Medical Engineering and Physics 38 (2016) 538–546

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

# A method to adapt thoracic impedance based on chest geometry and composition to assess congestion in heart failure patients

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ARTICLE INFO

*Article history:*
Received 13 May 2015
Revised 18 January 2016
Accepted 6 March 2016

*Keywords:*
Heart failure
Bioimpedance spectroscopy
Personalization
Simulation
Decompensation

ABSTRACT

Multi-frequency trans-thoracic bioimpedance (TTI) could be used to track fluid changes and congestion of the lungs, however, patient specific characteristics may impact the measurements. We investigated the effects of thoracic geometry and composition on measurements of TTI and developed an equation to calculate a personalized fluid index. Simulations of TTI measurements for varying levels of chest circumference, fat and muscle proportion were used to derive parameters for a model predicting expected values of TTI. This model was then adapted to measurements from a control group of 36 healthy volunteers to predict TTI and lung fluids (fluid index). Twenty heart failure (HF) patients treated for acute HF were then used to compare the changes in the personalized fluid index to symptoms of HF and predicted TTI to measurements at hospital discharge. All the derived body characteristics affected the TTI measurements in healthy volunteers and together the model predicted the measured TTI with 8.9% mean absolute error. In HF patients the estimated TTI correlated well with the discharged TTI ($r = 0.73$, $p < 0.001$) and the personalized fluid index followed changes in symptom levels during treatment. However, 37% ($n = 7$) of the patients were discharged well below the model expected value. Accounting for chest geometry and composition might help in interpreting TTI measurements.

## 1. Introduction

Congestion is a defining feature of decompensated heart failure (HF), a frequent cause for hospitalization, and a main target during treatment [1]. Despite this, there is a paucity of tools that provide a quantified assessment of the level of congestion. Current tools are often complex requiring invasive measurements to establish heamodynamic pressures or chest x-rays which exposes the patient to ionizing radiation and give equivocal results. Clinical judgment on the other hand is often inexact and requires substantial clinical acumen [2]. Preferably methods that establish congestion should be simple and easy to use with reliable results.

Trans-thoracic bioimpedance (TTI) can be used to assess tissue hydration as increased fluid levels increase the conductivity of the tissue. This has been used to show that non-invasive measurements of impedance at a single frequency correlates with radiographic and clinical indices of pulmonary oedema in HF patients [3,4]. Different frequencies have different progressions [5] and multi-frequency measurements can be used to improve estimates of body fluids by modeling the spectroscopic response [6]. For living biological tissues measured in the kilohertz to megahertz range this response, $\beta$ dispersion, can be approximated by a Cole model [7]. This empirical model describes the impedance based on four variables: $R_0$, the extrapolated zero frequency or DC component; $R_\infty$, the extrapolated infinite frequency component; $f_C$, the characteristic frequency; and $\alpha$, the dispersion parameter [8]. At low frequencies the resistance is impacted by the extra-cellular fluids to a larger extent than at higher frequencies, for which a larger part of the current passes through the cell membranes. Increased fluids in the lung interstitium and later into the alveoli should thus be reflected in the DC component of the model, $R_0$.

A challenge with bioimpedance measures is that the individual optimal value depends on the morphology and distribution of the different tissues. Without a target value one can only establish relative changes in fluid levels which can be difficult to interpret and

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http://dx.doi.org/10.1016/j.medengphy.2016.03.002
1350-4533/

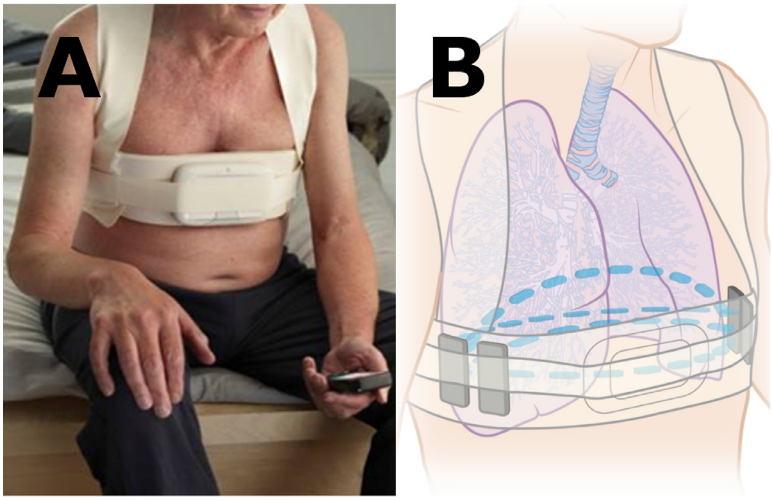

**Fig. 1.** The portable measurement device and vest. A: actual device showing proper placement (person shown is not a participant in the trials but a model) B: transparent sketch of the device showing the four textile electrodes and lungs [48].

use for clinical decisions. Multiple meticulously placed electrodes could be added measuring impedance between different configurations [9]. The resulting data could then be used to compute the likely contribution of different regions to the total impedance which addresses this shortcoming to a certain extent, but which might be difficult to apply in practice. Other frequency ranges that have been explored to establish lung fluid content from changed dielectric properties include RF [10] and microwave reflectometry [11]. Ideally, the system should be easy enough for daily monitoring, preferably applied by the patients themselves.

The aim of this study was to investigate a normalization method for a tetrapolar setup of trans-thoracic bioimpedance (TTI) measurement integrated into a wearable system. First, the relationships between TTI, the geometry, and the thoracic tissue composition (fat, muscle, and dry or fluid filled lungs) were explored using a simulation model (Sections 3.1 and 3.2). Results from the simulation model were then adapted to receive as input simple anthropomorphic measures to model TTI measurements from healthy "control" subjects (Section 4.1). Measurements from HF patients discharged after an episode of acute decompensation were then compared to the expected values from this TTI estimation model (Section 4.2). Finally, changes in an index based on the model and the estimated change in response to fluids (Section 3.2) was derived for the HF patients during a series of measurements from admission of acute decompensation up until hospital discharge and compared to assessments of symptoms of congestion (Section 4.3).

## 2. Materials and methods

### 2.1. The measurement vest

The wearable system was developed to provide an easy and simple method to reliably measure TTI so that it could be done by patients on their own. The system can connect to a mobile phone or tablet making it possible to guide the patient through the measurement and thus ensure proper posture and reduce inadvertent movements during a measurement.

The system is shown in Fig. 1 together with a schematic of the setup. It consists of three parts: an adjustable vest, a measurement device and a rigid panel with electrodes. The four textile electrodes on the panel are made of silver coated polyurethane yarn for comfort and kept at proper distance by the panel. The panel is wrapped around the chest at, approximately, the level of the tenth rib and kept together with the adjustable vest. The measurement device is then connected to the setup to inject current and log the resulting voltages (Philips Technologie Gmbh, Aachen, Germany) [12]. Sixteen frequencies are measured sequentially (10 kHz–1 MHz) during one acquisition. Before any measurements the textile electrodes are wetted to lower the interface impedance to the skin.

### 2.2. Simulation of thorax

A finite element method simulation of the setup was carried out to evaluate the theoretical influence of chest geometry and composition on the spectroscopic measurements. This approach has previously been applied to determine effects of thoracic fluids on impedance cardiography [13] and electrode placement [14,15]. To easily scale the different compositions of fat, muscle and circumference a simplified model of the human thorax was constructed based on the tissue proportions just above the liver from a computer tomography scan. The complex ovaloid shape was approximated as a series of concentric circles surrounding the lungs which simplifies scaling, see Fig. 2. Simple structures of ribs, spines, heart, and liver was added to the model in proportion with the tissues of the scan (See supplemental file for the geometric equations).

Dielectric properties of the tissues were taken from the equations provided by Gabriel [16]. The constants for deflated lung, infiltrated fat, transverse muscle, blood, cortical bone, heart, liver, and dry skin were used for the tissues representing lung, fat, muscle, fluids, bone, liver, and skin respectively. Fig. 3 shows the permittivity and conductivity of the first four of these parameters between 10 kHz and 1 MHz. Meshes were created for chest circumferences from 80 to 120 cm in increments of 10 cm in chest circumference. Fat layer and muscle layer were varied in proportion to the chest radius. Added muscle in proportion to chest radius was varied between 0 and 8% in increments of 2% and fat layer was varied between 3% and 15% in increments of 3%. For each mesh transfer impedances were calculated for 16 logarithmically spaced frequencies between 10 kHz and 1 MHz. All simulations were carried out in COMSOL 4.4 [17].

### 2.3. Data and study protocols

Real measurement data for model development and evaluation was taken from two trials. One on healthy subjects (control subjects) enrolled in a body-composition trial and a second one on