35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Optimal frequency range for medical radar measurements of human heartbeats using body-contact radar

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Abstract— **In this paper the optimal frequency range for heartbeat measurements using body-contact radar is experimentally evaluated. A Body-contact radar senses electromagnetic waves that have penetrated the human body, but the range of frequencies that can be used are limited by the electric properties of the human tissue. The optimal frequency range is an important property needed for the design of body-contact radar systems for heartbeat measurements. In this study heartbeats are measured using three different antennas at discrete frequencies from 0.1 - 10 GHz, and the strength of the received heartbeat signal is calculated. To characterize the antennas, when in contact with the body, two port S-parameters† are measured for the antennas using a pork rib as a phantom for the human body. The results shows that frequencies up to 2.5 GHz can be used for heartbeat measurements with body-contact radar.**

I. INTRODUCTION

Detection of heartbeats using radar has been widely reported in the literature. Most systems reported have been non-contact systems where the measurements have been performed with the radar antennas located at a distance from the human object [2]. In [3] it is concluded that the movement of the chest surface is the dominant factor that cause heartbeat modulation in non-contact radar measurements. In this case, the radar sensitivity to heartbeats increases with frequency since the radar cross section (RCS) of the chest surface increases, and because the motion becomes larger compared to wavelength [4].

With a body-contact radar the antennas are placed in contact with, or very close to the human body. In such systems the air/skin interface is no longer the dominant reflector, and the radar is able to sense electromagnetic (EM) waves that have penetrated human tissue and are reflected from the heart wall. Since body-contact systems measure the mechanical movement of the heart directly, the recorded signal possibly contains more information about the heart than the signal recorded by non-contact systems. In [5], measurements were conducted using a body-contact continuous wave (CW) radar operating at 1 GHz. Several states related to the heartbeat cycle were detected, such as opening and closing of the heart valves and ventricular ejection and filling. It was also shown that the measured waveform was dependent on the blood pressure, or the heart rate, or both.

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†S-parameters is the elements of the scattering matrix. S_{ii} measures the reflected wave from port i, and S_{ij} measures the transmitted wave from port j to port i [1].

The contactless nature of remote heartbeat detection using radar has been considered as the main advantage for radar systems over traditional monitoring equipment like Electrocardiogram (ECG). This argument cannot be used for a body-contact radar system, but since the radar measures mechanical heart activity were as ECG measures the electrical activity, different information is obtained about the heart dynamics. We believe that it is important to study what kind of information is available through body-contact radar measurements, because diagnostic information supplementary to conventional methods may be found.

In this paper an experimental approach is taken to find the optimal frequency range where heartbeats can be measured with body-contact radar. This is important knowledge for the design of such radar systems. A high frequency of operation is often desirable to keep the physical size of the antennas small, e.g. imaging systems using an antenna array were the size of the antennas are limited by spatial sampling considerations for the array. On the other hand, the range of frequencies are limited by the EM properties of propagation in the human body.

The characteristics of the antenna change, compared to the free space response, when it is placed close to the human body [6]. To characterize the antennas, two port S-parameters for the antenna has to be measured using a phantom for the tissues between the chest surface and the heart. Here we use a pork rib to characterize the antennas, and the same antennas are then used to measure the heartbeats on a male person. The signal strength of the recorded heartbeat signal is calculated as a function of frequency to find the frequency response for body-contact heartbeat measurements.

II. THEORETICAL CONSIDERATIONS

A. The radar cross section of the heart

The RCS of the human heart as a function of frequency is in general unknown. A very simple approximation would be to model the human heart as a sphere. Fig. 1 shows the RCS for such a sphere in the frequency range 0 - 5 GHz. The maximum point is when the circumference of the sphere is close to the wavelength [7], giving a maximum at

$$f \approx \frac{v_p}{2\pi a} \,. \tag{1}$$

v_p is the propagation speed of the EM-wave and a is the radius of the sphere. The propagation speed is dependent on the relative permittivity, ε_r', in the medium,

$$v_p = \frac{c}{\sqrt{\varepsilon_r'}} \,. \tag{2}$$

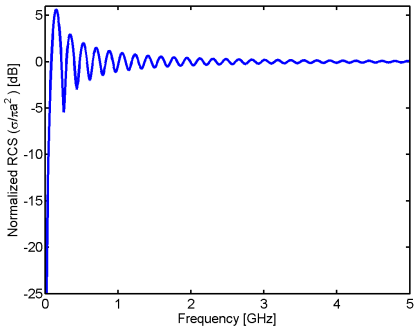

Fig. 1. Radar cross section (σ) for a sphere of radius (a) 5 cm, in a medium with relative permittivity (ε_r') 42, and propagation speed given by (2). The RCS is normalized to the projected area of the sphere and plotted in dB scale.

A database of the electric properties of human tissue is available from [8]–[10]. From 100 MHz to 10 GHz ε_r' for the heart falls from 91 to 42. Using these values together with an approximate guess for the heart radius of 5 cm, the maximum RCS of the human heart is found to be in the area from 100 to 150 MHz. From Fig. 1 it is seen that the heart's RCS can be approximated as constant when the frequency is above 100 MHz, the oscillating response is below ± 5 dB which is little compared to other factors like attenuation in human tissue.

B. Attenuation

The propagation constant, γ, for a lossy medium is [1]:

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu(\varepsilon' - j\varepsilon'')}\,, \tag{3}$$

where α is the attenuation constant, β is the propagation constant, μ is the permeability, and the complex dielectric constant is given as $\varepsilon = \varepsilon' + j\varepsilon''$. The attenuation, D, of a wave travelling through a medium of length z can then be calculated as

$$D = e^{-\alpha z}\,. \tag{4}$$

TABLE I

A SIMPLE LAYERED BODY MODEL

Tissue layer	Thickness	Deepness
Skin	2 mm	0 mm
Fat	13 mm	2 mm
Muscle	10 mm	15 mm
Bone	15 mm	25 mm
Heart	-	40 mm

Table I describes a simple layered model of the human tissues between the heart and the chest surface. The model is obtained by measuring the layers of the pork rib used in the experiments, and is similar to the model used in [11]. Using (3) and (4) and the dielectric properties from [8]–[10], the two way attenuation of a wave using this model is calculated and presented in Fig. 2. This model only describes attenuation and does not take into account losses due to mismatch between antenna and the body, as well as mismatches between the tissue layers in the body. The measured loss can therefore be expected to be higher than indicated in Fig. 2. However, the model shows that the attenuation alone is too high for frequencies above 10 GHz, making the 100 MHz to 10 GHz the region of interest for heartbeat measurements, and is therefore the region investigated in this paper.

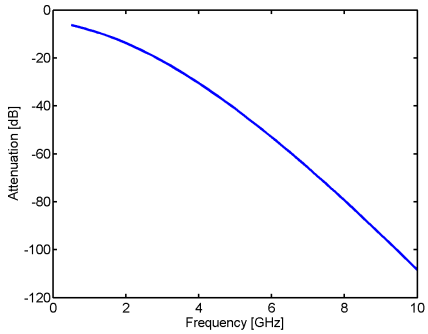

Fig. 2. The two way attenuation between the antenna and the heart calculated using the model described in Table I

III. METHODS AND MEASUREMENT SETUP

A. Prok rib measurements

To describe the behaviour of the body-contact antennas, three different sized antennas with different frequency responses in free space were used, see Fig. 3. Two port S-parameters were measured using a pork rib as a phantom.

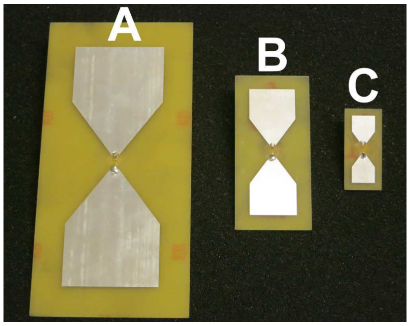

Fig. 3. The antennas used in the experiment. All antennas are fat dipoles with dimensions length/width of the conducting area: A: 122/44 mm, B: 62/22 mm and C: 32/11 mm

The measurements were performed using an Agilent N5245A vector network analyser (VNA). S11 and S21 measurements were taken in the frequency range from 50 MHz to 10 GHz with an IF-bandwidth of 1 kHz. The setup is illustrated in Fig. 4. The pork rib was obtained frozen, but was defrosted before the measurements. Although difference in electric properties of postmortem defrosted tissue and living tissue can be expected, we think the pork rib serves as a good phantom for the characterization of the antennas. The length and width of the rib was about 30 cm in both directions, and it was about 4 cm thick. All measurements were performed in an anechoic chamber.

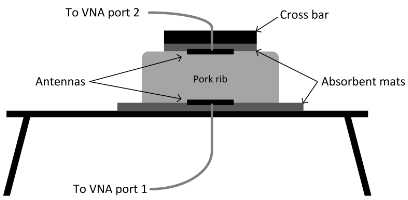

Fig. 4. The setup for rib measurements. The antenna connected to port 1 of the VNA was placed on top of a 2.5 cm thick absorption mat lying on a wooden table. The pork rib was placed on top of it with the skin side down. On top of the rib the antenna connected to port 2 was placed and held in place directly above the first antenna with a wooden crossbar. An absorption mat was placed between the antenna and the crossbar. When the antennas were changed the pork rib had to be removed. This means that there can be a slight difference in the placement of the pork rib with respect to the antennas between the measurements.

B. Measurement of human heartbeats

Human heartbeats were measured with CW measurements on a male test subject, 33 years of age. The CW measurements were repeated for each of the three antennas used in the pork rib experiment at the frequencies: 100 MHz, 250 MHz, from 500 MHz to 5 GHz with 500 MHz intervals, and from 5 GHz to 10 GHz with 1 GHz intervals. At each frequency 18 seconds of data were collected with a sampling frequency of 223.5 Hz. The same VNA as for the pork rib experiment was used, with an output power of 10 dBm and IF bandwidth of 200 Hz. The setup is illustrated in Fig. 5.

Calibration of the data were done by dividing the received signal from the heartbeat measurement, with the closed loop signal received when the cables were disconnected from the antennas and connected together. The test subject was holding his breath during data collection to eliminate interference from breathing. To remove contributions from stationary reflectors and coupling between antennas, the received signal was high pass filtered using a 8 point two way Chebyshev type 2 IIR filter with cutoff at 0.5 Hz. After filtering the dynamic heartbeat signal was detected. As a measure of the strength of this signal the RMS of the absolute value of the detected complex heartbeat signal was calculated.

IV. Results and discussion

A. Pork rib measurements

Fig. 6 shows S11 measurements of the antennas in free space. Comparing these measurements with the S11 measurements of the antennas in contact with the pork rib, Fig. 7, shows how the antenna response change when in contact with the rib. The lower cutoff frequency is shifted down, and the antennas are more wideband. In Fig. 8 the results of the S21 measurements of the antennas are shown. The system has a bandpass behaviour where the high frequency response of the pass band is independent of the antenna used. The upper cutoff region is a property of the attenuation through the pork rib. The lower cutoff region is dependent on the antenna and comparison with Fig. 7 shows that it is the antennas lower cutoff that is dominant in this region

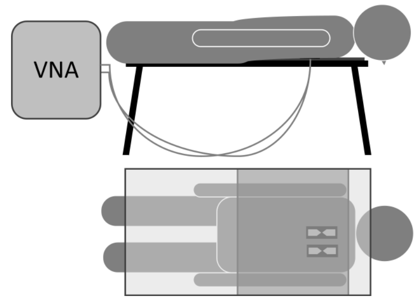

Fig. 5. Setup for the heartbeat mesurements. Two antennas were used, one Tx antenna connected to VNA port 1 and one Rx antenna connected to VNA port 2. The antennas were placed on top of a 2.5 cm thick absorbing mat on a table. The test subject was lying on top of the antennas so that the Tx antenna was at the centre of the sternum and the Rx antenna 8 cm to the left over the heart, as indicated in the lower sketch were the person is seen from underneath the table. During the measurements the person was wearing a T-shirt that was between the antenna and the skin. In the pork rib measurement the t-shirt was not present, although not investigated, we believe that the t-shirt has little effect on the measurements.

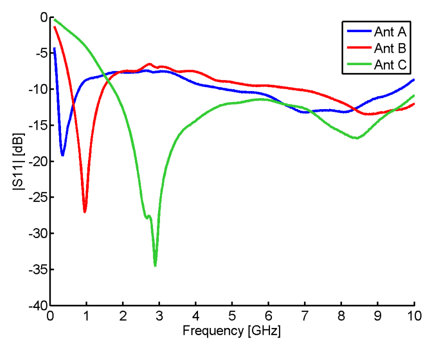

Fig. 6. The reflected power for the antennas in free space. The measurements were preformed by measuring S11 with the antennas in an anechoic chamber.

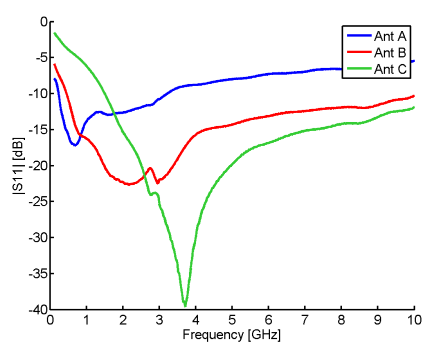

Fig. 7. The reflected power for the antennas when in contact with the pork rib. The lower antenna location in Fig. 4.

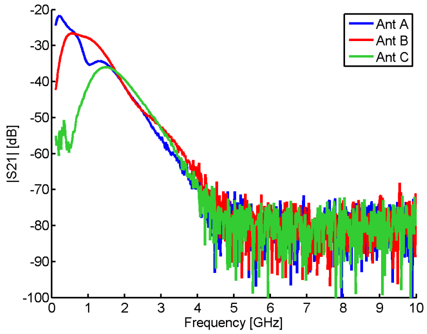

Fig. 8. The transmitted power through the pork rib. Referring to Fig. 4, the lower antenna location is the Tx, and the upper location is the Rx.

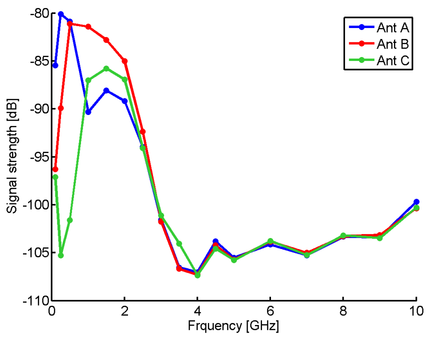

Fig. 9. As a measure for the heartbeat signal strength the RMS value of the absolute value of the recorded complex signal after high pass filtering was used. Here it is plotted against frequency in dB scale. Reliable detection of heartbeats were possible up to 2.5 GHz. The high signal strength for antenna C at 100 MHz is because the noise floor of the VNA is higher below 500 MHz than above.

B. Measurement of human heartbeats

The heartbeat signal strength is plotted in Fig. 9 for each antenna. Comparing the measured signal strength in Fig. 9 with the measurement of the transmission through the pork rib in Fig. 8 we find that the curves has similar shape describing the same band-pass behaviour. This strengthen the assumption that the the RCS of the heart can be regarded as constant from the sub GHz region and upward, since the frequency response shows low dependency of the heart presence.

Both experiments show the same behaviour from 2 GHz and above, and both show that in this region the response is, on a large scale, independent of the antennas used. Some influence from difference in the antenna gain and the beam pattern inside the human body may be expected. However the results indicates that the properties of propagation inside the body is the dominant factor, and sets the upper frequency limit for body-contact heartbeat measurements. The attenuation of the EM-waves in the body decreases with frequency, and below 2 GHz the signal strength of the heartbeats is dominated by the antenna response. Comparison of Fig. 8 and 9 shows resemblance between the the antenna response for the rib measurements and the response for the heartbeat measurements. This indicates that characterization of the antennas using a pork rib is a good indicator for the performance of the antennas used in body-contact radar measurements.

The measurements indicates that heartbeats can not be measured using body-contact antennas above 4 GHz with the system used in this experiment, and that good SNR can be expected up to 2.5 GHz.

V. CONCLUSIONS

For medical radar measurements using body-contact antennas, frequencies up to the 2-3 GHz region can be used. The exact cutoff is dependent on the radar system and individual differences in anatomy, and further studies are needed establish a more accurate result. The signal strength is higher at lower frequencies. However, considering the practical implications of locating the antennas on the body a small antenna is desirable both for single channel measurements and imaging arrays, a good choice would be to select as high a frequency or frequency band as possible up to the limit indicated by this study.

ACKNOWLEDGMENT

This work is part of the MELODY project funded by the Research Council of Norway under contract number 187857/S10

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