Non-invasive blood pressure as an application of electrical impedance: a short review

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Abstract. Electrical bioimpedance (EBI) has gained importance as a diagnostic technique in medicine to determine the electrical properties of tissues. For example, it has been used in tissue characterization, cancer detection, and electromyography. Some of the characteristics of EBI are its low cost, the absence of irradiation during the measurement process, and its non-invasive nature. In this sense, there is interest in developing medical equipment that performs non-invasive measurements of blood pressure (BP). Electrical Impedance Plethysmography (EIP) is a technique commonly used to extract the waveform associated with BP. In this short review, we will cover research articles published in peer-reviewed journals during the last decades, and show developments in the area of EIP, with a brief discussion of relevant results and current challenges.

1. Introduction

Blood pressure (BP) measurement helps to establish the current condition of the cardiovascular system (CS). Untimely diagnosis at the onset of problems associated with CS in individuals increases the probability of death, as observed in the latest report of the World Health Organization, where it is noted that more than 17.9 million people die yearly in the world due to problems associated with CS, a number that constantly increases [1].

Electrical bioimpedance (EBI) is a technique with several advantages: it is affordable, non-invasive, requires low power consumption, and offers transportability. EBI has three groups of applications: electrical impedance spectroscopy, time-varying electrical impedance, and electrical impedance tomography. In recent years, EBI has gained a particular interest in the scientific community due to the advantages mentioned above and a large number of possible applications, for example, characterization of the degree of ripeness of fruits and vegetables [2], tissue characterization [3], cancer detection [4], electrochemical characterization [5], electromyography signal extraction [6], organ volume estimation by electrical impedance tomography [7,8], among others.

The techniques used for blood pressure measurements, such as catheter and oscillometry, always present some degree of invasiveness, as they modify the blood flow inside the artery during the measurement process. Consequently, complications may arise during or after the procedure due to potential infection (use of a catheter) [9] or thrombus detachment (use of the cuff - oscillometry) [10]. EBI could be a useful alternative to these techniques, but first, it must overcome certain difficulties. A
very important one is that there is still no proven method for calculating the blood pressure value directly from the waveform obtained by EBI. Besides, improving the acquisition of this waveform requires defining the best settings for the location of the electrodes [11,12], frequency of the current signal [13], area of the electrodes [14], the separation between electrodes [15], and the pressure exerted on the electrode-electrolyte contact [16], among others. This review article aims to contribute to the scientific community whose area of research is to obtain the BP waveform using EBI. The review article is organized as follows: Section 2 discusses the methodology used to select research articles. Section 3 shows the behavior of the research from the perspective of time and countries. Section 4 summarizes the results of the review. In Section 5, we present some conclusions on the current state and future of the EIP technique.

2. Methodology
The search for articles was performed using digital libraries and search engines such as IEEE Xplore, Science Direct, Sensors, Scopus, PubMed, Springer, and Google Scholar. The keywords used during the search were: first, "electrical impedance" AND "review"; second, "electrical impedance" AND "pressure" and; third, "electrical impedance" AND "blood pressure." As a result of the search, a time window was defined between 1995 and 2021.

The next step was to construct a table containing the following information: title, year, authors, authors' country, keywords, electrode construction, article objectives, EBI technique used, measurement equipment construction, bandwidth used, signal magnitude (current or voltage as the case may be), body segment used for EBI measurements, methodology used during the research, conclusions, challenges defined by the authors, problems encountered during the development of the research, number of patients, pathologies and, the title of the journal of the publication. After this, the list was narrowed down to the 50 most representative articles.

3. Result
The first research showing a technique to obtaining the BP signal in a person using EBI was in 1950 [17]. The technique used was called electrical impedance plethysmography (EIP). In 1970, another research showed a different technique to extract the BP waveform called electrical impedance cardiography (EIC). The objective of the research consisted of monitoring cardiovascular system parameters for NASA's Apollo 11 astronauts [17]. These two publications are considered as the basis for developments in the following years until today. The EIP and the EIC techniques use the variation of the arterial volume due to the cardiac cycle. Both EIP and EIC are still the most relevant techniques for EBI measurement of BP [18,19]. Due to space constraints, in this article, we will focus on EIP.

Electrical impedance plethysmography (EIP) is characteristic of placing the electrodes in body segments of the extremities (lower, upper, or a combination of these). The body segment has complex geometries. So, it is necessary to simplify this complex shape. For example, the upper and lower body segments are used in a straight cylinder [20,21]. So, the arteries are also approximated with the same shape. The number of publications in EIP shows significant growth from 2014 onwards, but it decreases significantly after 2020, due in part to the SARS-CoV-2 virus pandemic. 80.6% of the selected publications focus on the EIP technique. The top five countries with the highest number of publications are Estonia, Germany, United States, Spain, and Italy. Mexico is the only Latin American country that has worked on this line of research.

Figure 1 shows a diagram with the publications of the last six years (2015 to 2021). This time window is where there is a more significant number of researches, which allows establishing advances in this area of research. It contains the main author's name, the flag of the country of origin, the configuration of electrodes used, and a colored circle to represent the measurement equipment (custom built is green and commercial equipment is yellow).

Some of the most relevant contributions based on the publications shown in Figure 1 are the following. In [22], the authors propose that the electrodes should be placed over the arterial artery to be measured to improve the BP waveform. A method to process noise generated by motion using an
accelerometer is developed in [21]. In [23], the authors propose to use the EIP and electrocardiography technique to measure the pulse transit time (PTT). An application to calculate the heart rate on a mobile device is shown in [24], and a way to measure intracranial pressure using EIP is shown in [25]. In [26], the authors develop an EIP measurement equipment from an adaptive design perspective using an FPAA; in the same vein, a four-channel simultaneous EIP electronic measurement system with an FPGA is developed in [13]. The location (electrodes and artery) should be close to improve some features in the BP waveform, according to [27], and it is also important to consider the arrangement of Cole electrical models (2R and a constant phase element) to explain the best placement of electrodes on a body segment for EIP measurements, as demonstrated in [28]. One way to improve the sensitivity in EIP measurements is to use focused impedance [11], and another aspect is to change the current signal (sinusoidal) for a Chirp signal to establish characteristics in the EIP signal (time and frequency variables) [29].

![Figure 1. EIP technical research in the timeline. Source: Authors.](image)

Table 1 shows the magnitude values for the electric current signal $i(t)$ and frequency ($f$) used in the selected investigations to obtain the EIP signal. The typical values of magnitude for the $i(t)$ signal and frequency to obtain the EIP signal are 1.0 mA and 50 KHz, respectively. The sensitivity for EIP measurements increases proportionally to the value of the current signal frequency $i(t)$ [23]. Another important aspect is the location of the electrodes in the body segment, which affects the sensitivity significantly.

As shown in Table 1, a high proportion of the publications located the electrodes in upper segments, especially the left forearm. The most frequent electrode configuration is tetrapolar (4E). There are two groups according to the location of electrodes: upper and lower segments, with the first group having the highest number of publications. Some authors propose to use dry electrodes made of different materials in the upper segments: graphite, copper, gold, and silver. On the other hand, in the second group, it is proposed to use metal plates as the electrodes and obtains the EIP signal in people without direct contact with the skin (on top of clothing).

4. Discussion

According to the reviewed studies, the main advantages of EIP are non-invasiveness [23,30–32], transportability [33], signal continuity [27,33], and lower power consumption compared to the photoplethysmography technique [34]. On the other hand, the disadvantages of the technique are that it is affected by variation of the distance between the electrodes and by the electrode-skin coupling [27,31];
therefore, calibration processes are necessary before starting the measurement to improve the accuracy in EBI measurements [35]. As discussed in [36], the increase in the frequency value of $i(t)$ signal produces orientation of red blood cells present in the blood. Some studies [36,37] have also demonstrated that medical gases (as anesthesia and $CO_2$ use for laparoscopy medical procedures) reduce the magnitude of EIP.

### Table 1. Electrode location. Source: Authors.

| General Segment | Segment      | Electrode Configuration | AC signal (mA) | Frequency (MHz) | Authors |
|-----------------|--------------|-------------------------|----------------|-----------------|---------|
| Upper           | Eyeballs     | Bipolar                 | 0.140          | 0.050           | [25]    |
|                 | Neck         | Tetrapolar              | 10             | 0.050           | [38]    |
|                 | Chest        | Bipolar and Tetrapolar  | 0.050 to 0.100 |                 | [39,40] |
|                 | Forearm      | Tetrapolar              | 0.003 to 5.0   |                 | [19,23,45,26,32,34,35,41–44] |
| Upper a         | Forearm      | Tetrapolar              | 0.1 to 1       | 0.001 to 2.000  | [12,31,46] |
| Upper - Combination | Chest and arm | Bipolar                   | 5              | 0.050           | [21]    |
| Lower           | Leg - foot   | Tetrapolar              | 0.3 to 1       | 0.023 to 0.143  | [10,14,47] |
| Lower - Combination | Upper and lower | Tetrapolar              | 0.1 to 5       | 0.002 to 1.000  | [13,22,24,39,48] |

* Simulation

The results of this review establish the following challenges in EIP: As observed in [19,21,24], it is necessary to improve techniques to process noise generated by movement, temperature, and humidity, since they negatively affect measurements. The variability in the measurements reported in the publications [13,23] suggests the convenience of establishing routines for the automatic adjustment of the devices developed to measure EBI, defining dynamic adjustment strategies for the amplification stages of the system. In [41,49], a factor that affects the precision in EBI measurements is the mechanical characteristics of the arteries, such as stiffness, so it is necessary to develop a method that establishes arterial stiffness based on EBI measurements. According to [50], the important problem is to define the relationships between the change in the phase value and the physiological changes. Furthermore, the publications [28] establish the absence of an electrical model that explains the changes in the value of the EBI produced in the artery during the cardiac cycle and models that explain changes in EIP due to different pathologies [24,26]. The possibilities of integrating artificial intelligence (AI) into EIP techniques in the future should also be considered in future studies.

As we mentioned previously, there is no consensus on how to extract the blood pressure values from the pressure waveform. As other plethysmography techniques, EIP gives us information about the changes in the volume of the artery, which is a direct consequence of changes in the blood pressure, but the exact relation between these volumes and the corresponding pressures depend on many factors and is yet to be determined. However, these calculations could share some similarities with those found in other non-invasive techniques reported in the literature, such as tonometry and pulse transit time (PTT). Tonometry requires a pressure sensor located perpendicular to the artery, flattening it, and obtaining the waveform associated with the cardiac cycle is extracted. In [51], the authors used the Spline multivariable adaptive regression method to estimate the value of blood pressure (tonometry), with errors of 1.4 and 4.77 mmHg for diastolic and systolic pressure, respectively. On the other hand, PTT calculates the blood pressure value by measuring the time it takes for the pulse to get from one point to another (proximal and distal) using two different measuring devices (usually electrocardiography (ECG)
and photoplethysmography (PPG)). This method has been implemented in [52] using ECG and EIP signals to calculate the BP value, obtaining a root mean squared error (arterial depression monitoring equipment as reference) of 12.09 ± 7.5 and 1.5 ± 1.35 mmHg in systolic and diastolic pressure, respectively. However, as this method requires combining two measurement techniques, it compromises portability and simplicity.

5. Conclusion
This paper presented a current review of the research carried out in EIP for measuring the arterial pressure waveform. The results show that the technique effectively obtains the waveform associated with the cardiac cycle in a non-invasive manner. However, three groups of challenges have been identified: first, which parameters affect EIP (electrode location, pathologies, and others) and how they do it. Second, improvements in electronic systems for measurements, such as versatility, self-adjustment routines, self-adjustable amplification stages, and an increase in the number of channels to perform more measurements. Third, EIP signal processing, which includes reducing noise generated by movement, increasing reliability, and, most importantly, determining how to calculate the blood pressure value from the waveform obtained. Working on these challenges will provide us with a non-invasive and reliable tool to diagnose cardiovascular diseases effectively and promptly.

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