Technical Considerations in Medical Radar

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ABSTRACT
Medical radar is an emerging area of research and development in recent years, spurred by rapid advances in electromagnetic modeling, simulation, component development, and signal and image processing algorithms. In this paper, we review various important considerations in the design and development of medical radar systems for diagnostic applications.

Categories and Subject Descriptors
A.1 [**Introductory and Survey**]: Literature Review

General Terms
Design, Theory, Algorithms

Keywords
Dielectric Properties of Human Tissue, Electromagnetic Wave Interaction with Tissue, Medical Radar

1. INTRODUCTION
Microwave imaging of the human body, primarily of the human breast, for tumor and cancer detection has been a topic of interest for several decades. Its advantages include non-ionizing and safe nature of microwave signals at low levels, low-cost implementation of practical systems, and the exploitation of high dielectric contrast between normal and abnormal human tissue [1]. Lower microwave frequencies over the 1-4 GHz range can penetrate skin, tissues, and clothing, and ease the requirement for the preferred half-wavelength spacing when architecting aperture antenna arrays [2]. Good down-range resolution requires a wide operational bandwidth, while good cross-range resolution is requires large real aperture arrays or synthetic aperture processing.

Ultrawideband (UWB) radars achieve excellent down-range resolution, since this is inversely proportional to the bandwidth. They can be implemented as pulsed radars (e.g. impulse) or frequency-modulated (FM) radars (e.g. chirp, linear FM, stepped FM, or UWB noise). UWB systems have been used for patient monitoring, vital signs detection, and in applications as diverse as cardiology, pneumology, obstetrics, etc. [3].

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Several interrelated design choices exist for UWB systems, with corresponding tradeoffs in system performance [4]. A large bandwidth is beneficial to achieve good spatial resolution, while low frequencies are desirable for achieving good penetration through lossy tissue. To focus lower frequency signals into the human body, a larger antenna is required, which increases the overall size of the device. A large peak signal power is important for obtaining good penetration through materials and lossy tissue. In order to improve the signal-to-noise-ratio (SNR), pulse averaging can be used, which increases the operating range and sensitivity but decreases the responsiveness to rapid motion.

The human body can be modeled, to a first approximation, as a multi-layer structure with each layer corresponding to a particular tissue. Different parts of the human body (e.g. head, breast, etc.) can be modeled as multi-layer structures [5]. Each tissue/layer is characterized by its relative permittivity and its conductivity (both of which are frequency dependent), and its thickness.

In addition to medical radar, UWB technology has been applied to wireless body area networks and capsule endoscopy [6]. For capsule endoscopy, the endoscopes are swallowed and travel through the body; hence, the circuitry must be very small and simple, yet capable of high transmission rates to transmit real-time video. Significant signal processing is needed to process the low level signals which have traversed several tissue layers.

Most medical radar applications basically need two components: a sensor and a communication infrastructure (transceiver and protocols) to share the data gathered by the former [7]. By combining sensing and communications in the same package, UWB radar could be used to measure vital signs information, and UWB communication standards could be used to transmit these measurements to a processor. Wireless networking is necessary to transmit and share the monitored data with a central repository.

It is important to ascertain which phenomenon actually impacts measured data. It was shown that body surface movements dominated remote radar measurements of heartbeat, compared to blood perfusion in the skin or internal body organ movements [8].

A comprehensive list of relevant literature on medical radar is presented in [9], which includes references on general UWB radar, radar calibration, radar heartbeat and respiration measurements, medical radar systems, and medical radar imaging.

2. DIELECTRIC PROPERTIES OF TISSUE
The dielectric properties of human tissue determine the radar reflections from different layers. Relevant data are available from several papers and reports over the past 60 years.

Some of the earliest permittivity and loss measurements of various human tissues, such as skin, fat, muscle, etc. were made at centimeter wavelengths, over the 1–26 GHz frequency range [10]-

[12]. Complex permittivity data at 3 GHz on skin, muscle, fatty tissues, and bone were presented in [13]. It was observed that specimens of pathological tissues, taken from near a fistula and from a fibrosed breast, showed dielectric properties different from the corresponding normal, which was attributed to a difference in water content.

Data on permittivity and conductivity at several frequencies between 25 MHz and 8.5 GHz were reported in [14]. Tissues included muscle, heart, liver, spleen, kidney, lung, brain, fat, and bone marrow. The dielectric properties of a wide variety of biomolecules and cells (amino acids, polypeptides and proteins, biological electrolytes) as well as mammalian tissues were modeled and data presented at different frequencies over the frequency range 1 Hz - 10 GHz [15]. Tissues included artery, blood, bone, bowel, brain, fat, kidney, liver, lung, muscle, ocular tissues, skin, and spleen. Their frequency and temperature dependence were also characterized. The dielectric properties of all tissues were found to generally follow the same dependence on frequency [16]. At frequencies above 100 MHz, differences between tissue types were largely lost, and the dielectric properties were directly correlated with the tissue water content. Differences between normal and cancerous tissues were attributed to the higher water content and sodium concentration of the latter, as well as different electrochemical properties of their cell membranes.

In vitro permittivity measurements of excised human liver, spleen, kidney and cardiac muscle at frequencies from 10 kHz to 100 MHz were compared with human data reported by other investigators as well as with the measured data on similar cat tissues [17]. The conductivity of human tissues was generally higher than that of the corresponding cat tissues, while the differences in the dielectric constant depended upon the tissue and frequency. *In vitro* dielectric measurements on human female breast tissues were reported at a frequency of 3.2 GHz [18]. Data were included fat and normal breast tissues, as well as on benign and malignant breast tumors. Comparisons of the normal and benign tumor data, normal and malignant tumor data, and of normal and fat data within individual patients revealed that these tissues are distinguishable based on dielectric measurements. However, malignant and benign tumors were not distinguishable based on dielectric data.

Relative permittivity and conductivity of malignant and normal human tissues were reported at frequencies from 50 to 900 MHz [19]. Tissues included bladder, colon, kidney, liver, lung, lymph nodes, mammary gland, spleen, and testes. In general, at all frequencies tested, it was found that both relative permittivity and conductivity values were higher in malignant tissue than in normal tissue of the same type. Mammary gland showed highest differences while kidney showed lowest differences between normal and malignant conditions

Extensive data (in both graphical and tabular formats) on the dielectric properties of body tissues over the 10 Hz to 20 GHz frequency range were presented in a technical report [20]. Data were reported on a very wide range of mostly human and some animal tissue, including brain, heart, kidney, liver, lung, spleen, uterus, muscle transverse, wet skin, aorta, bone cancellous, cervix, breast fat, thyroid, testis, ovary, and bladder. Contents of the report were published in three separate papers in open literature, the first focusing on literature survey [21], the second on measurements [22], and the third on parametric models [23].

The complex permittivity of human bile, bile stones, gastric juice, and saliva over the 2-8 GHz frequency range were presented in [24]. It was observed that normal and infected bile had different dielectric constants and loss tangents. Depending on the nature of the disease, the infected bile had a dielectric constant value greater or less than that of normal bile. The dielectric constant and conductivity of skin, fat, muscle, bone, intestine (large and small), bladder, blood, stomach, and liver were measured at 915 MHz and 2.45 GHz and reported in [25]. The data were used to develop a composite human model for EM wave propagation characterization.

Since the human skin is the first layer encountered by the EM wave, its dielectric properties are of special interest. The complex permittivity of living human skin was reported over the frequency range 8 to 18 GHz [26], 28 to 57 GHz [27], 10 to 60 GHz [28], 37 to 74 GHz [29], and 60 to 100 GHz [30], [31]. Differences between human skin *in vivo* and excised human skin tissue were attributed to variations of water content, blood content, and epidermal thickness. Multilayer models provided better fits to both forearm and palmar skin reflection data, especially for the latter with a thick stratum corneum. The skin depth of human skin at 10 GHz was about 2.7 mm, indicating that frequencies above 10 GHz, the skin could be considered opaque to EM waves. Thus, it can be assumed that millimeter-wave radiation incident on the human body will be almost entirely absorbed (or reflected) by the skin layer.

The complex dielectric constants of blood and blood plasma were measured over the 1.7 to 2.4 GHz frequency range and compared to those of water [32], [33]. Dispersion was found to occur, which was attributed entirely to dipolar orientation of part of the water present in blood and the ionic conductivity. Comparison of the results for blood with those for water led to approximate estimates of the erythrocyte intracellular ionic conductivity and hemoglobin hydration.

Since *in situ* tissue measurements are not always possible and excised tissues show rapid changes in their dielectric properties with time, it is advantageous to develop simulated human biological materials. This was done using appropriate chemical mixtures [34]. Formulas were presented for simulating bone, lung, brain, and muscle tissue over the frequency range of 100 MHz to 1 GHz. A realistic equivalent to the human body could be constructed using these preparations. By characterizing the dielectric properties of normal liver and liver tumor over the 300 MHz to 3 GHz frequency range, it was determined that the dielectric constant and conductivity of liver tumor were higher by 12% and 24%, respectively, when compared to normal liver [35]. Furthermore, by comparing the dielectric data of human liver to measurements of homogeneous phantom mixtures, in vitro bovine liver, and in vivo canine and porcine liver tissues, it was determined that several animal tissues could be used the model the average dielectric properties of human liver reasonably well.

The age-dependence of dielectric properties of biological tissues mostly relies on the fact that permittivity and conductivity may be expressed as a function of tissue water content, which decreases with age. Empirical formulas for estimating permittivity and conductivity of human biological tissues as a function of age have been developed [36].

The maximum frequency range limit was investigated for the dielectric property of human body tissues to be fitted with the Debye dispersion of up to three poles. It was determined that the dielectric permittivity of human body tissues is accurately represented by 1- to 3-pole Debye functions over a wider frequency range than before, i.e., from 1 MHz to 100 GHz or from 100 kHz to 10 GHz. using at most eight parameters with RMS errors of typically several % [37].

Data on animal tissues are also of interest as their characteristics are quite similar to corresponding human tissues. Experimental data on the complex dielectric constant and penetration depth of fat and muscle tissue from cattle over the 40-54 GHz and 85-90 GHz frequency bands were presented in [38]. Dielectric measurements on various soft tumor and normal canine tissues between 10 MHz and 17 GHz were reported in [39]. It was found that the tissue dielectric properties correlated well with their water contents. Empirical equations useful for prediction of the dielectric properties of other soft tissues within this wide frequency range were suggested. Dielectric permittivity and conductivity measurements were made of various soft excised mammalian non-tumor tissues at frequencies between 0.1 and 100 MHz [40]. These included dog and rabbit liver, dog spleen, dog kidney, dog brain, and dog and rat skeletal muscle, which were compared to corresponding human organs. *In situ* permittivities of several canine tissues were presented at microwave frequencies [41]. The effects of changing physiological conditions on tissue dielectric properties, specifically dog brain and kidney, were examined. It was determined that the tissue dielectric properties and blood flow (perfusion) were directly related. Complex permittivities of pig internal organs such as lung, liver, heart, kidney, blood, stomach, and small intestine were measured and compared with reported values of corresponding human organs [42]. It was found that for tissues with regular texture and composition, such as lung, liver, heart, and kidney, the values for pig and human organs were quite close. However, relatively large deviations were observed for stomach and small intestine due to significant differences in their internal contents.

A comprehensive data base on the dielectric properties of a wide variety of human tissues over the 10 Hz - 100 GHz frequency range is available from http://niremf.ifac.cnr.it/tissprop/.

3. EM WAVE INTERACTION WITH TISSUE

Accurate numerical and analytical techniques to predict the propagation of EM signals in biological tissue are essential for developing signal processing algorithms for medical diagnosis. A composite human body slice is modeled in terms of different tissue layers of appropriate complex permittivities and thicknesses. The reflection at the interfaces and the propagation loss through each layer determine the overall radar reflected signal. A technique to compute the reflected and transmitted fields from the first layer and progressively include succeeding layers, while neglecting mutual influence between contiguous layers without error, was developed and applied to normal incidence [43] and subsequently extended to oblique incidence [44].

Early studies on microwave absorption in human tissue were conducted to assess possible hazards of microwaves when used for therapeutic purposes. Penetration depths and reflection coefficients at the air-muscle and muscle-fat interfaces were presented for muscle, skin, and tissues at both high and low water contents at specific frequencies between 1 MHz and 10 GHz [45].

Simulations and measurements of EM wave propagation through human tissue (muscle and abdomen) over the 50 MHz - 1 GHz frequency range revealed the occurrence of small resonances at specific narrow frequency bands [46].

Two techniques for modeling the propagation of UWB pulses) in human tissue, namely, the planar technique and Finite Difference Time Domain (FDTD) technique, were developed and applied to normal tissues as well as cancerous soft tissue (sarcoma). Both approaches were able to identify the presence of the soft tissue sarcoma quite easily [47], [48].

An analytic UWB signal path model consisting of the antennas, the human body, and the signal processing system has been developed and implemented, taking into account the broadband frequency dependence of the complex dielectric properties of individual tissues. The individual continuous motion of intrathoracic layers was also included in the simulation of physiological signatures [49]. UWB signal propagation inside human chest was characterized using the time-domain Finite Integration Technique (FIT) simulations for line-of-sight (LOS) scenarios over the 100-1000 MHz frequency range. A voxel model of the human body incorporating the frequency-dependent material properties of the human tissues was used. The propagation scenario was defined and the radiograph of UWB power, spectral analysis of the in-body signals, the power delay profile (PDP) and the RMS delay spread of channels were presented [50], [51].

A method for automatic 3D model construction of various human body parts and organs to support Finite Element Method (FEM) modeling was developed. The geometric models used image slices data obtained from medical diagnostic equipment and bioimpedance measurements. Appropriate dielectric properties were used for each tissue type. Quantitative results for electromagnetic and thermal field distributions in internal organs were obtained [52].

4. ANTENNA AND EM WAVE COUPLING MECHANISMS

One of the most important aspects impacting antenna design is the coupling mechanism of the EM wave into the human body. The acquisition of physiological signatures requires small and efficient antennas, designed for UWB operation. The miniaturization of the radiating elements for a double-ridged horn antenna for 1-10 GHz operation was accomplished by either by immersion into a high-permittivity liquid dielectric [53] or by inserting low-loss high-permittivity solid ceramic material [54]-[56].

Since part of the EM wave travels outside the human body (antenna → body and body → antenna) and part inside, an impedance mismatch exists resulting in inefficient coupling of the wave into the body. Use of a matching layer of dielectric material of appropriate permittivity placed in contact with the human body was investigated and found to significantly reduce the path loss of the EM wave over the 100-1000 MHz range [57].

Although most UWB antennas used in medical radar applications, such as horn or Vivaldi antennas have high directivities, the maximum directivity is in the same direction of the maximum size of the antenna. For wearable radar systems, a high directivity in a direction perpendicular to the maximum size of the antenna is necessary. A novel small-size directional twin cross-polarized planar spiral antenna, consisting of two twin spiral antennas rotated by 180° to each other on the same plane, one for transmission and the other for reception, has been developed [58].

A major challenge in medical radar imaging is the strong reflection associated with the skin. A skin subtraction method was developed, which estimated the skin response of the target antenna using a filtered combination of signals acquired by all other antennas and exploiting the spatial correlation of the neighbors. The method's ability to subtract the skin response and preserve the tumor response has been demonstrated [59], [60].

5. RADAR DESIGN CONSIDERATIONS

One of the earliest radar waveforms investigated for biological radar applications is the linear FM waveform operating over the 2-4 GHz band for imaging a canine kidney [61]. The theoretical formulation for the imaging procedure was presented and regions of filtration were distinguishable from regions where the ultrafiltrate was concentrated. Combined sensing and communication using FM-UWB waveforms operating at 4.5±0.5 GHz were able to non-invasively monitor heart rate and transmit the data for over wireless channels [62].

A comprehensive study of UWB radar working principles explored various aspects, including multi-layered modeling, characterization of echoes from deep interfaces as well as superficial layers, natural radiation effects, and near-field operation [63]. The design trade-offs for impulse radars and applications to biological sensing, such as the detection of pneumothorax was presented in [64]. The design aspects of several UWB transceiver architectures applicable to medical radar, employing both carrier-free impulse signals and carrier-based FM signals, were discussed in detail in [65].

The design of a UWB radar radiating short 180-ps wide pulses for detecting liquids simulating various tissue types is described in [66]. A 200-ps pulse width UWB radar was developed and found promising to detect simulated tumors using FDTD modeling and experimental measurements [67]. The design of a swept threshold radar transmitting UWB impulses, and subsequently thresholding and sampling the received echo signal, combined with transmitting symbols coded as pseudo-noise (PN) sequences of pulses, was presented in [68]. A detailed formulation of the swept threshold sampling technique was used to derive variance and bias in the measurements [69]. An impulse based radar system with a transmit spectrum covering the 3.1-10.6 GHz employing a correlation receiver and a time delay adjustment using a variable phase setting for the trigger signals was developed [70]. The measurement of respiration and heart rate was successfully demonstrated.

A 4-6 GHz radar system design, which includes a multi-layered tissue model and derives strategic positioning of the antenna and incidence angle for determining various tissue echo layers is presented in [71], [72]. Procedures have been developed to maximize the echo strength of each layer adaptively [73]. Recently, pseudo-noise (PN) waveforms have been used for medical imaging applications [74]. Advantages of such a waveform include simple architecture, high measurement speed, high stability, and low crest factor signals.

A comparison of different UWB radar approaches were reviewed in detail in [75]. The Impulse Radio-UWB (IR-UWB), PN, and FM-CW (using a Vector Network Analyzer) were analyzed. It was inferred that the FM-CW technique outperformed the others in terms of stability and dynamic range.

Residual phase noise is a limiting factor in Doppler systems for heart rate and respiration measurements, and it depends on both the target range and oscillator phase noise. The design of a quadrature detector to overcome the range correlation effects was presented in [76].

The design of combined UWB radar and communication systems for biomedical applications was presented in [77]. Topics addressed included components for UWB radar sensors and communication systems, namely antennas and integrated circuits, signal processing, and design of bistatic UWB radar systems. Millimeter-wave measurements over the 37-74 GHz range were used to model human skin layers and show promise for estimating water content gradients in the stratum corneum [78].

Near-field UWB systems operate in close proximity to the body. Challenges caused by loading by the air-skin interfaces, and dependence on antenna position, alignment and pointing, must be met by designing problem-specific antennas [79]. Examples shown include a UWB radar-based heart monitor and a multichannel array-based microwave imaging chamber.

Ultra-wideband active array imaging has proven extremely valuable for biomedical diagnostics. To achieve sufficient resolution, dense antenna arrays using compact radiating elements and appropriate scanning techniques are required. The design aspects of such a system are presented in [80]. A UWB synthetic aperture radar (SAR) system for breast imaging and tumor detection was discussed in [81]. SAR array parameters as well as the image reconstruction algorithm were presented.

6. MEDICAL RADAR APPLICATION EXAMPLES

One of the most widely used applications of medical radar is heartbeat and respiration monitoring. Reported short-range (~2-4 m) systems include portable noncontact heartbeat and respiration monitoring system operating in the 5-GHz band [82], and an X-band FM radar system operating over 10-11 GHz [83]. Physical- and mental-stress induced changes in the chest cavity motions and breathing patterns were detected using UWB radars operating over the 7-8 GHz and 14-15 GHz bands [84]. The detection of the mechanical movement of heart (mechanocardiography), based on radar technology was found to be highly correlated to the acceleration-based ballistocardiograph signal. Heartbeat and breathing rates could be reliably detected using this system [85]. The movement of the thorax and the heartbeat were successfully recorded at low amplitude (up to 0.1 mm) from a motionless person at a distance up to 3.5 m [86]. In the supine position, the phase offset caused by relaxed abdomen positioned at a lower level than that of the thorax was successfully modeled and validated for extracting the respiratory parameters [87].

The capability of a microwave UWB radar technique to detect breast tumor was investigated. Small targets of ~5-mm diameter at various locations from the skin layer could be detected by visual inspection of the created image [88]. The application of medical radar for the imaging of the knee joint, with focus on the detection of meniscal tears was successfully validated using numerical and experimental results [89].

The mechanical representation of the cardiac contraction provided by UWB radar holds the potential to serve as a navigator technique for MRI. The results proved the ability of UWB radar to monitor physiological events directly at their origin inside the body [90]. A short pulse radar of 100-ps pulse width was shown to successfully detect tremor, which is a symptom for numerous neurological disorders, such as such as Parkinson's disease [91], [92].

Impulse radio UWB radar was investigated for detecting water accumulation in the human body, to aid in the diagnosis of different diseases such as pulmonary edema, ascites, etc. Simulation and measurement results demonstrated the feasibility of water detection in the bladder through the reflection from the boundary of muscle and urine [93], [94].

The performance of a synthetic aperture-based UWB radar imaging system with broadband adaptive beamforming was evaluated for head stroke detection via simulation. A 3-cm diameter hemorrhagic stroke was successfully detected within a 3D dispersive head model [95]-[97].

Real-time detection of pneumothorax was achieved using a short pulse radar transmitting a 1-ms pulse [98]. The suitability of radar technology for endoscopic capsule localization was investigated. It was determined that a frequency of about 4.8 GHz provided better resolution for localization purposes [99]. Use of microwave tomography was shown to be successful in detecting diseased organs whose permittivity changed by 15-20% over the normal organs [100].

7. CONCLUSIONS

While medical radar is making rapid progress, there are several related issues that merit consideration in future designs. Multimodal approaches combine complementary or uncorrelated information from different sources and with different sensitivities or resolution for improving diagnostic capability. By combining MRI and UWB radar, improved functional diagnosis and imaging were found to be feasible [101]. Electromagnetic compatibility is the most challenging issue when combining MRI with other modalities. A medical facility is an environment in which electromagnetic interference abounds. Factors influencing the medical electromagnetic environment include: radiated electromagnetic fields (due to other devices and cellular phones), noisy electrical power supplies and grounding (earth), magnetic fields (static and alternating), and surges (static discharge, lightning) [102]. Thus, the sensors electronics must be robust to EM interference. Also, the sensors themselves must not be a source of interference; thus the appropriate regulations and standards in different countries must be followed [103].

Medical sensors and radars can be interconnected using UWB interfaces thereby enhancing the mobility of patients during surgery or intensive therapy. All these systems can be combined into a single wireless body area network, with due care being taken to minimize the possibility of mutual interference [104]. Towards this end, a new wireless technology called Medical Body Area Network (MBAN) is being developed to sense human's vital signals through tiny nodes in, on, and around the human body wirelessly [105].

Compressive sensing is a new paradigm by which signals can be reconstructed by sampling them at a rate much lower than the Nyquist rate. The main conditions are that the unknown signal must have a "sparse" representation in some domain and that the set of signals used for measurement are "incoherent" with respect to the unknown signal. It has been shown that compressed sensing can substantially improve the performance of ranging with UWB radar in comparison with more conventional methods in scenarios with low SNRs [106].

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