Beat to Beat Continuous Blood Pressure Estimation using Transmission Coefficient of On-body Antennas

Mona K. ElAbbasi (me246@aub.edu.lb)
American University of Beirut  https://orcid.org/0000-0003-3595-4042

Mervat Madi
Higher Colleges of Technology

Karim Kabalan
American University of Beirut

Herbert Jelinek
Khalifa University of Science Technology - Abu Dhabi Campus: Khalifa University of Science and Technology

Research Article

Keywords: Blood pressure, microstrip patch antenna, transmission coefficient EM waveforms, brachial artery thickness to radius ratio, cuffless, systolic pressure, diastolic pressure.

Posted Date: November 8th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2206141/v1

License: ©  This work is licensed under a Creative Commons Attribution 4.0 International License.  Read Full License
Abstract

**Background**-Elevated blood pressure (BP) is a clear sign of hypertension, a condition associated with increased morbidity and mortality. Regular blood pressure monitoring is therefore crucial, but many cuff-based devices and their usage are restricted to monitoring while at rest.

**Method**-This paper reports on the use of a pair of microstrip patch antenna technology to obtain BP values through an innovative technique using the electromagnetic transmission coefficient waveforms. The change of transmission coefficient of EM waveforms emitted by the pair of antennas was analyzed and correlated with brachial artery thickness to radius ratios and hence, blood pressure assessment at different blood pressure points ranging from 60-140 mmHg. The latter is based on simulations and data algorithms performed at brachial artery diameters of 4.32, 4.33, 4.33, 4.56, 4.53 mm, to mimic the changing brachial artery diameter associated with a pulsatile blood flow.

**Result and Conclusion**-In conclusion, the largest brachial artery thickness to radius of 0.9 is associated with a high blood pressure of 140-160 mmHg while normal blood pressure levels are referred to radius to thickness ratios of 0.5 and 0.6. Thus, the use of the transmission coefficient has shown a high accuracy for determining BP from the micro-patch antennas, which provides a novel option for continuous real-time, in the wild BP assessment and therefore more accurate information for the clinician.

**Background**

The most significant and frequent clinical assessment is that of blood pressure (BP) [1]. According to the World Health Organization (WHO), elevated blood pressure is considered as a significant risk factor of cardiovascular diseases (CVDs) accounting for about 32 percent of worldwide mortality [2]. Regular out-of-office blood pressure monitoring is therefore crucial, especially for those who already have hypertension or other disorders that are associated with hypertension [3]. Continuous, wearable blood pressure devices are therefore essential for real-time evaluation of blood pressure and timely intervention [4].

There are various ways to record continuous blood pressure variations either using the photoplethysmogram signal (PPG) then applying machine learning algorithms to detect the variations of blood pressure [5] or by measuring the time difference between the peaks of electrocardiogram (ECG) and photoplethysmogram (PPG) [6]. These methods have been used to develop wearable devices that can non-invasively and continuously measure blood pressure. However, these methods require frequent calibration because of its lower prediction accuracy.

Several popular devices currently available include mobile phone Apps and upper-arm cuff or wrist worn sensors. These are mostly unregulated and unvalidated and can lead to under- or over-diagnosis of hypertension and inappropriate treatment [7]. Novel approaches to address these issues include the development of continuous wave radar and microstrip patch antennas [8, 9]. Penetration of electromagnetic waves generated by the antennas into human skin, fat, bones, muscles and finally blood provides a relationship between the electromagnetic waves and blood pressure parameters.

We propose two pairs of wearable and compact patch antennas for continuous and cuffless blood pressure monitoring. The topology is based on simulating two pairs of antennas on a simulated five-layer human arm model and then extracting the pulse transit time (PTT) from the proximal and distal transmission coefficient scattering waveforms measured out of the antennas based on the assumption that brachial artery walls have...
dynamic elastic properties. The standard non-linear Moens and Korteweg model relates the pulse wave velocity (PWV) and the incremental elastic modulus of the arterial wall \[6\]. The latter is compared to the model provided by authors in \[9\] showing a good correlation between systolic and diastolic blood pressures.

We propose a new method based on use of microchip antennas that determines the changes in BP relevant to changes in brachial artery thickness. The results of including radius estimates, along with electromagnetic (EM) antenna transmission propagation characteristics can be used to estimate continuous BP non-invasively. In this paper, we will discuss the feature points of the transmission coefficient waveforms from two pairs of antennas in order to derive continuous and noninvasive blood pressure variations. To the best of our knowledge, there is no mathematical model that demonstrates the correlation of the transmission coefficient between a pair of antennas in relation to variation of brachial artery thickness to radius ration changes and blood pressure. BP is then related to hypertension by a systolic blood pressure of \(> 140\) mmHg or diastolic blood pressure of \(> 90\) mmHg.

**Method**

**1.1 Antenna Structure and Principle of Operation**

A compact rectangular inset-fed antenna with a 50 \(\Omega\) microstrip feed line and a waveguide (partial ground plane, substrate and radiating patch) was designed and optimized in an ANSYS HFSS environment. The epoxy substrate was of 0.4 mm thickness \((h)\), of \(35 \times 35\) mm area, and the dielectric constant and dielectric loss tangent were \(\varepsilon = 4.3\) and \(\tan\delta = 0.004\), respectively. The epoxy substrate was utilized as it can be used across curved surfaces. The dual-antenna module designed and optimized at 2.4 GHz as shown in Fig. 1 (a) is used to measure pulse signals at two close points along the human arm where bloodstream flow and BP analysis is analyzed. It combines features such as sensing and through signal processing for the purpose of instant and long-term continuous monitoring of blood pressure. In the simulation stage, it is a common practice to simulate the antenna in a close proximity to homogeneous phantom models. Hence, the simplest model for a human arm to be used for studying the electromagnetic wave interaction can be a homogenous dielectric slab. The dielectric constant for the slab is calculated by performing an averaging on the dielectric properties of the different parts (i.e., skin, fat, muscle, etc.). To ensure communication signals are not radiated out, signal transmission through the conductive layers below the skin, which ensures critical signals stay mostly within the body. Note that the high-water content of our body provides a low-loss channel for signal propagation. The transmitted signal flows through the low resistance layers of the body below the skin and is picked up by the antenna at the receiver side.

Designing an antenna to operate at a high frequency can reduce not only antenna size, but also spacing between collocated antennas (e.g., transmitting and receiving antennas) of the system that must be at least a half wavelength to avoid mutual coupling. Let \(S_{12}\) be the measured amplitude variation of the transmitted signal \(S_{12}\) at frequency \(f\), which propagates through a sample of thickness \(d\). In this investigation, an isolation of more than 50 dB for the pair of antennas placed on a homogenous human arm (Fig. 1) has been achieved that causes extremely low mutual coupling. Isolation of more than 20 dB for the pair of antenna elements needs to be maintained for low mutual coupling and this can be achieved when the separation between the antenna elements is at least \(0.5\lambda\), which is about 6.25 cm.

In detail, this technology focuses on transmission coefficient data analysis combined with an arterial blood flow algorithm, which in turn, utilizes the relative change in brachial artery diameter to determine blood pressure. Analytic algorithms can detect the feature points of variation of blood pressure in respect to variation of brachial
artery thickness to radius ratio. The main goal of this work is to provide a model to correlate the transmission coefficient scattering parameter ($S_{21}$) with blood pressure. The relationship between the latter and the variation of brachial artery thickness to radius ratio will also be elaborated. The results successfully demonstrate how the radius estimates, along with EM antenna transmission propagation characteristics, can be used to estimate non-invasively the continuous BP.

### 1.2 The Dual Antenna Module on Heterogeneous Human Arm

Based on prior literature, incremental brachial artery diameter will allow us to examine the effect of blood flow on blood pressure vessel variation. Figure 7 shows the linear increase in diameter.

To investigate on-body antenna performance, the transmitting and receiving antennas are simulated on a multilayered human body equivalent phantom as shown in Fig. 2, and the properties of various tissues, skin, fat, muscle, bone, artery and blood are specified at 2.4 GHz and designed in HFSS ANSYS as shown in Fig. 3.

The electromagnetic coupling between the antenna and the lossy human body tissue affects the antenna performance including the matching, resonance frequency, efficiency, and gain [4]. This leads to a shift in the resonance frequency of the antennas. Based on the available information, our developed model can provide a closer approximation for the performance of the antenna than the homogenous model does. Since the model consists of multiple layers with different permittivity, which makes it closer to voxel model to a certain level.

### 1.3 Pulse Artery Information

To obtain desired artery pulse information from received signal, it is necessary to design a signal processing method based on physiological understanding. For artery pulse, to measure the desired pulse wave velocity (PWV), a classic measure of arterial stiffness, there must be two peaks, Peak 1 and Peak 2, measured from the proposed dual-antenna system, antenna1 and antenna 2, shown in Fig. 4.

Therefore, the pulse transition time, $PTT$, is obtained from the time difference ($t_2-t_1$) of Peak 1 and Peak 2. The distance, $D$, of blood travelling is defined from the antenna design (6.5cm), thus the blood PWV, $V$, can be calculated by:

$$PWV = \frac{D}{t_2 - t_1}$$

(1)

Since the proposed method is used to monitor artery pulse signal continuously, the individual waveform of artery pulse signal will be analyzed.

### 1.4 Proposed BP Estimation Algorithm

The block diagram of the proposed BP estimation algorithm is shown in Fig. 5. We will present the algorithms to effectively extract the key features of transmission coefficient waveforms. The proposed method is mainly performed in Matlab Central (MathWorks Inc. USA). Preprocessing algorithms including normalization, filtering,
pulse wave peak and valley point detections are applied to remove noise from the recorded signals and allow
determination of the transmission coefficient waveforms, followed by detecting and extracting the key points of
the waveforms. Finally linking the BP levels to the waveforms by regression tree models, which is validated
according to the mathematical model proposed in our previous work.

The relationship between blood pressure and brachial artery thickness to radius ratios throughout the cardiac
cycle has been reported [10–12]. Relative changes of the artery radius are linearly related to relative changes of
blood pressure. The difference in electromagnetic properties is related to the instantaneous artery properties in a
wave reflection, and at the same time to instantaneous changes in pressure. The area under the curve (AUC) value
of the transmission coefficient curves for variation of brachial artery radius is then used here as a basis to
determine the presence or absence of cardiovascular risk factors. The built logistic model assures that any
increase in area under curve leads to an increase in cardiovascular risk. Previous studies [13–17] rarely prove the
relationship between the electromagnetic transmission coefficient waveforms and blood pressure. However, subtle
variations in the morphology of transmission coefficient waveforms, presented in this study, appear correlated to
the pressure imposed by blood flow on the walls of blood vessels as shown in Fig. 6. The graph shows direct
association between brachial artery diameter and variation in transmission coefficient between the two antennas.
Numerical simulations conducted on the heterogeneous sample demonstrated that the sensing thickness to radius
variation depends strongly on variation of the dielectric properties between the frequency range from 2 GHz to 3
GHz. The variation of the dielectric properties of the simulated human arm leads to variation of the extracted
transmission coefficient waveforms between the pair of antennas. The ratio of areas confined under transmission
coefficient waveforms increase with the increase in brachial artery thickness to radius ratios. These confined areas
are related to blood pressure coefficient levels. By breaking the area under the transmission coefficient pulses into
two parts based on the location of the inflection point, the blood pressure parameters can easily be determined.

Before extracting the features of the transmission coefficient waveforms, the key points of each pulse need to be
detected. As transmission coefficient curves have different morphologies, the point detection algorithms should
have minimal sensitivities to different morphologies. If the brachial artery size changes due to variation in blood
pressure, then the wave characteristics are altered. Accordingly, the response of our radiofrequency-based sensors
maps these alterations to indicate the change in the BP, hence tracking its variation. Scattering-parameters are
used here to describe the input-output EM relationship between the terminals of the sensor antennas.

A transmission coefficient waveform has a few key points, such as maximum slope point, systolic peak and
diastolic peak as shown in Fig. 7. The regression tree model built in Matlab can detect the blood pressure features
due to differences in diameters of the vascular system from elastic arteries via capillary networks to veins in
addition to their pulsatile nature associated with the heartbeat. This variation is reflected also in the brachial artery
thickness to radius ratios. Here, we identify the proposed method for detecting the key points to relate to systolic
and diastolic BP features.

The following key cardiac frequency features are extracted by Fast Fourier Transform (FFT) from frequency
domain to time domain. The extracted features are listed below:

a. Heart Rate:

Heart rate tracking can be obtained by recording the time interval between two consecutive systolic peaks or two
consecutive minima [18]:

Page 5/16
b. Reflection Index:

Reflection index is a percentage ratio of pulse reflection. It is related to the height of systolic peak to the inflection peak. It can be obtained using [19]:

\[ RI = \frac{Y}{X} \]

(3)

Where \(Y\) is the amplitude of the inflection point and \(X\) is the amplitude of the systolic pulse shown in Fig. 2.

c. Large artery stiffness index (LASI):

The artery index of an individual is a measure of the stiffness of his arteries and is expressed by [20]:

\[ LASI = \frac{h}{\Delta T} \]

(4)

where \(h\) is the height of the individual and \(\Delta T\) is the time interval between the systolic peak and the inflection point of a given pulse. Since the height of the subjects is not considered in this study, we set it to 1 for all subjects.

d. Ratio of Pulse Areas:

The ratio of pulse areas is the ratio of different areas under a given pulse. By breaking the area under a transmission coefficient pulse into two parts based on the location of the inflection point. The authors in [14, 15] showed that the ratio of these two areas is related to the total peripheral resistance and BP. From here, the Inflection Point Area ratio is calculated from:

\[ IPA = \frac{A_2}{A_1} \]

(5)

\(A_1, A_2\) are the areas of the first and second parts as shown in Fig. 7. The Figure indicates two slope features, two power areas, and three amplitude ratio features. The two-area ratios represent the relation of systole to diastole blood pressures. There is a significant positive correlation between brachial artery thickness and hypertension.

e. Crest Time:

The crest time is defined as the time from the minimum point of the waveform to its peak [18] as shown in Fig. 4. The accurate extraction of features such as maximum slope point, systolic peak, inflection point, and diastolic peak, are directly correlated to BP variation levels. The blood pressure fluctuations in the human arm phantom are associated with changes within the transmitted waves. These characteristics are then processed and converted into BP levels by means of data analytics and smart algorithms. Due to different artery radius estimates, this can
be expected to track the blood pressure over the short term. Any increase in brachial artery thickness-to-diameter coefficient can lead to an indication of an increase in cardiovascular risk due to increased stiffness of not only the brachial artery but the arterial system. The set of transmission coefficient values therefore, obtained at five different ratios [11–12] along the human arm reflect the effect of blood flow and thus the blood pressure estimation levels. The brachial artery diameters are given in clinical medical reports and experimented here to show the link between the electromagnetic waves and blood pressure variation. More precisely, the changes in transmission scattering parameters are associated to the estimates of BP variation levels as predicted (Fig. 8).

## Results

Blood pressure was classified based on transmission coefficient waveforms. Data was collected from the transmission coefficient waveforms based on the variation of thickness to radius ratio of a simulated human arm brachial artery. The analysis of transmission coefficient waveforms was conducted. Each waveform was extracted into 2000 points. The feature extraction uses raw values of the transmission coefficient signals at a given time interval and was carried out point by point to optimize the relation to physiological data as shown in Fig. 8. brachial artery feature extraction from the different transmission coefficient waveforms was correlated to mean BP levels through a set of algorithms and with different brachial artery thickness to radius ratios. A significant positive correlation between brachial artery thickness and hypertension can be observed in Fig. 8 for hypertension being defined as a systolic BP > 140 mmHg and diastolic pressure > 90 mmHg.

## Discussion

In this study, a comparative analysis was conducted with other models of related work mentioned in [9] in relation to methodology, and estimation error. The results of both methods, the present method and our work [9], successfully demonstrate how brachial artery thickness to radius ratio dynamic changes along with electromagnetic transmission coefficient waveforms, can be used to non-invasively measure BP.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Case 1:h/R = 0.5</th>
<th>Case 2:h/R = 0.7</th>
<th>Case 2:h/R = 0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>SBP</td>
<td>DBP</td>
<td>Average Error</td>
</tr>
<tr>
<td>[9]</td>
<td>120</td>
<td>60</td>
<td>0.17%</td>
</tr>
<tr>
<td>Present Study</td>
<td>110</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

We in [9], proposed extracting the pulse transit time from the variation of transmission coefficient analysis in respect to change in thickness to radius of the artery. Analyses of the blood pressure variation outcomes of the current method and previously reported method [9] were broadly compared, showing evidence of effects in electromagnetic transmission waveforms in determining systolic or diastolic blood pressure categories. In comparison with the work in [24], the authors exposed the same method of correlating the change of the radius of a human artery can reach ∼30% due to blood pressure. This change of the radius of a human artery can cause low and high blood pressures corresponding to two disease states called hypotension and hypertension. As the
study in [24] reveals the same results as in our study, the increase in brachial artery thickness to radius results in an increase in blood pressure levels.

The results demonstrate the applicability of the proposed algorithm in estimating BP noninvasively, cuff-less, calibration-free, and by using only the electromagnetic transmission coefficient signal. Both our proposed methods can work efficiently with high accuracy in a wearable estimation system that enables home monitoring of systolic and diastolic blood pressure. The current system is currently being tested and validated on human subjects.

**Conclusion**

This paper establishes a relation between the change in electromagnetic transmission waveforms between a pair of antennas and brachial artery thickness to radius variation. This theory is validated by several medical reports. The present study shows that the major features of the arterial system in essential hypertension include small and large artery remodeling, is characterized by normal and an increase in blood pressure levels, respectively. The key cardiac features including the heart rate and reflection index are extracted into 2000 points and analyzed in Matlab. These features used to predict cardiovascular events in hypertensive patients. In addition to, stiffening of the artery is considered as a principal cause of increasing the systolic pressure and lowering the diastolic ones. This may cause the gradual fragmentation and loss of elastin fibers by time. By observing the effects of the physical changes in the cardiovascular system in the hypertension were directly reflected in the transmission coefficients waveforms.

Therefore, at the next step, efforts are to clinically test the outcomes of the antennas on different human arm subjects of different brachial artery characteristics and then the way to develop a cuffless continuous and home-use BP monitoring device.

**Declarations**

**Ethics approval and consent to participate**

Informed consent was obtained from all subjects involved in the study.

**Consent for publication**

Written informed consent has been obtained from the patient(s) to publish this paper.

**Availability of data and materials**

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Competing interests**

The authors declare that they have no competing interests.

**Funding**

This research was funded by Biomedical Engineering Department and Health Innovation Engineering Center, Biotechnology Center, Khalifa University of Science and Technology, Abu Dhabi, United Arab University.
Authors’ Contribution

Mona El Abbasi and Karim Kabalan conceived of the presented idea. Herbert Jelinek led the group work. Mona developed the theory and performed the computations. All authors verified the analytical methods. They also encouraged to investigate and supervised the findings of this work. Mona designed, derived the models and analyzed the data. Mona also took the lead in writing the manuscript. Herbert Jelinek, Mervat Madi and Karim Kabalan provided critical feedback and helped shape the research, analysis and manuscript. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript. All authors reviewed the results and approved the final version of the manuscript.

Acknowledgments

Many thanks to the technicians of the laboratory of the Electrical and Computer Engineering department at the American University of Beirut, for their help in offering me the resources in running the program.

References


8. Picone DS, Deshpande RA, Schultz MG et al. Nonvalidated home blood pressure devices dominate the online marketplace in australia: Major implications for cardiovascular risk management. Hypertension 2020;75(6):1593-9.10.1161/hypertensionaha.120.14719


17. G. Monroy Estrada, L. Mendoza and V. Molina, "Relationship of blood pressure with the electrical signal of the heart using signal processing", *TECCIENCIA*, vol. 9, no. 17, pp. 9-16, 2014.


**Figures**
Figure 1

(a) Proposed patch antenna geometry. (b) Simulated reflection coefficient for the proposed antenna. The transmitting/receiving antenna module is placed on a simulated homogeneous human arm phantom in ANSYS HFSS to show the simulated transmission coefficient response in between the two antennas. S12 is optimized to provide maximum transmission by moving the antennas symmetrically against homogenous upper arm. Maximum transmission was obtained when both antennas had minimum return loss.
Figure 2

Brachial artery thickness/radius ratio variation.

Figure 3

Transmitting/receiving antennas placed on simulated human arm model.
Figure 4
Illustration of pulses measurement by proposed method.

Figure 5
Block diagram of the proposed BP estimation method based on detecting key points of the transmission coefficient variation waveforms.
Figure 6

Transmission coefficient pulses of transmitting/receiving antennas due to brachial artery thickness/radius waveforms in respect to pressure level variations in frequency domain analysis. h/R = brachial artery thickness/radius.
Figure 7

Correlation between cardiac feature extracted from the different transmission coefficient waveforms due to different brachial artery thickness to radius ratios.
Figure 8

Correlation between cardiac feature extraction from the different transmission coefficient waveforms correlated to mean BP levels.