Analysing and designing an impedance-based heart rate monitoring wearable.

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Index

Thesis

Abstract

Bioimpedance is a viable option for a non-medical non-invasive wearable cardiography device. Currently impedance cardiography is barely available for non-medical applications and obstacles such as a stable skin-electrode interface and limb targeted measurements are still being overcome. Here the current state of ICG is explained and the steps to further the development of a commercially available device for non-medical users are explored.

Introduction

Of all American deaths, heart related disease is still the number one contributor. Among others the list contains coronary heart disease, heart attacks, congenital heart defects, arrhythmia and dilated cardiomyopathy. One of the key diagnostic tools for recognizing and/or preventing these diseases is the continuous measurement of heart rate (HR) and blood pressure (BP).

Measuring cardiac parameters such as BP, HR and cardiac output (CO) is essential in a medical setting, but is also of use in a non-medical setting. For sporting, elderly or recreational use, cardiac measurements are equally if not more important. According to the Centers for Disease Control and prevention (CDC) one of the most important preventive measures is keeping your BP in check [1]. At this moment preventive checkups for high blood pressure are generally done by GP's once every 2 years. Having a reliable and continuous cardiac monitor at all times can prevent and inform people about an essential part of their health.

Currently an electrocardiogram (ECG) is the gold standard for heart rate measurements, however this method requires the user to connect electrodes to at least two limbs and may therefore not be practical for non-medical use. There have been many methods that have been developed as alternatives for the gold standard. Examples include thermodilution, optical and pressure based measurement methods. Bioimpedance has been picked up as a reliable, cost-effective and technically simple method for cardiac [2] and pulmonary [3] measurements.

Photophotoplethysgraphy (PPG) is the method that is currently most used in wearable heart rate measurements. Plethysmography is the measuring of volume change in a certain area of the body, in this case change of blood volume. PPG uses the fact that blood volume change influences the amount of light that is absorbed. Most smartwatches today use this method and it has some advantages: it is cheap, rather accurate and uncomplicated [4]. Among the disadvantages are needing a precise measuring spot, motion artifacts, sensor displacement artifact and needing a relatively constant pressure on the skin. These disadvantages are especially present during exercise and this is unfortunately the exact moment the measurements ought to be precise.

Impedance cardiography (ICG) was first introduced as a method to measure over the thorax and neck as a substitute for ECG [5,6], but over the years it has been proven a useful non-invasive method for many applications. While impedance does have some of the same obstacles as PPG, it does have the advantage that it does not need to be stationary, it just needs to be constantly in contact with the skin. An impedance-based heart rate monitoring wearable could therefore improve on the primarily PPG-focused wearables used today.

Problem definition

Cardiac-related disease is still the number one contributor to deaths in America [1]. There are many different causes, however there are often only treatments and no cures. Besides treatments, there is also the option of prevention and the best way to do this is by giving people information on their health. Health monitoring is one of the key things when preventing heart-related disease. There are, however, a few problems with current health monitoring devices. PPG for example has trouble with movement artifacts and continuous measurement during exercise. The problem at hand is therefore a lack of a reliable and accurate heart rate monitoring device that is easy in its daily use.

Goal

To solve the problem mentioned above, a health monitor needs to be developed that is reliable under tough conditions, accurate, and easy to use. The goal thus is to develop such a device to inform its user about their health and hopefully prevent any serious cardiac-related disease.

Boundaries

In this study, the focus will be on using bioimpedance to achieve the goal of a health monitoring device. Furthermore, the device itself will focus on measuring heart rate, related parameters such as blood pressure, heart rate variance, and stroke volume will be addressed in a literature research, but will not be a focus of the to-be-developed device.

List of requirements

1. The device should be able to measure heart rate with an accuracy of 95%.
2. The device should be able to measure heart rate non-invasively.
3. The device should be able to measure heart rate continuously, even during exercise.
4. The device should be able to maintain optimal contact with the skin, even during exercise.

5. The device should not be hindering the user's movement.
6. The device should have sufficient battery life to be operational for at least 16 hours.

List of wishes

Performance

1. The device should be as accurate as possible.
2. The device should have the longest battery life possible.
3. The device should be as durable as possible.

Costs

4. The device should be as cheap as possible.
5. The device should be as easy to manufacture as possible.

Ergonomics

6. The device should be as small as possible.
7. The device should be as lightweight as possible.
8. The device should be as easy to use as possible.
9. The device should be as good-looking as possible.
10. The device should be as comfortable as possible.

Safety

11. The device should be as safe as possible.

Function analysis

As seen in figure 1 the device should do the following:

1. Be fixated on the wrist
2. Store electrical energy
3. Convert the electrical energy into information
4. Present the information to the user

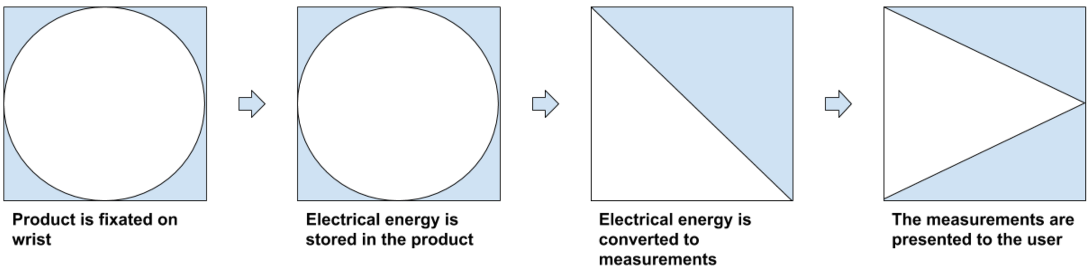

Figure 1

Background

Impedance

To understand impedance cardiography it is essential to first understand impedance (Z). Impedance is by definition the opposition of a circuit to current [6]. Therefore Z can be expressed via Ohm's law in ohm's (V=I*R). However impedance is not the same as resistance; impedance, unlike resistance, is also dependent on the frequency of the current. Therefore Z has not only a magnitude but also a phase. Z can be expressed in polar form as Z = |Z|e^j(arg(Z)), where |Z| is the impedance expressed as the resistance of the circuit and arg(Z) in θ the phase difference between voltage and current.

Capacitors and inductors are the two electrical components that can be used to describe a certain reaction of a system to current and voltage. Both the capacitor and inductor shift the relative phase be it in different directions. A capacitor will output a forward phase shift of the current compared to the voltage. The voltage lags the current. An inductor will output a forward phase shift of the voltage compared to the current. The current lags the voltage.

Any system with a capacitor or inductor is described by impedance rather than resistance. The body can be viewed as a system with many capacitors. Cells tend to have both resistive and capacitive properties. Therefore, if we measure any kind of opposition of current through the body, it is expressed in impedance. As we saw in the polar form of Z, there is a direct relationship between frequency and impedance. Intuitively we can say that if the frequency of current through an inductor is increased, the impedance also increases, while the inverse is true for a capacitor.

Impedance Cardiography

The main way ICG provides measurements is through measuring the change in impedance, with a change in blood volume in the artery the impedance changes as well [8]. This model was originally developed for the thorax and is therefore called the thoracic electrical impedance (TEB) model. One can express the relation of the impedance of the artery and the tissue as follows. Take as an artery a cylinder with cross-section A and length L as seen in figure 2 [8], R as the resistance, and ρ the resistivity of blood, which is assumed to be 150 ohms per cm. The resistance of this volume can then be formulated as such:

$$R = \frac{\rho * L}{A} \qquad (1)$$

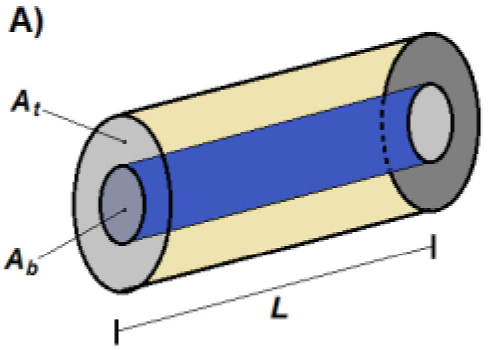

Figure 2

Current is divided over the tissue and the artery and therefore impedances of tissue (Zt) and artery (Zb) can also be divided as seen in figure 3 [9]. This gives the expression for the overall impedance follows:

$$Z = \frac{Zt*Zb}{Zt + Zb} \quad (2)$$

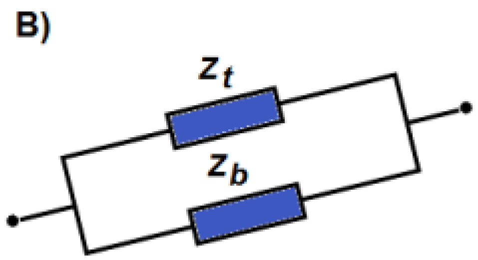

Figure 3

Determining Zb is not necessary when evaluating blood flow in the artery since Zt should not change. Zt does of course change sometimes with flexing muscles or other movements in the targeted area. However, these artefacts can often be distinguished quite easily. For signal processing therefore it is possible to take Z and not Zb when determining HR.

Finally, the important formula (3), derived from (1) and (2), gives the relation between change in impedance and change in arterial volume. This is of great aid when assessing cardiac parameters such as stroke volume (SV).

$\Delta V_b = -\frac{\rho_b * L^2}{Z^2} * \Delta Z$ under the condition that $\Delta Z >> Z$ (3)

Electrical Cardiometry

Another way to measure blood volume changes is the Sigmann effect. When blood flow velocity is low red blood cells have random orientations which hinder current flow. When blood flow velocity is high red blood cells will orient themselves parallel to each other in the direction of flow, which aids current flow through them. Therefore, high blood flow results in lower resistivity. This method of estimating cardiac parameters is called electrical cardiometry (EC).

The difference between EC and ICG is a subtle one, both methods rely on impedance change however they both attribute this impedance change to a different phenomenon [10]. Where EC contributes the change of Z to the Sigmann effect, ICG contributes it to volume change.

Electrode placement

There have been many successful attempts at making an accurate impedance-based device for cardiac measurements [11,12]. However, it is important to make a distinction between thoracic measurement devices and wrist-worn devices. Thoracic devices use two sets of 2 electrodes stuck to the neck and chest as seen in figure 4. Wrist-worn devices have gathered more attention lately and have their electrodes on the wrist above the radial and ulnar arteries. The configuration of these electrodes can differ depending on the type of measurements. For pulse transit time (PTT) and subsequently BP it is necessary to have electrodes along the arteries, another layout of the electrodes is along the width of the wrist. See Figures 5 and 6 respectively.

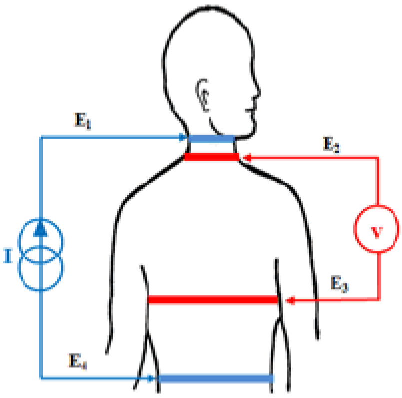

Figure 4

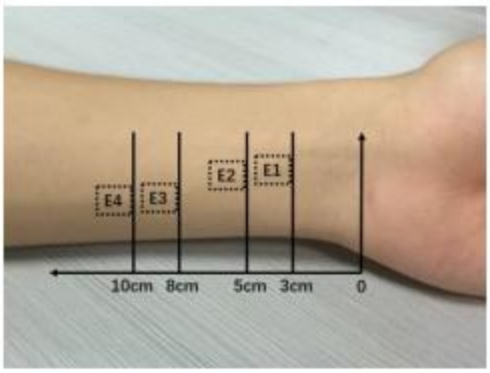

Figure 5

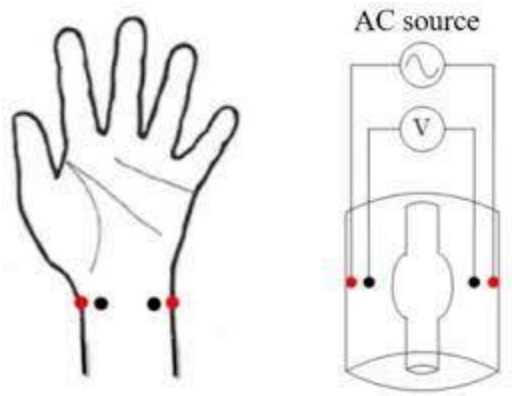

Figure 6

The configuration greatly influences the impedance measurements. As seen in figure 7.

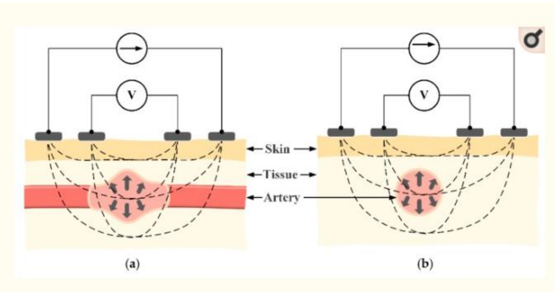

Figure 7 [13]

There are other places on limbs where ICG measurements are possible, for example, a plantar measurement device [14] or a wrist to ankle measurement device [15].

Signal processing

After obtaining the impedance signal and the derivative impedance signal you can identify the different points that are good indicators in ECG. In Figures 8 and 9 the different points can be identified. The side-by-side comparison shows the correlation of the periodic impedance and ECG signals.

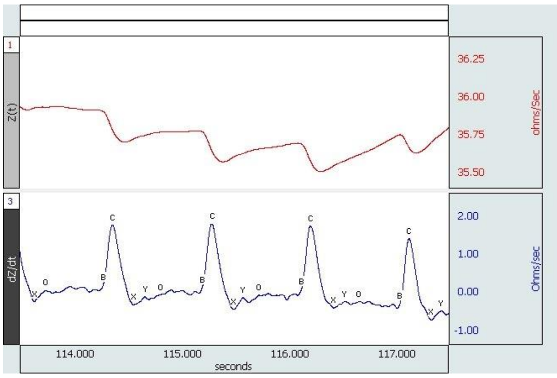

Figure 8

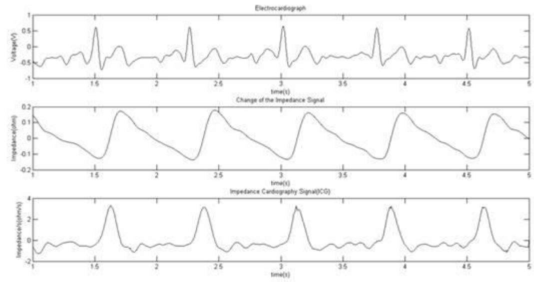

Figure 9

In the examples of Figures 8 and 9, the signal is quite clear. The placement of the electrodes and the absence of movement can greatly influence the noise on these signals. Therefore, sometimes it is necessary to select certain parts and leave out disrupted signals. The amount of noise greatly depends on the quality and type of setup used. When a clear signal is obtained as seen above, measurements such as HR can be calculated.

Hemodynamic parameters

After the impedance measurements have been acquired and graphed they will need to be interpreted to cardiac measurements. This is important because these are used for diagnosing patients and provide more intuitive information about a person's cardiac condition. In the table below are a selection of the most relevant hemodynamic parameters and how to calculate them from the impedance signals.

*Systolic is the moment of contraction of the heart while diastolic is the moment between two contractions of rest.
** Where: $\rho = 150\,\Omega/cm, L = 0.17 * height(cm), Z_0 = base\ impedance, Tlve = left\ ventricular\ ejection\ time$
*** Limited to transthoracic approach

Hemodynamic parameter		Formula(s)
Heart Rate (HR)	HR in beats per minute (BPM)	Peak to peak analysis from impedance graph.
Stroke Volume (SV) [20]	Difference between the end-diastolic* volume (EDM) and end-systolic* volume (ESV). Can be calculated from impedance signals through one of the three equations.	- Kubicek equation** *** $SV = \frac{\rho * L^2}{{Z_0}^2} * \frac{dZ(t)}{dt_{max}} * Tlve$ - Sramek equation $SV = \frac{L^3}{4.25} * \frac{dZ(t)/dt_{max}}{Z_0} * Tlve$ - Sramek-Bernstein equation

		$SV = \delta * \frac{L^3}{4.25} * \frac{dZ(t)/dt_{max}}{Z_0} * Tlve$
Cardiac Output (CO)	The volume of blood pumped by the heart per minute (L/min).	SV*HR/1000
Blood Pressure (BP) [21]	Can be calculated from PWV. (mmHg)	BP =α*PWV^2 + β With α = 0.046 kPa·$s^2 \cdot m^{-2}$ and β = 5.1 kPa
Mean Blood Pressure (MBP) Systolic Blood Pressure (SBP) Diastolic Blood Pressure (DBP)	Blood pressure changes after, DBP, and during, SBP, contraction of the heart.	MBP = ⅓*(SBP + 2*DBP)
Pulse Pressure (PP)	The difference between SBP and DBP. Reflects the force of the contraction of the heart.	PP = SBP - DBP
Pulse Transit Time (PTT)	The time it takes for a pulse to travel along the length between two points of an artery.	Measured from impedance graph.
Pulse Wave Velocity (PWV)	The speed at which pulse waves travel along the length between two points of an artery. With distance D between two points.	PWV = D/PTT

Current state

Examples of medical bioimpedance devices

To be able to measure impedance and then translate this to an accurate estimation of HR or even BP, hard- and software is needed. Currently, there are multiple ICG devices available, such as BIOPAC [16], Physioflow Enduro [17], and the ICG setup of Philips [18]. There is also the ICON device [19], however, this setup is based on EC rather than ICG as explained before.

BIOPAC is a commercially available impedance measurement setup. It consists of a set of hardware components and software that can be installed on a PC. The hardware components are:

- MP36/35
    - Connects SS31LA with PC
- SS31LA
    - Provides a low current and reads the voltage over the electrodes
    - Outputs Z and dZ
- Cables
    - Electrodes for chest and neck
    - Cables for connecting SS31LA and MP36/35

To break it down: the setup provides a low current that runs via the electrodes through the body. Because the current is constant the voltage measured is directly dependent on the impedance of the measured tissue.

ICON is another commercially available system. It consists of a handheld and has a battery life of 2 hours. In contrast to BIOPAC, it is based on EC. However this only affects the processing, the impedance measurement setup is almost the same, with a device outputting the Z and dZ and electrodes placed on the neck and chest.

State of non-medical devices

For non-medical applications, the practical use of these devices is a major influence on the design. Where for medical applications accuracy and reliability are the most important factors, for the daily user the place of the device, the type of electrode, and the integration in other devices are of equal, if not greater, importance.

First the place of the device. Currently, most commercially available medical impedance devices have electrodes placed on the neck and chest [19,22]. For a regular user, however, this is not practical. For daily use, a wrist-worn device with the rigidity and practicality to be able to be used by sporters and the accuracy and reliability to be able to be used as a passive medical check for, for example, elderly is among the best options.

As for electrodes: in a medical setting sticking electrodes to the skin is practical, however for day-to-day use it is not. For practical use, a dry electrode is needed such as an in-garment electrode [9], where the electrode is kept in contact through the skin embedded in cloth or an electrode strapped tightly to the skin through another material that is flexible enough to form tightly around the limb. The movement of the electrode can cause artifacts, and sweat from the skin influences the signal. The skin-electrode interface, therefore, presents a major challenge in designing a functional device; it is a balance between keeping the electrode in place and still being comfortable to wear.

Recently an ICG wearable has become commercially available [23]. The AURA is a state-of-the-art smartwatch that has been developed with the intent of measuring not only cardiac processes but also body composition and hydration levels. To do so the smartwatch has multiple sensors built into it; an ICG module, an accelerometer, and an infrared (IR) sensor. The electrodes are made of stainless steel and have been built in the strap with a dimpled pattern. Presumably to optimize the skin-electrode interface and to minimize loss of contact. The IR sensor is used for HR heart rate variance (HRV) and oxygenation measurements. ICG is not used for any cardiac measurements, instead only for body composition and hydration.

Some non-commercially available watches have appeared as well [12]. With the focus on accuracy and wearability, Biowatch uses an accelerometer to measure the arms position to optimize predicting the blood pressure.

Another non-commercially available ICG watch has very recently emerged [24]. This device does focus on HR measurements by bioimpedance. It does however rely on entire body cardiography, with one electrode pair inside the watch on the wrist and another on top of the watch. The user has to press their finger on the latter electrode to complete the circuit through the body as seen in figure 10.

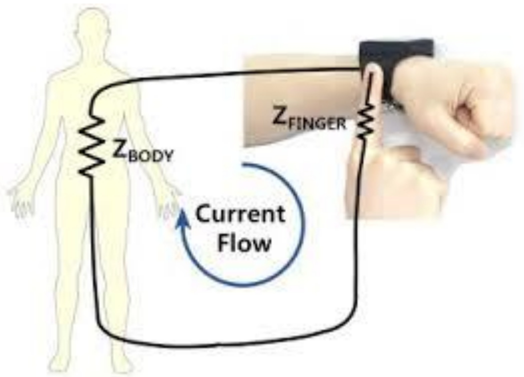

Figure 10

Other applications

Before impedance cardiography bioimpedance was primarily known as a method to determine body composition. As impedance does not just rely on blood volume but varies over many tissues[1] measuring hydration and body composition is also possible [25].

Another type of measurement entirely is that of finger movement. The neural signals to the muscles that control the fingers can be picked up by a method called surface nerve conductance (SNC) [26]. The electrodes for this method are also placed on the inside of the wrist.

[1] Bioelectrical Impedance Methods for Noninvasive Health Monitoring: A Review

Conclusion

Bioimpedance is an old measuring technique that can be applied in multiple fields. Up until recently ICG was limited to the medical world, primarily because of practical reasons such as size and skin-electrode interface. At this point in time interest in impedance for wearables has increased, the first functional devices have started to appear. However there is still a little ways to go, the AURA device still uses an optical measuring method for it’s cardiography and wrist-only ICG has been proven feasible[12] but has yet to become commercially available.

The goal of a reliable, accurate and easy to use health monitor is twofold. First there is the goal of a commercially available ICG-based smartwatch with wrist-based cardiac impedance measurements. To reach this goal, a few things have to be perfected, the electrode integration in the watch for an optimal skin-electrode interface and electrode placement for example. Most of the technology has been developed already, at this point it is a matter of perfecting and putting the right ideas together. Secondly, bioimpedance has proven itself a versatile measuring technique, combining cardiographic and pulmonary measurements with body composition and hydration levels. Health monitoring can be brought to a new level if bioimpedance would find even more applications and if it could combine them all in an easy-to-use device.

The future looks bright for bioimpedance, a lot of development has already been done. Many applications seem to be feasible. Likely there are only a few final steps left to be able to make ICG devices available for daily use.

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