A Preliminary Investigation of Human Body Composition Using Galvanically Coupled Signals

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ABSTRACT

Intrabody communication (IBC) archetype is a novel healthcare network technology that enables non-RF based wireless data communication through the human body. The low-power IBC signals are confined to the body, making it suitable for transmitting health data of monitored vital human body signs such as heart-beat and blood pressure. Research in IBC communication usually focuses on channel characteristics for transceiver improvements in reliability, data rates and energy savings. In this paper we introduce a novel application of IBC galvanic coupling circuit for investigating human body composition. We compare empirical measurements using a vector network analyzer with circuit model simulations. The results show different attenuations observed for different proportions of the body tissue such as fat, muscle and bones. We found that a difference in body mass index (BMI) by 1 kg/m^2 between the subjects results in approximately 1 dB increase in attenuation. Also, the signal attenuation increases with the BMI of the subjects but are also affected by their respective hydration states. We also found that frequencies above 5 MHz would not be suitable for estimating human body composition in a galvanic coupling IBC circuit. However, a wider experiment is required to give the range of data values that will correspond to attenuation for different body mass index by sex and age.

Keywords

Body mass index, Galvanic coupling signals, Attenuation, Intrabody Communication

1. INTRODUCTION

Developments in healthcare devices that can be attached to the body without obstructing the user's regular activities are breakthroughs in a healthcare sensor network system [9], which is currently undergoing increased research and development. Intrabody communication (IBC) is a novel healthcare network technology that enables non-RF based wireless data communication through the human body. The low-power IBC transceivers are attached directly to the human body making it desirable for transmitting health data of monitored vital body signs such as heart-beat and blood pressure. In the galvanic coupling IBC method the signal is applied differentially between a pair of transmitter electrodes and received equally differentially by the opposite pair of receiver electrodes [14]. This means that the safe frequency signals propagates along the body and are not affected by the external environment. With the human body as the communication channel, an understanding of the channel electrical and physical characteristics by empirical and simulation experiments will provide useful insight on how the tissue layers contribute to the observed signal behaviour as it propagates from the source to the sink. We shall employ the impedance properties of the tissue layers to current flow to examine the effects of the variations in the tissue physiological parameters such as thickness on the signal attenuation as a way to investigate human body composition. In the literature, the modeling approaches adopted in IBC communication study include: Phantoms made to provide dielectric properties similar to the human body example skin and muscle [14],[8],[12] and simulations using finite element methods [16] and circuit models [15], [13]. Other methods of studying the electromagnetic propagation through the human body include models of the limb as a quasi-static dielectric cylinder [10], each providing specific relation between the signal propagation and the channel characteristics under different modulation schemes, frequencies and coupling techniques. Each of these studies was devoted to the modeling, simulation and development of IBC transceiver designs but did not apply the result of the characteristic differences and properties of the channel for body composition estimation and prediction.

Research on wireless communication usually focuses on signal attenuation in relation to the channel characteristics for improvements in reliability, data rates and energy savings [1]. In this paper, we propose for the first time the use of the variations in the signal attenuation due to changes in

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the physiological composition of the contributing channels (tissues) to estimate and predict human body composition. Body composition estimation and prediction are necessary for the evaluation and monitoring of malnourished, acute and chronically ill patients [6]. Prediction of human body composition usually requires the measurement of a physical property to calculate a component with known degree of dependence on the physical property. We will apply both empirical and simulation results from energy losses in signal transmission using IBC galvanic coupling equivalent circuit to predict and estimate the tissue layer compositions in human body. The rest of this paper is organized as follows: Section II describes the tissue impedance properties and the effects on signal propagation. Section III presents the IBC circuit model simulations and experiments with different proportions of the participating tissues. This section will also highlight graphical results from empirical measurements on different volunteers. Section IV opens with a discussion on the results and the application for body composition estimation followed by the conclusion in section V.

2. TISSUE IMPEDANCE AND SIGNAL PROPAGATION

The arm can be represented as an equivalent circuit of admittance Y consisting of a parallel combination of Conductance G and Susceptance B which are based on the specific conductivity and relative permittivity of the constituent tissues [5]. The analysis of the tissue responses to applied electrical potential is examined based on its specific conductivity and relative permittivity over a range of frequencies. Gabriel et al. in [4] provided a comprehensive parameter for human body electrical properties which we shall use with Cole-Cole dispersion relation [2] in this work.

For our experiment, we have selected 300 kHz to 10 MHz frequency range which falls within the β-dispersive region in the biological tissue dielectric spectrum as higher frequencies may result in human body antenna effects and possible electromagnetic radiations [12]. The Cole-Cole equation [2] provides the mathematical expression for the changes in the dielectric property of tissues over a wide range of frequencies. The summation of multiple Cole-Cole equations (1) can predict the dielectric property of each tissue layer with careful selection of the required parameters of the particular tissue layer taking into consideration the polarization of the tissues, the dispersive regions and the tissue anisotropic properties. The frequencies corresponding to the various dispersive regions are appropriately explained in Grimnes and Martinsen [5]. From Cole-Cole equation we have that:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \sum_n \frac{\Delta\varepsilon_n}{1 + (j\omega\tau_n)^{(1-\alpha_n)}} + \frac{\sigma_i}{j\omega\varepsilon_0} \quad (1)$$

where $\varepsilon^*(\omega)$ is the complex dielectric constant at angular frequency ω, and $\Delta\varepsilon_n$ is the degree of the dispersion calculated by subtracting from the permittivity at an infinite frequency ε^∞, the permittivity at static ε_s; τ is the relaxation time constant and α_n is the distribution parameter. σ_i is the static ionic conductivity and ε_0 is the permittivity of vacuum. The complex conductivity σ^* and the complex specific impedance z^* of the tissue are:

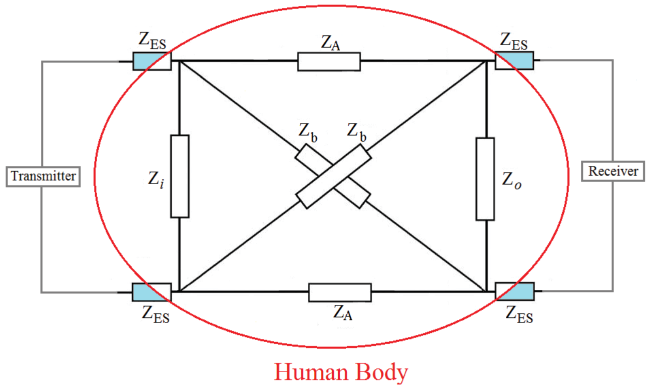

Figure 1: Four terminal human body circuit model [15]

$$\sigma^* = j\omega\varepsilon_0\varepsilon^* \quad (2)$$

$$\sigma^* z^* = 1 \quad (3)$$

The circuit diagram in Fig.1 [15] represents a simplified model of the human body in which all the impedances of the connecting wires were ignored.

Ignoring the impedances of the connecting wires, we have ZES representing the coupling impedances to the body at the transmitter and the receiver nodes, Zi and $Z0$ the input and output impedances of the body, and ZA is the impedance of the transmission path. The cross impedance between the transmitter and the receiver is represented as Zb. To simplify the circuit model for our investigation we consider the circuit to represent the human arm consisting of the skin, fat, muscle, cortical bone and bone marrow. When an alternating current (<1mA) is applied to the body by galvanic coupling technique, the potential difference between the transmitter and the receiver will cause a longitudinal signal flow from source to sink. Similarly, there will be a transverse signal path created between the pair of each connecting electrodes. The primary current would expect to flow longitudinally to the receiver electrode while the secondary residual current flows farther into the deeper layers of the tissues as a result of the pairing electrodes. The signal attenuation is affected by both the electrical properties of the tissues and the physiological parameters such as thickness, the distance between the transmitting and the receiving electrodes and the inter-electrode separation Since tissues have different conductivities the proportion of the constituent layers affects the signal attenuation as shown graphically in section III. Fig.2. shows variations in the conductivities of the various parts of the human arm: skin, fat, muscle, cortical bone and bone marrow at different frequencies. It can be observed from the graph that the muscle is more electrically conducting than wet skin and fat and above 10 MHz the conductivity of wet skin increases highly and almost approaches the conductivity of the muscle. This means that a high body mass index from greater muscle mass will have lower attenuation than similar BMI resulting from high body fat. Invariably, high BMI from high proportion of body fat is expected to result in high signal attenuation. So that variations in fat and muscle mass or changes in the proportion

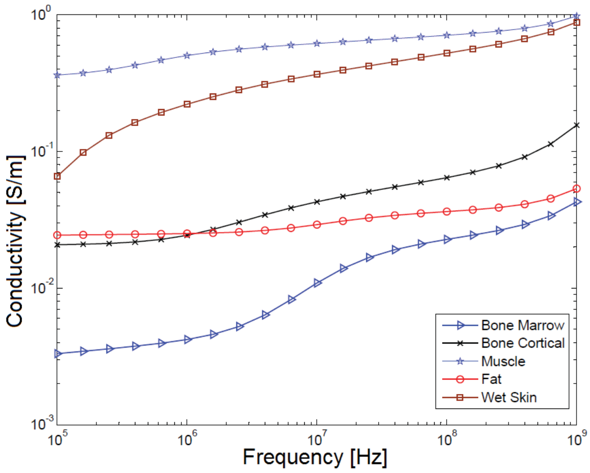

Figure 2: Conductivity of the body tissues at different frequencies

of the epidermal layer of the skin for an individual can be detected by observing the changes in the signal attenuation over time. To confirm these postulations we used the circuit in Fig.1. Based on Wegmuller [15] we have that for an arm radius of 50 mm, the corresponding tissues have thickness proportions as 3% skin, 17% fat, 55% muscle, 12% cortical bone, and 13% bone marrow). We used this proportion to calculate the thickness of the tissue layers at different arm radii and to find the effect of the changes in thickness of fat and muscle of the same person. However, because the body parts have many-sided geometry with complex internal structures we shall assume uniform concentration of these proportions over the entire arm. We will then use measurements from empirical data to compare our equivalent circuit simulations. In our experiment we found that the proportion of each tissue is correlated with the attenuation result. The impedance of each tissue follows the general Ohm's law in which the resistance is directly related to the transmission length and inversely to the surface area whose radius is equivalent to the thickness of the corresponding tissue. We have that the result of our investigation using our galvanic equivalent circuit can be applied to estimate various tissue compositions of the measured body parts by observing the changes in attenuation at different frequencies. In order to determine the appropriate transmission distance for our experiment, we measured the attenuation at 10 cm and 20 cm with inter-electrode separation of 4cm. The reduction in transmission distance between the transmitting and the receiving electrodes by 10 cm resulted in 3 dB gain in attenuation for low BMI and 8 dB gains for high BMI (Fig.3 and Fig.4) at inter-electrode separation of 4 cm. We therefore used 20 cm as the transmission distance on all subjects with inter-electrode separation of 4 cm since our focus is in using the observed attenuation changes for body composition estimation.

2.1 Body Mass Index on Signal Propagation

A moderate estimation of body fat content in the human body is performed by dividing the weight by the square of the height. The knowledge of the composition of the fat content in the body has both physiological and medical importance but the body mass indices from the formulae are a measure of excess weight rather than excess body fat. Moreover, BMI are affected by other factors such as age, sex, muscle mass and bone bass [3], [11]. For example, a high BMI from a weight lifter can be from a developed muscle mass rather than fat. Because our proposed method could predict variations in muscle and fat content we measured the BMI of 5 volunteers to find the relation between the signal attenuation and their body mass indices.

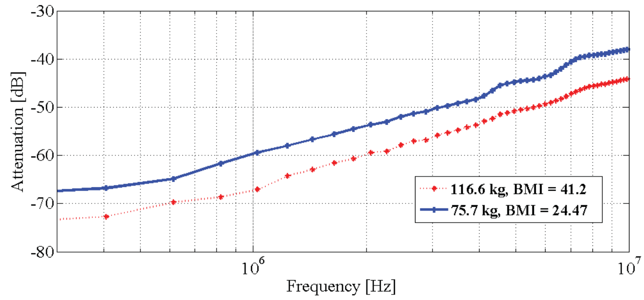

Figure 3: Attenuation versus frequency for high and low BMI at 10 cm distance between transmit and receive

3. IBC CIRCUIT MODEL SIMULATIONS AND EXPERIMENTS

Verifying the application of IBC circuit model for human body composition estimation and prediction; we considered the human arm consisting of skin, fat, muscle, cortical bone and bone marrow. From Fig.1 the transfer function of the galvanic coupling circuit is

$$H = \frac{V_0}{V_i} \tag{4}$$

The attenuation is:

$$G = 20log_{10}\frac{V_0}{V_i} \tag{5}$$

The equivalent of the coupling impedances Z consisting of parallel RC circuit corresponding to the different tissue layers can be represented as longitudinal impedances ZA and transverse impedance Zi corresponding to

$$Z_A = \frac{1}{\frac{\sum_{i=1}^{5} \sigma_{if} A_i}{l} + \frac{j\omega\varepsilon_0 \sum_{i=1}^{5} \varepsilon_{rif} A_i}{l}} \tag{6}$$

$$Z_i = \sum_{i=1}^{5} \frac{1}{\sigma_{if}\pi r^2 + j\omega\varepsilon_0 \pi r^2} \tag{7}$$

Where σ_{if} and ε_{rif} are the conductivity and relativity permittivity of the i^{th} layer at frequency f and l is the length of the signal transmission path while t_i is the thickness of the i^{th} layer of the human arm. Since the signal flows along the different layers of the arm the resultant attenuation comes from the combined effect of the impedances of each contributing tissues which has been linked to their dielectric properties and physical parameters.

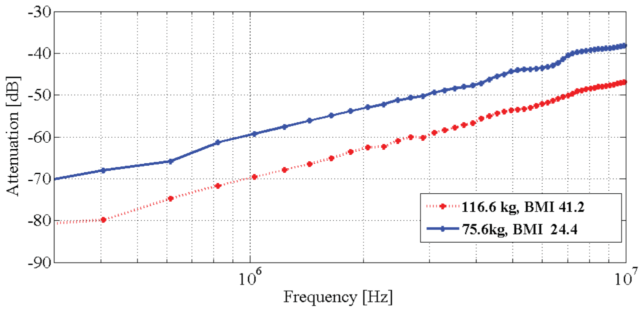

Figure 4: Attenuation versus frequency for high and low BMI at 20 cm distance between transmit and receive

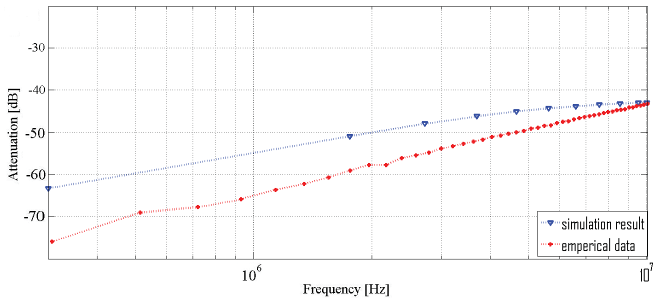

Figure 5: Attenuation versus frequency for simulation result and empirical data

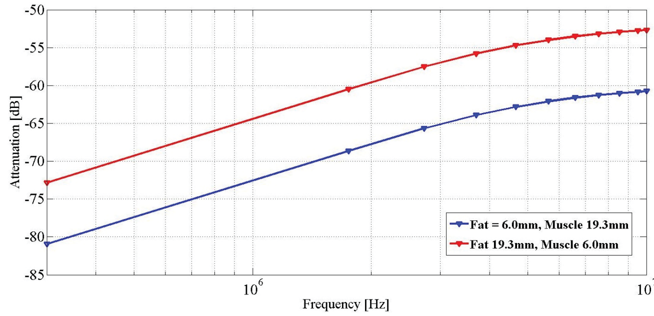

Figure 6: Simulation result of attenuation versus frequency for different compositions of muscle and fat of the same person. The galvanic coupling circuit simulated responded to changes in the thickness of the muscle and fat while other tissue components were kept constant

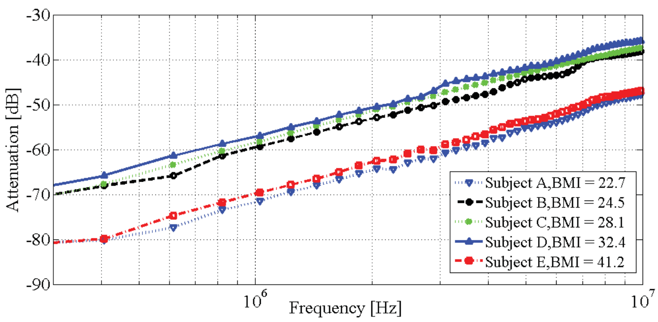

Figure 7: Graph of average attenuation against frequency for 5 subjects with different BMI

4. EXPERIMENTAL SETUP

Using the human lower arm as the medium of transmission, we performed in vivo measurement of the changes in galvanic signal attenuation as a result of variations in skinfold thickness and body mass index (BMI) of 3 male and 2 female human subjects. We confirmed that increasing the electrode distance between the transmitter and the receiver increases the signal attenuation in our circuit (Fig.3 and Fig.4) similar to the field measurement. We chose a sweep frequency from 300 kHz to 10 MHz and took the average attenuation of 10 separate measurements per subject. The measurement set up comprises miniVNA Pro by mini Radio Solution with input and output impedances of 50 Ω each, frequency range 100 kHz - 200 MHz. The VNA was calibrated with standard open short 50 ohm load calibration kit. This was necessary to give a zero reference point at the connector measurement reference plane. We also used a coaxial Rf transformers called baluns with frequency range 200 kHz - 500 MHz, FTB-1-1+, by Mini-circuits to decouple the miniVNA ports from each other and provide zero return loss over the required frequency range and circular pre-gelled self-adhesive Ag/AgCl single surface electrodes 1.0 cm in diameter by Noraxon which interfaces the VNA directly with the outer layer of the skin. The VNA has 0 dBm output power. We set it to sweep our selected frequency (300 k to 10 MHz) which is appropriate for safety standards set by the Non- Ionizing Radiation Protection agency (ICNIRP) [15]. The VNA connected to a laptop suited with the VNA software calculates the S-parameters for attenuation (S_{21}) and reflection (S_{11}) and phase changes since we are looking at the frequency response of the human body over a wide frequency range. We could not use the signal generator because it can only take one frequency input at a time and will not be able to get the body response at different frequencies simultaneously. Subjects were allowed to stand straight and relaxed with arms flowing down and separate from any object to ensure full confinement of the current in the arm. We also took measurements of the skinfold thickness of the lower arm at 5 cm interval using skinfold caliper by British indicators Ltd and off the shelf digital weight scale fitted with BMI calculator.

5. RESULT AND DISCUSSION

From Fig.2, it can be observed that muscle has higher conductivity than wet skin and fat while the largest impedance is with the bone which is located below the skin, fat and the

Table 1: SUBJECTS TISSSUE GEOMETRIES AND PHYSIOLOGICAL CHARACTERISTICS

Subject	BMI[kg/m^2]	Skinfold[mm]	Attenuation [dB] (average at 2.0 MHz)	Attenuation [dB] (average at 10.0 MHz)
A	22.7	3.2	64.32	47.82
B	24.5	4.1	52.91	38.21
C	28.1	5.7	51.16	37.37
D	32.4	8.2	50.44	35.83
E	41.2	21.0	62.52	46.98

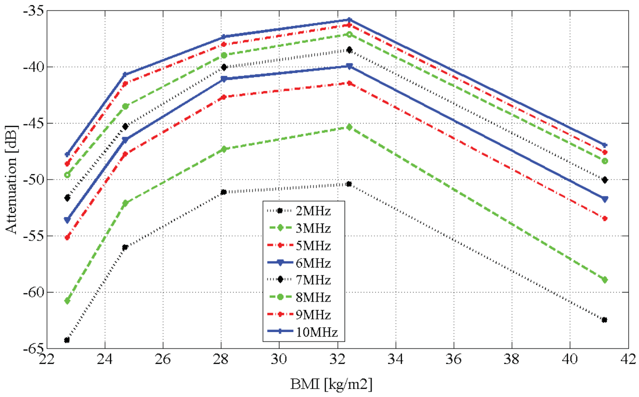

Figure 8: Graph of average attenuation versus body mass index of the 5 volunteers at frequency between 2.0 and 10.0 MHz.

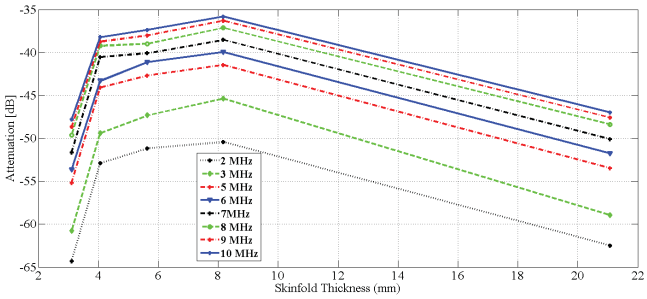

Figure 9: Graph of signal attenuation against skinfold thickness of the lower left arm for the 5 subjects

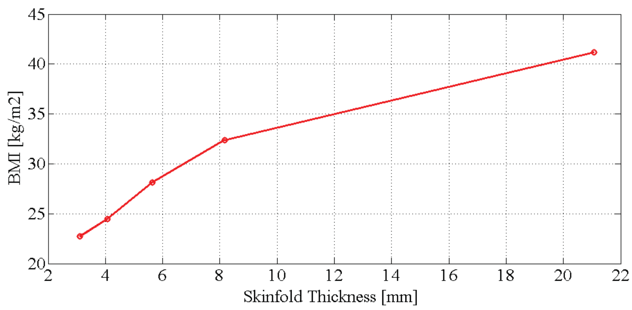

Figure 10: Body Mass Index of each subject against the respective skinfold thickness.

muscle. This means that the small current flows between the skin, fat and the muscle. We have that the attenuation experienced in the tissue layers at a given length increased with the increase in the mass of each tissue at that frequency. As the frequency increases, molecular ionization cause the conductivity to increase and attenuation to decrease therefore we spanned our investigation 10 MHz which is also within the frequencies appropriate for safety standards [7]. By carefully observing Fig.3 and Fig.4 we have that the attenuation decreased with increase in frequency in both high and low BMI and also increased with increase in distance between the transmit and receive electrodes. We compared our simulation results with empirical data in Fig.5. We establish that our circuit follows the general performance of the galvanic coupling circuit. Then we used the model to investigate the effect of the changes in the proportion of fat and muscle of an individual (Fig.6) and found that the attenuation increased when the proportion of fat increased and decreased when the proportion of the muscle was high. Fig.7 shows the attenuation of the 5 subjects with different BMI. Below 400 kHz attenuation is highest and falls as the frequency increases. This is because at low frequency the stratum corneum (SC) which contains dead cells has higher insulating property than the rest of the skin. A careful observation of Fig.7 shows subjects D, C and B have higher conductivity. Subject A with low BMI and unexpected low conductivity has thicker SC or low fluid volume. Subject E with high attenuation and high BMI is expected and shows high impedance fat in the subject. We investigated further the relation between the attenuation and the BMI at different frequencies and found that the attenuation is mostly higher with high BMI which agrees with our definition of BMI as a substitute measure of body fat (Fig.3). We measured further, the skin fold thickness of the 5 subjects with skinfold caliper Table I. Similarly, we plotted in Fig.8 the graph of attenuation (from 2.0 to 10.0 MHz) against the BMI. The result shows that the high BMI is associated with high attenuation for most subjects. We investigated and confirmed that the skinfold thickness has a similar relationship with attenuation and that the skinfold thickness is directly related with the BMI as seen in Fig.10. The skinfold thickness (fat plus skin) Fig.9 was largely responsible for the attenuation observed in subject A, BMI 22.7 and subject E, BMI 41.2. Subject E with average skinfold of 21.0 mm has more body fat and high attenuation. Subject A (skinfold, 3.2 mm) has unusual low attenuation and would form the subject of future investigation. We have that a difference in body mass index (BMI) by 1 kg/m^2 between the subjects results in approximately 1 dB increase in attenuation. Also, the galvanic signal attenuation is largely affected by the BMI of the subjects and their respective hydration states. The low attenuation recorded as the frequency increases shows that the signal is no longer propagating through the underlying layers of fat and muscle but through the ionized skin surface meaning that frequencies above 5 MHz would not appropriately give the right indication for human body composition. We conclude that the IBC galvanic coupling circuit can be employed to estimate human body composition at frequencies between 300 kHz and no more than 5 MHz.

6. CONCLUSIONS

We simulated a galvanic circuit model using Cole-Cole equation and represented tissues by their equivalent RC circuit. We propose a prediction of the body tissues with their attenuation graph. We measured using galvanic coupling intrabody communication the lower arm of 5 subjects with different BMI and analyzed the signal attenuation in relation to the body mass index and skin fold. Finally, we found that the IBC galvanic coupling circuit has the potential to provide better estimation of the human body composition than the body mass index could do for predicting body fat and muscle mass. The IBC circuit can provide better information about the body composition for persons with high BMI but low body fat as well as low BMI and low body fat that can aid early health diagnosis such as in subject A. We also show that BMI and skinfold are directly related and that the galvanic circuit can usefully predict fat when the thickness of the skin is known, thus IBC galvanic circuit can detect and predict changes in the composition of the human body. Finally, we acknowledge that this is a preliminary test and would require elaborate experiment to be able to provide the data range of attenuation and frequencies that corresponds to a region of BMI and skinfold anthropometry.

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