary. In this respect, metamaterials can provide solutions that can lead to the decrease of the antenna-to-body coupling, thus improving the antenna's performance.

In-body antenna design entails several requirements that have to be fulfilled in terms of biocompatibility, tuning, miniaturization, and patient safety [1]. In the case of implantable antennas, optimization of the biocompatible insulation layer thickness should be investigated not only for avoiding unfavorable reactions within the body, but also for lowering power loss without aimlessly increasing the antenna size [21]. Moreover, detuning or attenuation issues due to heterogeneity of body tissues, causing reduction in both efficiency and bandwidth, should be addressed through the adoption of multi or broadband data transmission. Fundamental radiation limits due to operation in a lossy tissue medium have to be taken into account, and rigorous quantifications between size and performance must be performed toward achieving optimal compromise between volume, gain, and bandwidth [11]. In the ingestible antennas' field, focus should be placed on the variation of radiation characteristics and performance with antenna position and orientation, while specific factors that pose uncertainties (e.g., anatomy around the gut) should be considered during antenna design [21].

Research should also be devoted to the design and fabrication of tissue-mimicking phantoms, enabling experimental testing of in-body and on-body antennas [1], [9]. Regarding patient safety, temperature rise in human tissues induced by in-body antennas, even though crucial to assess patient safety, has not been thoroughly studied and should be adequately addressed [21].

B. Reliability of the Communication Link

Limited research has been performed regarding propagation modeling inside the human body, and only particular scenarios with specific conditions (i.e., specific antennas and orientation) have been applied so far [10]. Moreover, the impact of passive in-body medical devices on the on-body radio channel characteristics is still a scarcely studied topic. Interference issues are also important, including potential harmful effects in terms of false implantable device activation, link unavailability, and data corruption. Thus, novel approaches for modeling the biotelemetry channel should be developed, taking into account operation frequency, intrabody propagation and wireless channel characterization, in order to facilitate high data rate transmission and efficient, high-quality communication between the in-body device and the on-body monitoring/control unit [21].

C. Powering

Despite advances in electronics and powering technologies, the use of batteries continues to dominate the field of WBANs, thus introducing requirements for frequent recharging and/or battery replacement. Several alternative solutions have been proposed, including WPT, fully passive operation and energy harvesting techniques that could realize batteryless in-body medical devices [1]. Extensive research is needed to improve the efficiency of the aforementioned methods and enable their use for powering in-body devices out of thin air. Flexible, conformal, compact, low-power WPT modules that are easy to fabricate, low-cost and maintain efficient performance on diverse host structures are required, which should also fulfill biocompatibility and compliance with electromagnetic safety standards. Moreover, power conservation techniques should be more thoroughly investigated in order to address potential longevity requirements of in-body devices, and guarantee their on demand availability.

D. Innovative Sensor Technologies

Integration of rapid advances in areas such as microelectronics, microsensors, and biocompatible materials has fueled the development of innovative sensing technologies that realize specific clinical applications in an unobtrusive manner. Such applications require compact antenna structures that display efficiency in lossy environments and enable integration with biomedical sensing chips. Attention should be placed on achieving long-term stability, selectivity, calibration, as well as adequate power in portable devices integrated with advanced sensing technologies. Biocompatibility and "chronic implantability" issues should also be addressed and new ways to fulfill these requirements should be proposed [2].

E. Novel Imaging Modalities

The utilization of MI can contribute to the development of novel imaging modalities that materialize wireless imaging systems. Although a number of promising MI strategies have been recently reported, further improvements are essential to enable adoption of wireless MI systems in clinical practice. Antenna design constitutes one of the main challenges in an MI system and has to accommodate requirements related to size, shape and performance, which arise from operation in a lossy tissue medium and variations in the patients' anatomical features [24], [25]. Compact antenna structures should be developed based on the introduced tradeoff between spatial resolution and penetration depth, so that successful image reconstruction along with optimal computational time are achieved [23].

Overall, the emerging field of wireless healthcare biotechnology is fueling significant advancements, enabling a personalized, preventive, more efficient and cost-effective approach to healthcare delivery. Future research is needed to provide further insights in a wide range of wireless healthcare biotechnology related applications, ranging from implantable, ingestible and wearable systems to MI systems. Extensive research efforts should be pursued in order to concurrently address technological concerns related to antenna design, development and evaluation, propagation and communication issues, and wireless power transmission, along with developing novel sensing and medical imaging technologies that realize new clinical applications.

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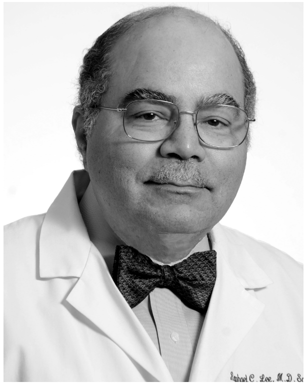

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