Ultra-wideband Radar for Angiography

Abdulhameed Habeeb Alghanimi* and Rashid Ali Fayadh

Department of Medical Instrumentation Techniques Engineering, Electrical Engineering Technical College, Middle Technical University, Baghdad 1022, Iraq

*Corresponding author: abdurck@yahoo.com

Abstract. An ultra-wideband (UWB) medical radar has been designed for cardiovascular imaging instead of the X-ray angiography. The aim of this work is to obtain a medical image for human body tissue with all its layers (especially for heart and blood vessels) and to decrease the X-ray biological side effects on the patients, doctors and medical staff during the operation. The elimination of these effects represents the main objective of this paper. This mission can be achieved by using two different types of antennas (transceivers). The first antenna is placed around the human body and the other one is a micro-strip antenna which is inserted to the blood vessel in front of the guide wire of catheterizing angiography. As a result, the distance between two antennas will be measured by calculating the time of arrival (TOA) and propagation direction (Θ). On the other hand, TOA and Θ will depend on the ultra-wideband frequency, shape and other specifications. This distance between the antennas includes the human tissue with its different layers, where each layer has certain dielectric properties enabling us to recognize the tissue type. The required equations and the proposed radar simulation, as well as the output UWB signal were presented in this study. Also, the experiments for image improvement have been applied by improving the blood dielectric properties to enhance the cardiovascular image.

Keywords—ultra-wideband, imaging radar, ultra-wideband cardiovascular

1. Introduction

Many commonly used medical imaging devices for cardiovascular imaging has been found, such as X-ray angiography, cardiac Magnetic Resonance Imaging (MRI), cardiac Computed Tomography (CT) and cardiac ultrasound (echo). These devices have some limitations such as radiographic exposure, high cost, high complexity, long time requirement, limited resolution or other medical preventions. These limitations motivate us to begin this research and attempt to find a new technique that avoids the ionizing radiation as well as minimising the cost and the complexity. The ultra-wideband with its distinctive specifications was the aimed technique.

1.1. Theoretical background

UWB is an emerging wireless communication technology that introduces a wide approach of wireless techniques in various disciplines, especially in medical applications. This technology works with a frequency range of 3.1 to 10.6 GHz and power spectrum density (PSD) of -41.3 dBm/MHz according to the American Federal Communications Commission (FCC) as depicted in Figure 1 [1].
This frequency range with low power consumption makes the technology suitable for use in medical applications. It has no biological side effects and has non-ionizing radiation as well as it has a good ability to penetrate the human tissues. Many studies have been suggested to invest UWB in medical applications, including breast tumour detection in the microwave imaging with oblique projection and Rao detectors. These were used for reducing the cumbersome clutter and detecting the existence of the tumour, where the tumour region denotes the maximum power. The drawback of this method is that the image is not quite distinguishable in the low signal-to-noise ratio (SNR) [2]. Vital Sign Monitoring using penetrating impulses based on the changes in the frequency of the reflected waves from the body [3]. Heartbeat and lung movement detection using impulse radio ultra-wideband (IR-UWB) radar for measurement, the fast Fourier transform has been applied for autocorrelation, then re-applying the process after dividing the received signal to the sets of bins, with removing one block to form the heartbeat rate signal. On the other hand, the pleural periodical movement appears on the image caused by chest periodicity movement, looks as a drawback [4].

Detection of vascular pressure based on the detection of vascular dilation inside an inhomogeneous tissue, where the correlation relationship between the major peak of signal in the time domain and the amplitude of supposed values have been found. These peaks represent the reflection from the boundary layers of the proposed phantom, depending on the relative and propagation times. The drawback of this study was that all the experiments are applied for homogenous tissue and with one layer (silicon) [5].

Bone cancer detection using monopole antenna in the frequency range 1-10 GHz based on image reconstruction technique that measures the change between the dielectric properties of bone tissues and tumour by determining the reflection coefficient with a certain algorithm. However, inaccurate size detection and long calculation time are associated with this technique [6]. Brain haemorrhage detection based on the changes in the electrical impedance of human tissue at frequency range 1-4GHz with using of the scattered signal to produce a microwave image (MI). The main drawback in this work was the increase in the skull induced distortion that makes the procedure becomes quite complicated multi-input multi-output (MIMO) when the stroke is near the skull [7]. Most of the previous medical UWB radars suffer from many problems and the main important ones are the following: signal decay by attenuation, the calculation of return echoes positions, a reflection of the most signal on the skin layer and signal weakness from the depth layers [8].

The proposed UWB radar which is considered to be a new perspective for cardiovascular imaging and blood visualization. This radar will attempt to solve these problems and will be explained in many sections including: an explanation of cardiovascular angiography, biological hazards of X-ray Radiofrequency RF, UWB monocycle pulses, new proposed UWB medical radar, calculations of human tissue characteristic according to its dielectric properties, Snell’s law of electromagnetic wave propagation in different mediums, and dielectric properties improve experiments.

1.2. Angiography
It is an X-ray device designed for diagnostic vascular imaging and vascular interventional procedures. To provide real-time images of blood flow and vascular organ activity for assessing the patency of blood
vessels after trauma, disease, or surgery [9]. Or, for observing abnormal vasculature associated with tumour growth, and for providing anatomic and physiologic information before and during surgery. Through inserting a small-diameter plastic catheter into a large superficial blood vessel (e.g., femoral artery, brachial artery, jugular vein) and guided to the area of interest. An iodine-based on contrast medium, either ionic or non-ionic, is then injected into the vessel. A thin wire is advanced through the brachial or femoral artery, into the aorta and finally, into the heart. Because iodine absorbs X-ray photons more than the surrounding areas, where no iodine is presented.

1.3. Biological Hazards of X-ray RF

Patients and operators are exposed to X-ray ionising radiation during R/F procedures. The total radiation of dose to the patient, which may be equivalent up to 9,000 chest X-rays with the maximum dose rate for high-level fluoroscopic procedures which can be ranged from 21 to 93 R/min [10]. The dose rate from a single-slice computed tomography CT scanner is 4 R/min, and the dose rate from the mammography is 0.4 R/min. Radiologists often receive the highest dose of radiation due to the proximity of their hands to the X-ray tube, and these risks become the motivation for this paper [10]. Ionising radiation is a form of radiation that has enough energy to potentially cause damage to DNA. Also, less increase in the possibility that a person exposed to X-rays will develop cancer later in life. Tissue effects such as cataracts, skin reddening, and hair loss, which occur at relatively higher levels of radiation exposure and are rare for many types of imaging exams. For example, the typical use of a CT scanner or conventional radiography equipment should not result in tissue effects, but the dose to the skin from some long, complex interventional fluoroscopy procedures may be high enough to result in such effect. Another risk of X-ray imaging is possible reactions associated with an intravenously injected contrast agent, or “dye”, that is used to improve visualization [11].

1.4. UWB Monocycle Pulses

UWB medical radar naturally is dealing with human body tissues which will absorb and affect on the radiated energy of UWB pulses, Therefore, we have a challenge with increasing the radiated energy without crossing the FCC mask [1], which is depending on the Gaussian pulse shape (derivative order), width and repetition time (frequency) where the first derivative of the Gaussian pulse equation is:

\[ G_s(t) = A \exp\left[-\left(\frac{t}{\tau}\right)^2\right] \]  \hspace{1cm} (1)

The use of the fifth derivative also with a frequency range between 4 to 6 GHz for indoor application introduces the best performance and best fit-limit to PSD of FCC mask [1, 12]:

\[ G_s(t) = A \left(-\frac{t^5}{\sqrt{2\pi \nu^6}} + \frac{10t^4}{\sqrt{2\pi \nu^9}} + \frac{15t^3}{\sqrt{2\pi \nu^{12}}}\right) \exp\left(-\frac{t^2}{2\nu^2}\right) \]  \hspace{1cm} (2)

where \( A \) is the pulse amplitude, \( t \) is time, and \( \nu \) is a time constant [13]. Therefore, it has safe electromagnetic field according to the FCC and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines and it may be causing thermal effects related to the power absorption by human tissue [1, 14, 15].

1.5. The Dielectric Properties

The dielectric properties are the fundamental parameters that affect the propagation of the electric field. They are a measure of how much the electric field interacts with materials, which can be used (for example) to understand how easily an electric field will polarize a given dielectric material. Dielectric constant and loss tangent are both numerical values using which can be defined permittivity of a dielectric material. While the conductivity is the extent that it allows an electric current to flow through it, where it is used for the rate or degree that electromagnetic wave, electricity, heat, or sound travels through a certain medium.

The dielectric properties of the blood have been affected by many coefficients such as blood temperature [16], applied electromagnetic wave frequency, human gender [17], blood group type (A, B, AB and O) [18], clotting rate [17], blood composition, blood hematocrit level and hemoglobin percentage [19].
2. Methodology

2.1. The Proposed Medical Radar Methodology and Simulation

The proposed UWB radar is a new approach for medical multi-static radar based on the use of two different antennas (transceivers). The first type is horn-type antenna which is established at the body of angiography (around the human body). While the other is a microstrip antenna which is inserted into the blood vessel in front of the guidewire of angiography. The proposed radar wave pulses have been sent through the human body tissues then arrived into the receiver. According to the high difference in the dielectric properties between the blood and other human tissue, we can recognize the blood vessels. Where the blood and the tissue with a high percentage of water have greater dielectric properties (conductivity and permittivity) than another tissue type. Also, the depth of blood vessel has its effects on the reflection coefficients amplitude and time of peaks, thus make a UWB very suitable for cardiovascular imaging. The time of arrival (TOA), the propagation direction (θ) and the distance between the two antennas have determined to form a medical image. The TOA and θ will be different from region to another according to the dielectric properties of each tissue. Where the wave pulses have arrived faster when they pass through high dielectric properties materials like blood. Also, the tissue layers can be recognized by measuring the reflection pulses TOA and θ.

The proposed radar has been designed according to IEEE 802.15.3a channel standard model parameters a UWB fifth derivative Gaussian pulses with a frequency range of 5 GHz. These pulses are pass through a hypothetical medium, which represented by Additive white Gaussian noise (AWGN) and medium gain with certain delay, the delay in real radar will depend on the medium that passes through it, also the propagation direction will be depending on the mediums pass through them. Finally, the received signal will be compared with the transmitted signal by using cross-correlator. As illustrated in Figure 2, which represents the MATLAB simulation for the proposed radar with all steps.

![MATLAB simulation for the proposed UWB medical radar.](image)

Figure 2 illustrates the wave transmission through the body layers with all possible scenarios for wave propagation, which are mentioned in the conclusion. This radar will work instead of the X-ray angiography when there is no need for a very accurate image to minimize the biological side effects of X-ray RF. X-ray angiography will take place when we need accurate real-time imaging which is necessary at the desired area to be visualized clearly.
2.2. Medical Radar Equations

UWB waves transmit through the body tissue layers (mediums) under electromagnetic wave propagation laws, where the velocity of waves different from one to another layer according to the dielectric properties (permittivity) of this medium [20, 21]:

\[ V_i = \frac{c}{\sqrt{\varepsilon_i}} \]  

(3)

where \( V_i \) is the velocity in layer \( i \), \( c \) is the velocity in free space and \( \varepsilon_i \) is the permittivity of the medium. The transmitted angle between two layers will be different from medium to another depending on the intrinsic impedance of the two mediums \( \eta_o \) and \( \eta_i \) and as in Figure 3 and [22].

\[ \Theta_{\text{t}i-1} = \sin^{-1}\left(\frac{\eta_o}{\eta_i} \sin(\Theta_{\text{in}})\right) \]  

(4)

where \( \Theta_{\text{in}} \) is the incident angle which must be greater than the critical angle [20]:

\[ \Theta_c = \sin^{-1}\left(\sqrt{\frac{\varepsilon_i+1}{\varepsilon_i}}\right) \]  

(5)

where \( \Theta_c \) is founded only if the wave transmits from a denser to a less dense layer. To find the one-way distance between the two transceivers of our radar, we need to find the one-way distance of each layer individually and the distance for the first layer \( (d_1) \), the second layer \( (d_2) \), and any layer \( (d_i) \) as follows [22]:

\[ d_1 = \frac{l_1}{\sin(\Theta_{\text{in}})} \]  

(6)

\[ d_2 = d_1 + \frac{l_2}{\sin(\Theta_{\text{t}_1})} \]  

(7)

\[ d_i = d_{i-1} + \frac{l_i}{\sin(\Theta_{\text{t}_2})} \]  

(8)

where \( l_1, l_2 \) and \( l_i \) are obtained from the following equations:

\[ l_1 = w_0 \tan(\Theta_{\text{in}}) \]  

(9)

\[ l_2 = w_1 \tan(\Theta_{\text{t}_1}) \]  

(10)
where $\omega$ is the frequency of the wave. The vertical offsets between the two antennas ($l_i$) can be obtained by the equation:

$$l_i = l_1 + l_2 + l_3 + \ldots + l_i$$

(12)

Also, to find the time $t_1$, $t_2$ and $t_i$ for each layer:

$$t_1 = \frac{d_1}{v_i}$$

(13)

$$t_2 = t_1 + \frac{d_2 - d_1}{v_i}$$

(14)

$$t_i = t_{i-1} + \frac{d_i - d_{i-1}}{v_{i-1}}$$

(15)

where $V_i$ is the velocity of the wave in the medium. Also, the most important law in our calculations is the intrinsic impedance $\eta$ for each layer (medium) [23]:

$$\eta = \sqrt{\frac{\mu}{\varepsilon \left[1 + \left(\varepsilon \omega \mu \right)^2\right]}}$$

(16)

where $\mu$ is the permeability, $\varepsilon$ is the permittivity, $\sigma$ is the conductivity, and $\omega$ is the frequency of the wave. While considering the human body tissues as lossy mediums, that $\mu = \mu_0 \mu_r$, $\varepsilon = \varepsilon_0 \varepsilon_r$, $\sigma \neq 0$, $\mu_0$ is the permeability of free space, $\mu_r$ is the relative permeability, $\varepsilon_0$ is the permittivity of free space, $\varepsilon_r$ is the relative permittivity, and the dielectric properties of free space are: Permittivity $\varepsilon_r = 8.854 \times 10^{-12}$ (F/m), permeability $\mu_r = 4\pi \times 10^{-7}$ (H/m), conductivity $\sigma = 0$ [23]. Finally, there are other parameters can be obtained from the intrinsic impedance. And these parameters are a reflection ($\Gamma$) and transmission ($T$) coefficients between mediums [21, 24]:

$$\Gamma_{1/2} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$$

(17)

$$T_{1/2} = \frac{2\eta_2}{\eta_2 + \eta_1}$$

(18)

Finally, the amplitude of the transmitted wave ($E_x$) will decrease (attenuate) exponentially and can be obtained from the equation:

$$E_x = e^{ax}$$

(19)

where $x$ is the crossing distance and $a$ is the attenuation coefficient, while the equations of this wave after incidents at the boundary between two mediums with different dielectric properties will be:

$$E_t = T \cdot E_i$$

(20)

$$E_r = \Gamma \cdot E_i$$

(21)

where $E_i$ is the incident wave, $E_t$ is the transmitted wave, $E_r$ is the reflected wave, $T$ is the transmission coefficient, and $\Gamma$ is the reflection coefficient. The dielectric properties of human body tissue are estimated by Gabriel [25, 26], so the thicknesses of the tissues (layers) in any region of the human body are represented in [27]. The equations above can be applied on the human body layers depending on the characteristic properties of each tissue which are dependent on the transmitted wave frequency.
2.3. Blood Dielectric Properties Measurement Using Open-Ended Coaxial Probe Experiment

The dielectric properties will be different from one material to another where it will enable us to recognize the substances by recognizing its dielectric properties [28]. And in this experiment, we will attempt to increase the dielectric properties of blood individually to increase the degree of its appearing over other substances (clear blood image). It is a microwave measurement method, the experiment will be done in the frequency center of 5 GHz and in 37°C temperature on many blood samples with various additions and several concentrations, the parts of the experiment are following as shown in Figure 4:

- Dielectric probe (open-ended coaxial probe model: 85070E performance probe).
- RF vector network analyzer (compatible with the above probe model: E5063A ENA series).
- Water bath and thermistor.
- Adjustable probe stand.
- PC computer (laptop).
- Glass sample containers and Alcohol wipes.
- The permittivity equation will be as follow [29]:

\[ \varepsilon = \frac{2r\sin(2s) + \frac{2m(l_2 - l_1)}{\lambda}}{s[1 + r^2 + 2r\cos(2s) + \frac{2m(l_2 - l_1)}{\lambda}]} \]  \hspace{1cm} (22)

where \( r \) is the reflection coefficient, \( s \) is standing wave ratio and \( \lambda \) is the wavelength.

3. Results and Discussion

The equations above can be applied on the human body layers depending on the characteristic properties of each tissue which are dependent on the transmitted wave frequency.

3.1. Intrinsic Impedance and Transmission Angle Calculation

The intrinsic impedance of human tissues and transmission angle between two tissues have been calculated in Table 1 with a frequency of 5 GHz and an incident angle of \( \pi/4 \) and depending on the conductivity and permittivity of each tissue. We note that the intrinsic impedance has directional proportion with the frequency of the transmitted wave, while the transmission angle is depending on the incident angle and the intrinsic impedance and it has inverse proportion with the frequency of the transmitted wave.
The above results are necessary for distance and time calculation, which are benefited in the tissue recognizing and image reconstruction, as mentioned in section 2.2.

3.2. Distance and Time Calculations
The distance, time, and the velocity between the two antennas (one-way distance and time) have been calculated according to the characteristic properties of human tissue which is illustrated in Table 1. Note that the thickness of the layers is taken in the thorax area and the layers of human tissue as ordered and shown in Figure 2.

| Tissue type | Conductivity $\sigma$ (S/m) | Permittivity $\epsilon$ (F/m) | Intrinsic impedance $\eta$(Q) | transmission angle $\Theta_t$ |
|-------------|-----------------------------|-------------------------------|-------------------------------|-----------------------------|
| Air         | 1E-20                       | 1                             | 376.734309                    |                             |
| Skin        | 3.06                        | 35.774                        | 42.7032786                    | 0.24488786                  |
| Fat         | 0.24                        | 5.0291                        | 138.539578                    | 1.17884328                  |
| Muscle      | 4.04                        | 49.54                         | 36.9706969                    | 0.21196925                  |
| Bone        | 0.96                        | 16.05                         | 72.5312559                    | 0.74134990                  |
| Heart       | 4.86                        | 50.27                         | 34.2849767                    | 0.88705125                  |
| Blood       | 5.4                         | 53.95                         | 32.6208079                    | 0.17272680                  |
| Lung        | 3.94                        | 44.859                        | 37.7366007                    | 0.06408701                  |

The above results are necessary for distance and time calculation, which are benefited in the tissue recognizing and image reconstruction, as mentioned in section 2.2.

Table 2. Distance and time between the layers.

| Tissue type | Thickness | L | distance | time    | velocity |
|-------------|-----------|---|----------|---------|----------|
| Air         | 50        | 50| 58.76    | 2E-07   | 3E+08    |
| Skin        | 1.3       | -0.32| 60.1    | 2.2E-07 | 5E+07    |
| Fat         | 9.5       | 22.98| 84.97   | 4.1E-07 | 1E+08    |
| Muscle      | 13.5      | -2.91| 98.78   | 7.3E-07 | 4E+07    |
| Bone        | 6.6       | -6.04| 107.7   | 8.5E-07 | 7E+07    |
| Heart       | 5.65      | -6.93| 117.9   | 1.1E-06 | 4E+07    |
| Blood       | 1.2       | 0.209| 108.9   | 8.7E-07 | 4E+07    |
| Lung        | 5.7       | -0.37| 123.6   | 1.2E-06 | 4E+07    |

From the above results in Table 2, we observe different times and distances for each layer according to the dielectric properties of each layer. These differences enable us to reconstruct a medical image depending on the velocity of pulses in the tissues.

3.3. Reflection and Transmission Coefficients Calculation
The reflection coefficient and transmission coefficient with different frequencies are illustrated in Figure 5 and Figure 6, respectively.
From the above results, we note that the reflection coefficient and transmission coefficient have a directional proportion with the transmitted wave frequency, and from Figure 5, we note that the blood has the smaller reflection coefficients that mean the UWB waves need shorter time when passing through blood and the transmitted waves. Also, the skin-air transmission coefficient is smaller than the air-skin transmission coefficient. So that, the finding of reflection and transmission coefficients introduces the ability to the radar to make the process of imaging in the two directions either from the outside to the inside transceiver or from the inside to the outside transceiver as illustrated in Figure 3. Also, it can make both processes to get a very clear image which makes us addressing the problems of old radars, which is represented by losing the power in the first two layers and receive very weak signals from the other depth layers and choose the way that has the lower reflection coefficient and the higher transmission coefficient to minimize the power absorption [8].
3.4. Experimental Results

The first experiment was done by adding glucose water intravenous nutrient with different concentrations to detect its effects on the dielectric properties of blood (especially on the permittivity), where the glucose concentrations from 0mg/dL to 16000mg/dL was used as shown in Figure 7. According to the above results illustrated in Figure 7, we could conclude that the blood permittivity decreases gradually when we increase the glucose concentration in the blood and the opposite is right where we could increase the dielectric properties of blood by decreasing the glucose concentration. Also, we could use these results to design a new ultra-wideband device that could detect glucose concentration in the blood non-invasively.

![Figure 7. Blood permittivity as a function of glucose concentration.](image7)

The second experiment was done by adding normal saline intravenous nutrients with different concentrations to detect its effects on the dielectric properties of blood (especially on the permittivity), where we use the salinity concentrations from 0% to 2%, and Figure 8 shows the results. According to these results, we could conclude that the blood permittivity decreases gradually when we increase the salinity concentration in the blood and the opposite is right where we could increase the dielectric properties of blood by decreasing the glucose concentration. Also, we could use these results to design a new ultra-wideband device that detects salinity concentration in the blood non-invasively which could be served in blood pressure measurements.

![Figure 8. Blood permittivity as a function of salinity.](image8)
The last experiment was done by adding anti-coagulant material (EDTA and Citrate) to the blood samples and measure its effects on the dielectric constant (permittivity). Where the pure blood permittivity is 58 F/m, while the permittivity for blood with citrate is 62 F/m and for blood with EDTA is 63.5 F/m. These results show that the adding of anti-coagulant increases the blood permittivity when it is added to the blood. Note that all experiments were practiced in the frequency of 5 GHz which was fit to FCC mask and under the accepted SAR level, also at a temperature of 37°C and with fresh blood and the donor blood group is (+O). We faced some limitations in the real case to add these materials to human blood, depending on the patient’s condition and his disease background.

4. Conclusion

After finding the results in section 3, we got a direction-selective multi-static UWB radar image with many features, and the most important is minimising the power absorption by human tissue to the half which decreases the attenuation of the signal in the human tissue. Also, minimising the time of arrival TOA to the half, where the transmitted signal will be received from another antenna on the other side and not need to pass through human tissue again (one-way distance and time). In addition, the proposed system enables us to cancel the position calculation of return points. And just we need to know the position of the received antenna on the other side which is achieved by finding the total offset (t) as shown in Figure 3. In addition, the ability of imaging in the two directions make us avoid the problems of old radars with power losses. This proposed radar can be developed in the future to work with other devices like endoscopes, and with the same principle of work and design, and study the ability to improve its image by injecting the body with a certain material that manipulating in the dielectric properties of tissues.

The finding of transmission and reflection coefficients between the layers in multi-layer tissue enables us to choose the best way to the image, which is determined according to the dielectric properties of tissues under the test. If the wave transmitted from a layer with a high dielectric properties to the next layer with lower dielectric properties, then the reflection coefficient will have negative value and the transmission coefficient will have high positive value according to the equations (17) and (18), that means most of the wave will pass the boundary between the two layers and transmitted to the second layer, and small percentage of wave will be reflected from the boundary and return to the opposite direction of wave propagation and vice versa.

On the other hand, the results of the experiments in section 3.4 can introduce another feature that can be used to improve the UWB image by manipulating the reflection and transmission coefficients through adjusting the blood dielectric properties according to our requirements. This is mentioned in the previous paragraphs, where if we want to take an image from the outer to the inner antenna (one-way image), we must improve the transmission coefficient. While if we want to take an image from outer to the outer antenna (two-way image), we need to improve the reflection coefficient. Finally, we could highlight that the proposed approach has proven to be a successful alternative of X-ray technique.

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