Calculation of Impedance Cardiography Measurement Sensitivity - Application of Reciprocity

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Abstract: Reciprocity theorem and lead field analysis are applied to obtain sensitivity of conventional Impedance Cardiography to detect resistivity changes of various tissues and organs in human thorax and neck. The effect of changing from circumferential band electrodes to spot electrodes is also examined.

The National Library of Medicine's Visible Human Project data is used to construct a three-dimensional physiologically accurate computer thorax model based on finite difference element method. The results obtained indicate that ICG is sensitive to impedance changes in all major inhomogeneities.

INTRODUCTION

Measurement of body impedance has been in existence since early 1930's [1]. Impedance measurements using band electrodes around the neck and lower thorax was first reported by Patterson et al. in 1964 [2], who developed an empirical equation for measuring stroke volume. The band electrode arrangement is difficult to apply and uncomfortable for the patient, therefore, spot electrodes have often been used to place band electrodes. Limiting factor which has restrained wider acceptance of Impedance Cardiography (ICG) as a diagnostic tool is the controversial issue of signal origin and formation. There is no detailed and accurate information of the formation of ICG signal.

Many investigators have conducted empirical measurement and validity studies comparing different electrode arrays and equations defined for calculation of stroke volume. Most comparison studies have shown high correlations with accepted comparison methods. However, in search for the origin of the ICG signal no studies have been published in which measurement sensitivity to different tissues and organs has been analyzed in the entire area of the thorax. A precise theoretical definition of what is actually being measured has not been provided thus far.

Volume conductor analysis including reciprocal energization of leads and lead field analysis can be utilized to theoretically clarify the information content of ICG measurement. In present work the sensitivities of conventional band electrode and modified spot electrode array to detect impedance changes in different tissues and organs in human thorax and neck are calculated using resistive properties of human thorax. The measurement sensitivity distribution of any ICG configuration, i.e. the lead field, can be calculated using the reciprocity theorem applied to finite difference element method (FDEM) computer model of the thorax. The reciprocal current field generated by the energized lead is identical to the lead field.

METHODS

The properties of ICG leads to detect changes in the resistivity of tissues and organs in the thorax between the electrodes can be obtained by changing the resistivity values of tissues or organs in constructed model. Simulating with the original and altered values the change in the impedance level due to varied resistivity is obtained. With this method the properties of a lead setup to detect conductivity changes can be calculated for certain tissue or organ. However, the complicated structural changes of organs and to an unknown extent changing electrical properties of tissues all contribute to ICG signal and taking all these factors into account would cause a radical increase in work that is required to build and solve these models.

Another technique to analyze the sensitivity distribution of a lead system is to reciprocally energize the lead to obtain the current field in the thorax. This current field is the sensitivity distribution that is directly related to the lead field. The measurement sensitivity distribution of four electrode ICG, i.e. where current is delivered and voltage measured from two different electrode pairs, can be obtained by first determining the current field between the current injection electrodes in the volume conductor. Then, the second field is obtained by calculating the current field which would be produced if current was injected between the voltage measurement electrodes. These two current fields, or lead fields, of current and voltage electrodes form the combined field of sensitivity as follows

$$S = \overline{C} \cdot \overline{P_i}$$

where S is the scalar field giving the sensitivity to conductivity changes at each location in the model, $\overline{C}$ is the current field produced by current excitation electrodes, and $\overline{P_i}$ is the current field produced by reciprocal energization of voltage measurement leads [3]. The overall sensitivity of any tissue type to contribute to measured signal is obtained by integrating the sensitivity values of the tissue over the volumes occupied by the tissue.

Three-dimensional FDEM model of the thorax and neck was constructed based on the U.S. National Library of Medicine's Visible Human Man anatomical data. The original axial images taken from a male cadaver were 2048 pixels by 1216 pixels taken at 1 mm intervals. 112 cross-sections were segmented with IARD method [4] and used for model construction resulting to 404307 nonuniform elements with volumes varying from 0.01 cm^3 to 2.8 cm^3.

Two electrode configurations were studied. In addition to the standard system another setup proposed by Qu et. al.

[5] using eight spot electrodes at the levels of the standard configuration on the sides of the thorax was studied. Volume integrals of sensitivity distributions (S) to detect conductivity changes in each tissue type were calculated and normalized to the total sensitivity of the measurement setup.

RESULTS

The percentages of the total sensitivity of each organ and tissue type to contribute to the measured impedance signal using the two measurement configurations is given in Table 1. It can be noted that measurements are not very sensitive to detect resistivity changes in the region of blood masses and heart muscle. More than 75 % of the measurement sensitivity was concentrated on skeletal muscle, which also occupies the largest volume in the model.

Simulated basal impedance values were slightly high, 32.0 Ω for conventional and 38.7 Ω for spot electrode arrangements. The total volume of the model was 60.6 *l*. As much as 35.0 % of the model was identified as fat, which was poorly conducting and strongly affected current flow in the thorax. The volume of blood masses and the heart muscle was only 1.53 %.

Table 1. Percentages of tissues and organs to contribute to ICG signal calculated for conventional and spot electrode configurations.

Tissue	Conventional [%]	Spot [%]
Skeletal Muscle	84.8	76.7
Fat	4.75	7.72
Bone	0.794	0.626
Right Lung	2.34	1.68
Left Lung	1.24	1.08
Stomach	0.752	2.13
Kidney	0.0098	0.0826
Liver	0.956	1.06
Heart Muscle	0.201	0.170
Heart Fat	0.0249	0.0166
Left Atrium	0.0336	0.0284
Right Atrium	0.404	0.259
Left Ventricle	0.0272	0.0247
Right Ventricle	0.193	0.122
Aortic Arch	0.153	0.112
Ascending Aorta	0.121	0.0891
Carotid Artery	0.103	0.157
Descending Aorta	0.150	0.115
Inferior Vena Cava	0.188	0.125
Jugular Vein	0.900	1.57
Pulmonary Artery	0.152	0.109
Pulmonary Vein	0.0953	0.0694
Superior Vena Cava	0.284	0.223
Other Blood	0.0611	0.161
Other	0.0788	4.75

DISCUSSION

One of the essentials of impedance measurements is the clarification of sensitivity distribution of the measurement configuration. The relationship of measured impedance signal to the mechanical functioning of the heart is not clearly understood. Reciprocity theorem utilized to FDEM modelling enabled efficient analysis of ICG measurement sensitivity distribution.

One assumption for the original ICG was the uniform current distribution in the thorax. However, human body forms a complex inhomogeneous volume conductor and current distributions are greatly affected by different conductivities of various tissues, especially the fat, lungs and large arteries and veins. The reported data suggests that ICG is not highly selective or sensitive to directly measure conductivity changes on the region of the heart and aorta as assumed. The property of ICG to measure specifically the function of right ventricle is not selective since only 3.4 % proportion of the measurement sensitivity is produced by the blood masses with conventional method. Poor conductivity of fat might reduce the current flow in the center of the thorax resulting to higher basal impedance and relatively poor measurement sensitivity to blood masses and heart muscle. Using spot electrodes the measurement sensitivity distribution concentrated slightly more to the regions of blood masses, especially carotid artery and vein, raising the sensitivity to 4.0 %. Thus, spot electrode setup used in this study does not contain the same information as conventional band electrode system.

Reciprocity theorem and lead field analyses are powerful tools in developing alternative, accurate impedance measurement lead systems, which could be more selective and sensitive to measure a particular region or organ in the human body. Impedance technique for monitoring haemodynamic function can become a clinical reality provided that measurements of physiologic parameters using impedance technique can be accurately defined based on appropriate model studies and clinical validation.

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