Medical radar literature overview

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English summary

In this document we present and overview of the literature on medical radar, with main focus on heartbeat and respiration monitoring and detection, ultra wideband (UWB) medical radar and imaging in medical radar. First a historically oriented introduction to the field is given. Literature on the use of radar for heartbeat and respiration detection dates back to the early seventies. Since then, the number of applications and technological approaches has increased. Recent years have spawned an interest in using UWB radar for medical applications. The second part of this literature overview, is a compilation of noteworthy articles in the field. These have been sorted under a number of categories, and each category is presented chronologically.

Sammendrag

Dette dokumentet presenterer en oversikt over litteraturen innen feltet medisinsk radar, med hovedfokus på hjerteslag- og pustdeteksjon, ultrabredbånds (UWB) medisinsk radar og avbildning i medisinsk radar. Først blir en historisk oversikt over feltet gitt. Dette daterer tilbake til tidlig syttitall, da de første rapportene om bruk av radar til å overvåke pust og puls ble utgitt. Siden den tid har antallet bruksområder og teknologiske tilnærminger til medisinsk radar økt. I de senere årene har vi sett interesse for bruk av UWB radar i medisinske anvendelser. Del to av denne litteraturoversikten er en samling artikler innen feltet. Disse er sortert i kategorier, der hver kategori blir presentert kronologisk etter utgivelsesdato.

Contents

1 Introduction

Radar was originally conceived to detect large objects at far ranges. Emphasis was primarily on air traffic control and surveillance, detection of sea vessels and navigation. Channel separation was motivated both by the physics of electromagnetic propagation and coexistence with other radio systems. The foundation of pulsed radar technology was essentially formed during the WWII era, and the approach was largely to use narrowband waveforms, with high power levels. At the time little effort was made to explore the possibilities of short range measurements on complicated structures. However, the unique ability of electromagnetic waves to penetrate non-metallic objects have later come to suggest other uses, such as ground penetrating systems for geological surveys, and probing of the human body.

Radar technology was not seriously considered for medical instrumention until the early 70s. The attention had up to this point been limited to the study of adverse effects of tissue heating or possible curative influence on particular illnesses, such as arthritis (Susskind). Measurements of minute organ movements and qualitative detection of water condensation in human lungs were among the first proposed uses in medical diagnostics (Kazamias et al. (1971); Susskind).

A radar’s ability to extract valuable information about a complex structure, such as the human body, is to a large extent technology driven. For example continuous wave (CW) radars are very sensitive devices in detecting movement, such as time varying physiological phenomena. The use of CW radar to monitor heart rate and pulmonary motion, appears to be the predominant interest in medical radar during the 80s. The potential usefulness of radar in rescue operations, was clearly emphasized in experiments to detect vital signs of subjects buried under rubble (Chen and Chuang (1988); Wu and Huang (2008)). However, to retrieve the material profile of a compound object, range information is necessary. Range profiling requires some sort of modulation, such as a pulsed waveform or frequency modulation (FM). The 90s marked a change in paradigm with the microwave impulse radar (MIR) attributed to McEwan at the Lawrence Livermore National Laboratory in 1993. The MIR was a system-on-a-chip radar employing extremely short pulses at about 200 ps duration, which in turn signifies a large bandwidth. As the bandwidth of a radar is directly indicative of range resolution, new potential to probe the human body was apparent. The pulsed waveform made possible both measurements of movement, and range localisation of the movement (Staderini (2002a)).

McEwan‘s invention represents the ultra wideband (UWB) class of radars. The term UWB was allegedly first coined in 1989 (Barret (2001)). The usual definition of the term is that all radio devices operating at a fractional bandwidth of more than 25 per cent or a bandwidth of more than 500 MHz can be considered UWB (Gezici (2007)). Impulse radar is attributed to de Rosa through his patent in 1956, although his patent description was filed already in 1942, according to Barret

(2001). The MIR, however, was a landmark mainly due to its small size and low cost. The research within medical radar to follow McEwans work can by and large be divided into CW systems and UWB systems.

The new millennium has shown an increasing interest to include radar as a non contact medical sensor. One of the earliest proposed applications of medical radar was long term monitoring of heartbeat and respiration rates in patients (Lin et al. (1979); Caro and Bloice (1971)). The advent of small UWB radars working at short ranges with high range resolution have expanded interest from simple holter-type heart rate monitoring and qualitative detection of symptoms to also include medical imaging and quantitative measurements of physiological parameters, such as arterial blood pressure (Solberg et al. (2009)), or wearable heartbeat monitoring devices (Immoreev (2006); Zito et al. (2007)). With an increase in proposed applications, new challenges have been adressed. These include through the wall vital signs detection (Immoreev et al. (2005); Chia et al. (2005)), detection of people buried underground (Chen and Chuang (1988)), separation of heartbeats and respiration (Lohman et al. (2002)), exploration of the physiological activity that is measured (Muehlsteff et al. (2006); Thiel et al. (2009)) and vital signs detection with multiple persons in the scene (Petrochilos et al. (2007)).

The first publications on medical imaging with UWB radar are largely based on MRI derived tomographic techniques, supported with finite-difference time-domain (FDTD) simulations of propagation in phantoms of the human body (Miyakawa et al. (2004); Semenov et al. (1996)). Other approaches that have more in common with established ultrasound methods and synthetic aperture processing have also been considered (Abedin and Mohan (2007)). Feasibility studies concerning the possibility of detecting and quantifying early stage breast tumors are numerous.

A variety of medical radars operating in a great span of frequencies have been described in the literature. The technologies that are most used in respiration and heartbeat monitoring are CW Doppler radars and impulse UWB radars.

Despite the number of publications regarding propagation characteristics in human and animal tissue, there is, however, still considerable uncertainty as to what is actually measured. There are some reports that CW measurements of cardiac activity is increasingly more effective in the higher frequency ranges such as X- , Ku- and Ka- band, than is the case for the lower frequency bands, such as the L-band (Li and Lin (2007)). However, there is no consensus on this in the literature as indications that lower frequency bands are better suited for heartbeat monitoring are also reported (Jelen and Biebl (2006)). If indeed higher frequencies are better at heartbeat detection, this may indicate that mainly secondary surface movements are detected, as the penetration depth of electromagnetic waves at higher frequencies in human tissue is generally less than for the lower part of the microwave spectrum (Staderini (2002a); Ossberger et al. (2004); Zito et al. (2007); Pisa et al. (2008)). Radar heartbeat recording patterns that are similar to Apexcardiography (ACG)(Berger et al. (2008)) patterns hints that reflections from the chest is dominating, although further analysis is required.

There are regulations on which frequencies that are allowed for medical radar. The Federal Communications Commision (FCC) in the USA has approved the use of the frequency band from $3.1 - 10.6GHz$ with emission limit -41 dbm/MHz for UWB medical systems. In Europe the frequency bands $4.2 - 4.8GHz$ (until june 2010) and $6.0 - 8.5GHz$ are authorised for generic UWB devices with emission limit -41 dbm/MHz (Hanna (2009)).

The increase in range resolution provided by UWB radar together with a suitable choice of frequency band is considered a promising approach in understanding what physiological phenomenons can be measured and analyzed remotely (Staderini (2002a)). Research in the beginning of the 21st century is therefore possibly at its early childhood considering the use of UWB radar in medicine, while the use of CW radar to detect and analyze motion is still being appreciated and refined. There are many examples of both heartbeats and respiration being monitored using both different radar technologies and at a large span of frequencies. While there are examples of radar systems being tested in hospital environments (Immoreev and Tao (2008); Li et al. (2006)), the majority of the experiments reported in the literature were conducted under controlled laboratory conditions. Thus the feasibility of real life implementations of radar vital signs monitoring is still unclear. Which frequencies that are best suited for heartbeat and respiration monitoring is also an open question. In this overview of the literature, it was found that vital signs detection is possible at a large number of frequencies. However, there exist no quantitative comparison of frequencies or technologies for this purpose.

Noteworthy Articles

2 General UWB radar

1996 McEwan and Azevedo (1996): A description of the Micropower Impulse Radar (MIR). This is one of the early works on using wideband radar for hearbeat and respiration detection. The MIR was patented in 1996 by McEwan (1996).

2003 van Genderen and Nicolaescu (2003): The system description of a stepped ground penetrating UWB radar for mine detection.

Immoreev (2003): Article about UWB. The definition of UWB is presented, and a comparison of UWB attributes and narrowband radar attributes is performed.

2005 Brooker (2005): Titled ”Understanding Millimetre Wave FMCW Radars, a nice introduction to understanding the theory of FMCW radar.

2007 Zetik et al. (2007): An article about a pseudo-noise UWB radar. Some applications with data examples are given, among them heartbeat measurements.

Yarovoy and Ligthart (2007): An article discussing some applicatinos of UWB radar, such as mine and human being detection, and suggested radar systems. Also includes a UWB radar recording of a breathing person, wchich shows chest movement of about $0.6cm$.

2009 Hanna (2009): Speak on UWB regulations at the 2009 IEEE Conference on Ultra Wideband. Summarizes ETSI regulations on UWB: "*Adopted a decision authorizing Generic UWB Devices at* -$41.3dBm/MHz$ *in* $6.0 - 8.5GHz$ *and with DAA in* $3.1 - 4.8GHz$. *The band* $4.2 - 4.8GHz$ *can use* $-41.3dBm/MHz$ *until June 2010.*"

2.1 Calibration

1994 Morgan (1994): Uses calibration of UWB radar to improve measurements. The technique consists mainly of subtracting measurements of empty room and divide by measurements of transmitting directly into receiving antenna over some distance.

2006 Hantscher et al. (2006): Describes calibration of UWB measurements by subtracting clutter and cross talk, and normalizing with a reference measurements. Wiener filters are employed to remove spike artifacts.

2008 Gashinova et al. (2008): Article on calibration in UWB radar. Proposes a time domain adaptive calibration scheme for UWB radar to reduce distortions from antennas, clutter and antenna leakage. Also a description of simple FD calibration procedure.

3 Radar heartbeat measurements

1971 Kazamias et al. (1971): Kymography is the process of measuring and graphically displaying motion of internal organs. This article describes the use of a radarkymograph to detect and follow left-ventricular-wall motion disorders in patients with acute myocardial infarction and chronic coronary-artery disease. The article is presented from a medical standing point, and technical details concerning the radar technology involved, is sparse.

1979 Lin et al. (1979): Measuring heartbeats using Microvawe apexcardiography. The signal source is a signal generator operating between 2.1 and $2.5GHz$.

1980 Iskander and Durney (1980): This publication is an overview of electromagnetic techniques for medical diagnosis at the time of submission. Microwave Doppler radar is presented as a feasible means to measure relative displacement of the arterial wall.

1986 Chen et al. (1986): A $10GHz$ radar operating at $10 - 20mW$ was used to detect heartbeat and breathing in humans at ranges up to $30m$, by phase detection in the received signal.

1988 Chen and Chuang (1988): Radar operating at 2 and $10GHz$ was used to detect breathing and heart beats through rubble.

1992 Lin (1992): Review of microwave sensing to detect physiological volume changes.

1999 Geisheimer (1999): This is an IEEE potentials article describing the use of CW Doppler radars in the $8 - 40GHz$ range to measure human vital signs, such as heart beats and respiratory movement. Potential uses as a ballistocardiograph is covered.

2000 Chen et al. (2000): Description of a $1150MHz$ and $450MHz$ Doppler radar system for detecting human heartbeats and breathing through rubble or barriers. Experiments show that vital signs can be detected at up to 10 feet thickness of rubble.

2001 Droitcour et al. (2001): A description of a microwave narrowband radar for vital signs detection. It is demonstrated that heartbeat and respiration can be measured at $1892MHz$ with a comparison with PPG.

2002 Lohman et al. (2002): An outline of digital signal processing techniques for sensing heartbeats and breathing using a doppler radar. Experimental results using a $850MHz$ and a $2.5GHz$ radar are presented.

2004 Ivashov et al. (2004): Shows some recording examples of human respiration and heartbeats using a $1.6GHz$ FMCW radar.

2005 Thijs et al. (2005): This publication compares CW Doppler radar measurements of heartbeats to simultaneously recorded ICG signals.

Matsui et al. (2005): Simultaneous measurements from a $1215MHz$ CW doppler radar and an ECG are presented in this article. The results support the use of CW Doppler radar to perform non-contact monitoring of heart rate variability (HRV).

Xiao et al. (2005): This article presents measurements of human heartbeats, breathing signals and acoustic signals recorded with a Ka-band low power Doppler radar system.

2006 Droitcour (2006): PhD-thesis on using narrow band doppler radar for measuring heart and respiration. Chapter 2 contains an overview of medical radar history.

Zakrzewski et al. (2006): An x-band CW Doppler radar is used to measure heart rates in this article. The article emphasizes the potential of using Doppler radar to monitor heart rates in a home environment.

Muehlsteff et al. (2006): A narrowband $2.45GHz$ CW Doppler radar is used for characterization of heart motion phases. These are compared to the phases of an ECG during a heart beat.

Li et al. (2006): Long term monitoring of human vital signs using a $27GHz$ radar. Measurements from the front, back and both sides are made. Experimental data shows that correct heartbeat detection from the back is highest due to little interference from respiration harmonics from this angle.

Izadi et al. (2006): System design of a radar operating at $1150MHz$ is described. Simulations on the system's performance on heartbeat detection is also presented.

Jelen and Biebl (2006): Experiments on $440MHz$, $2.4GHz$ and $24GHz$ CW radar for heartbeat measurements. Measurements of heartbeats and respiration are presented.

Pasquali et al.: This article addresses the validation process of a laboratory $9.9GHz$ CW Doppler radar designed to monitor heart activity in mice.

Ishihara et al. (2006): The use of a $1215MHz$ CW Doppler radar to monitor vital signs of patients in isolation units is addressed in this article. Periodic signals corresponding to heart rate and respiratory motion are presented.

2007 Park et al. (2007a): Describes the use of arctangent demodulation of quadrature (I& Q) signals to improve accuracy over selecting only one channel. Experimental data is presented.

Jianqi et al. (2007): FMCW radar operating at $24GHz$ sampled in frequency used to detect heartbeats and respiration. Using wavelets is suggested for separating respiration and heartbeat signals where this is difficult because of respiration harmonics and heartbeat frequencies coincide.

Petrochilos et al. (2007): Explores two different algorithms, Real Analytical Constant Modulus Algorithm (RACMA) and Independent Component Analysis (ICA), used for separating pulse and respiration of two different targets in the same room. Experimental results included.

Massagram et al. (2007): Feasibility study on using Single-Channel Doppler radar for Heart Rate Variability measurement. They compared results using the radar with a finger pulse sensor.

Guohua et al. (2007): Study of using Wavelet transform to separate respiration and heartbeat recorded with radar. Their preliminary results are that using a Symmlet mother wavelet of order 8 is optimal. Using this processing, the radar hearbeat rate shows good correspondence with the reference ECG.

Park et al. (2007b): Experiments with CW radar recording of a person wearing body armor are presented. They conclude that heartbeats can be detected, although with lower amplitude than without the armor.

Hafner et al. (2007): A CW radar with wireless data transmission based on a baby monitoris presented. Results show that heartbeats and respiration can be detected while wirelessly transmitting the data in the FM band.

Vergara and Lubecke (2007): A data acquisition system for a CW Doppler radar vital signs monitoring device is presented in this paper. Measurements of heart beats during held-breath condition are presented.

Muehlsteff et al. (2007): A handheld device that combines ECG with Doppler radar measurements of heart activity is presented in this publication. The main motivation to combine the two different technologies is to distinguish between mechanical and electrical manifestations of heart activity.

Nguyen et al. (2007): This paper describes and quantifies thermal noise, residual phase noise and Flicker noise in a CW Doppler radar for life signs detection.

Li et al. (2007): This article discuss three different receiver architectures and their implications on a vital signs radar monitor front end. The performance of a non-quadrature direct conversion receiver architecture was compared to direct conversion quadrature architecture and double sideband indirect conversion architecture. The article addresses the frequency range from $5GHz$ to the lower region of the Ka-band.

Li and Lin (2007): The optimal choice of carrier frequency for a vital signs CW Doppler radar is the topic of this article. The article maintains that the optimal carrier frequency is found in the lower region of the Ka-band.

2009 Morgan and Zierdt (2009): Respiration rate and heartbeat rate estimation using Doppler radar. An harmonic cancelling technique for removing respiration from the signal is presented, and tested on simulated and real data. The method estimates respiration and heartbeat rate in stationary persons, but fails when the person is moving.

Droitcour et al. (2009): Uses a $2.4GHz$ Doppler radar transmitting at $10dBm$ for heartbeat and respiration measurements. Experimental data from 22 subjects are used to compute SNR in the measurements. Results show reliable measurements of heartbeats at up to $1m$ and respiration up to $1.5m$. Accurate measurements are found for SNR down to $-1dB$, but $\sim 10dB$ is needed for consistent results.

3.1 Heartbeat measurements with UWB radar

2002 Staderini (2002a): An overview article on UWB radars in medicine, with description of possible applications.

Staderini (2002b): Proposes the use of UWB radars as stealthy lie detectors and car driver monitoring. Some heartbeat rate results from a prototype system is shown. Extensive reference list.

2004 Pavlov and Samkov (2004): A simple processing scheme for processing heartbeat UWB radar measurements is presented. The algorithm use no frequency filtration methods, and the authors present some example results where respiration and heartbeats have been separated.

2005 Immoreev et al. (2005): A prototype UWB radar with some examples of use. I.e. heartbeat detection and through the wall radar examples are shown.

Chia et al. (2005): Experimental data of UWB radar operating within the FCC mask of $3.1 - 10.6GHz$ are presented. Heartbeats and breathing is measured, also through a wall.

2006 Immoreev (2006): Demonstrates the use of UWB radar for heartbeat detection. Both remote radar and radar attached to the wrist and neck are used. Examples of through the wall radar are also presented.

Bilich (2006): An article discussing the use of an UWB device for both heartbeat monitoring and communication. Considering the heart as a sphere of radius $6cm$, the RCS of the heart is calculated to be $0.001m^2$. Cites Staderini (2002a) and Ossberger et al. (2004) in computing the two way attenuation from skin to heart including the projected area of the heart to be $50 - 55dB$.

Rivera et al. (2006): Describes use of clustering and MUSIC algorithm for estimation of respiration and heartbeat rates of several persons in the same room, using UWB radar. The radar used is an impulse radar with $300ps$ pulse length using TEM horn antennas.

2007 Staderini and Varotto (2007): A theoretical view on pulsed UWB for heartbeat detection.

Bilich (2007): Theoretical view on using UWB radar for both heart rate sensing and communications. Presents a highly simplified model of UWB measurements of heart rate, and concludes that under the FCC regulations it is possible up to $15cm$.

Zito et al. (2007): Describes a radar and communications system integrated in CMOS 90nm chip for insertion in clothing. The system will be used for heartbeat and respiration monitoring. The authors cite simulation results that attenuation of the UWB signal will be attenuated $60 - 160dB$ from $3.1 - 10.6GHz$ in the two way travel from chest to heart.

2008 Immoreev and Tao (2008): An overview of experimental use of an UWB radar for monitoring heartbeat and respiration rate of patients at hospitals in Russia and Taiwan is given. Radar operating in $6.2 - 6.6Hz$ range is used.

Pisa et al. (2008): A circuital model of UWB cardiac monitoring is presented. Various simulations of EM attenuation through the body are shown. The simulations show an increasing attenuation from $\sim 25dB$ at $0.1GHz$ to $\sim 47 - 60dB$ at $3GHz$.

Wu and Huang (2008): A UWB impulse radar is used to measure heart activity and respiratory motion in this article. The pulse roundtrip time is used to determine the range of the subject, while heart beats and breathing signals are detected by the phase change of the reflected waveforms.

Berger et al. (2008): Design and demonstration of an UWB radar for vital signs measurements. Recordings of both respiration and heartbeat through the wall are presented. Various aspects of radar vital signs detection is discussed.

2009 Anitori et al. (2009): FMCW radar for life-sign detection in humans. They propose that radar scatterers are at body surface, and hence many different frequencies can be used. FFT based and autocorrelation based methods for heartbeat and breathing frequency extraction is presented on real data.

Petkie et al. (2009): A $228GHz$ radar system for vital signs detection up to $50m$ is demonstrated. The recorded data is compared to recordings using both ECG and Respiration belt.

Thiel et al. (2009): Proposes the use of UWB radar instead of ECG to trigger MRI. A comparison between ECG and UWB radar measurements of the heart is made. The UWB measurement varies with breathing, but they conclude that it is possible to use UWB radar as a trigger device for MRI measurements.

4 Radar respiration measurements

Many of the articles listed in Section 3 also deal with the topic of respiration measurements using radar.

1971 Caro and Bloice (1971): Radar was used for contactless monitoring of breathing in infants to detect apnoea.

1973 Susskind: This article is considered to be the first comment on the use of a microwave radiator to detect and map lung disease characterized by excess water in the lungs. The author discusses briefly the implications set by the choice of frequency and transmitted power.

1975 Lin (1975): Measuring respiration in both rabbit and man using microwave doppler radar.

1976 Pedersen et al. (1976): This publication presents contact measurements of water content in human lungs using a mechanically microwave reflectometer. The measurement setup is based on a network analyzer, and the experiments are performed at $915MHz$. The article concludes that changes in water content can be detected qualitatively with a single-frequency apparatus, and that the technique can be of help in intensive care situations.

1978 Pedersen et al. (1978): This paper describes both a single-frequency and a swept frequency microwave reflection technique in order to evaluate their potential to detect excess condensation of water in lungs.

2009 Kiriazi et al. (2009): Uses measurements made with CW radar to compute the RCS of a breathing person from the front and back. Absolute values of the persons RCS are found by compensating for various losses using theoretical values.

4.1 Respiration measurements with UWB radar

Many of the papers listed in Section 3.1 also deal with Respiration measurements using UWB radar.

2004 Ossberger et al. (2004): Respiration monitoring through the wall using pulsed UWB radar.

2005 Venkatesh et al. (2005): A presentation of a mathematical framework for estimation of respiration using impulse UWB radar measurements. Good results from experiments are displayed.

2006 Chen et al. (2006b): Theoretical framework and simulations on UWB respiration rate monitoring.

Nezirovic et al. (2006): Experimental study using UWB radar to detect human breathing, for application in victim search in emergency situations.

2008 Nezirovic et al. (2008): Computes the Human breathing cross section from measurements on a real person using UWB impulse radar. Displays relative amplitudes of motion when viewing the person from differend angles.

Zaikov et al. (2008): Demonstrates the use of UWB radar for detection of people trapped under soil and building materials. It is demonstrated that detection of both movement and respiration is possible.

2009 Soganci (2009): Derives the General Cramer-Rao lower bound for respiration estimation using UWB radar. Simplified bounds for a sinusoidal respiration model is presented, and suboptimal estimators proposed.

5 Other medical radar and UWB radar topics

1993 Mikayawa (1993): This article presents a means to measure temperature distributions in the human body, using a chirped frequency bistatic radar setup. The measurements are performed on phantoms of the human body submerged in a water tank.

2006 Chernyak (2006): Signal processing in UWB radar for searching for survivors in rubble. Computer simulations of the algorithms are presented.

Matsui et al. (2006): This article describes the role of using a $1215MHz$ CW Doppler radar in an experiment to non-invasively measure arterial blood pH. The radar was used to track cardiopulmonary motion while measuring exhaled CO and CO_2 together with infrared surface temperature.

2007 Gezici (2007): Article on limits for estimation of periodic movements in pulsed UWB radar systems. It contains a definition of UWB signal: absolute bandwidth $> 500MHz$ or relative bandwidth $> 20\%$.

Teh-Ho Tao (2007): Short range UWB radar for measuring changes in prf because of Doppler caused by arterial vessel movement. The article presents both measurements on a metal tube on a vibrometer and tests on human subjects.

2008 Yarovoy et al. (2008): UWB radar for human being detection. A method using frequency analysis to detect motion is presented with experimental results. The conclusion is that it detects human movement, primary due to small movements, secondary due to breathing.

2009 Solberg et al. (2009) A feasibility study on using UWB radars for aortic blood pressure measurements. The article presents simulations on estimating blood pressure from variations in the blood vessel diameter.

6 Medical radar imaging

1996 Meaney et al. (1996): A publication that describes the outcome of a $300 - 700MHz$ microwave imaging prototype. The apparatus demonstrated a potential to map tissue material properties.

Semenov et al. (1996): Description of a 2D Microwave tomography system at $2.45GHz$ using 32 emitters and 32 receivers. The system transmits through an object in a tank, and uses amplitude and phase changes to estimate dielectric characteristics. They reference that $2 - 8GHz$ is best suited for microwave imaging, and their own calculations show that $0.9 - 3GHz$ is optimal.

2001 Li and Hagness (2001): This article presents a two-dimensional MRI- derived FDTD simulation that supports the use of UWB radar to image malignant lesions in cancerous breasts. The signal waveform used was a $110ps$ differentiated Gaussian pulse with a center frequency of $6GHz$.

2002 Fear et al. (2002): The use of a UWB radar to perform three-dimensional imaging of a malignant breast tumor is supported. The signal waveform was a $170ps$ differentiated Gaussian pulse with a center frequency of $6GHz$. The Image in the simulation was formed by processing the signals received in a surrounding helical synthetic antenna array, and a planar synthetic antenna array against a flattened breast.

2004 Miyakawa et al. (2004): The imaging capability of a $2 - 3GHz$ chirped pulse UWB radar is presented in the context of early stage breast tumor detection. Analysis is supported with the aid of FDTD simulations.

2005 Li et al. (2005): Overview article on the use of UWB radar and space time beamforming for early breast cancer detection.

Xiao et al. (2005): An method to create a 3D image from 2D simulation results from a confocal focusing algorithm is proposed in this paper.

2006 Sabouni et al. (2006): An FDTD simulation of electromagnetic scatter from a cancerous breast is presented in this paper. The signal source was a $30ps$ Gaussian pulse, implying a UWB radar scenario. Moreover an image of the electrical properties of a modeled cancerous breast is reconstructed by implementing a two-dimensional inverse scattering algorithm based on a 72-element receiving antenna array.

Zhi et al. (2006): This paper proposes a near-field ultra wideband linear constraint minimum variance (LCMV) beamforming algorithm for breast tumor imaging. A two-dimensional homogeneous breast model was used in conjuction with FDTD simulations to form the scattered field of a $110ps$ UWB radar impulse waveform.

Chen et al. (2006a): A generic framework for the modeling of UWB radar signal propagation in a human breast is described in this article. The model provides a way to study the effects of tissue structures, pulse shapes and antenna array configuration on the performance of a specified UWB TOA radar imaging system.

2007 Abedin and Mohan (2007): The time reversal (TR) MUSIC algorith is used here to form the image of malignant tissue in a simulated breast model.

Li and Lin (2007): A demodulation technique to eliminate the effect of random body movements in vital sign radar measurements is proposed in this paper. Multiple tranceivers and polarization multiplexing is used to detect signals for different body orientations. The article presents measurementss performed with a $5 - 6GHz$ radar.

2008 Lim et al. (2008): The delay-multiply-and-sum (DMAS) algoritm is proposed perform imaging of cancerous breasts with UWB radar. The results are based on different numerical models of breast phantoms, and propagation is simulated with the use of FDTD.

Winters et al. (2008): This paper presents an algoritm to localize the breast surface from UWB radar backscatter. This is desirable in order to define the shape and orientation of the breast during the process of UWB breast imaging.

Williams et al. (2008): This paper proposes a scanning method to localize the breast surface to define regions of interest during UWB medical imaging. FDTD is used to simulate the propagating field in a numerical breast model.

Davis et al. (2008): This paper investigates the feasibility of using UWB microwave backscatter in the $1-11GHz$ range to classify features of dielectric targets. The results apply to UWB breast imaging, and are indicative of the potential to determine the shape, margin and size of a tumor. The propagation of the electromagnetic field is simulated with FDTD.

2009 Wiesner (2009): Describes the use of several antennas to detect range and direction of vital signs signals, using a CW radar.

7 Other useful articles

1972 Johnson and Guy (1972): Effect of electromagnetic waves in biological materials. A broad study including tables of reflection coefficients, dielectric properties and penetration depths in body interfaces for various frequencies. A summation of the work in the litterature this far.

1985 Periasamy and Singh (1985): They use laser speckle interferometry to measure the chest displacement during the heartbeat. This is proposed used to detect various heart deceases. Displacements of $0.2 - 0.4mm$ in amplitude are measured.

1990 Jofre et al. (1990): Medical imaging using microwave tomographic scanner. The article includes a table with simulated dielectric properties of a human body.

1997 De Groote et al. (1997): Paper on the motion of the chest during breathing.

Kondo et al. (1997): Paper on the motion of the chest during breathing, measured with laser. 2.5-5.8 mm chest displacement.

2000 Rad (2000): A short history of radar, starting at WW2.

Matthews et al. (2000): This publication presents a $35GHz$ FMCW radar developed by the USAF to clinically assess the condition of fallen soldiers. The potential of the radar is discussed, but an accurate account for its capabilities is not covered.

2004 Lui et al. (2004): This article deals with the potential of UWB radar to detect metallic hip prosthesis in the human body. The concept is investigated by means of FDTD simulations.

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