Bioimpedance and Bioreactance

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11.1 Introduction

Electrical bioimpedance and bioreactance are two techniques for measuring cardiac output (CO) that can be used for hemodynamic monitoring. They are both based on the principle that during the cardiac cycle, changes in intrathoracic volume, and more particularly in the volume of the aorta induced by systolic ejection, lead to changes in electrical conductivity and impedance of the thorax. Quantifying these changes over the course of a cardiac cycle makes it possible to estimate stroke volume (SV) and hence CO. Bioreactance can be viewed as a technological improvement over bioimpedance.

In this chapter, we will summarize the mode of operation of these two techniques, detail the clinical studies which evaluated their reliability, list their limitations, and conclude their potential indications.

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11.2 Bioimpedance

11.2.1 Operating Mode

In 1950, Nyboer described the relationship between SV and the changes of the electrical impedance of the thorax during the cardiac cycle [1]. The use of bioimpedance in cardiovascular monitoring started in the mid-1960s, when the continuous measurement of CO was described for the first time in aerospace medicine [2].

The basic principle of the technique is that the cardiac cycle induces changes in the electrical impedance of the aorta, with simultaneous changes in the amplitude and phase of an electrical current applied through the thorax. These changes in thoracic electrical impedance are proportional to changes in the volume of the thoracic aorta and then to SV.

In practice, the system requires that a high-frequency electrical current is applied at a fixed amplitude across the thorax by electrodes located on the skin on the neck and at the lower part of the thorax (thoracic bioimpedance) or around the cuff of an intubation probe (endotracheal bioimpedance). Adjacent electrodes detect the beat-to-beat variations of voltage of the outward current (Fig. 11.1) [3].

The impedance of an electric current is defined by the ratio between voltage and current intensities. At baseline, basal impedance is closely related to the thoracic total fluid content. During cardiac ejection, blood flow through the aorta increases the total volume of iron in the thorax, inducing a decrease in its impedance. A basic hypothesis to derive CO from bioimpedance is that changes in impedance during the cardiac cycle are related to changes in the aortic volume and not in the volume of the cardiac chambers. This is likely true since the heart chambers are electrically isolated by the myocardial wall and since the volume of the atria and the other thoracic vessels is relatively constant [3].

Stroke volume (SV) is obtained from the product of the ventricular ejection time (VET) and the slope of the initial change of the aortic volume obtained from the first derivative of the impedance signal (dZ/dt_{max}). Since these changes only indicate relative changes of CO, a calibration factor (CF) is necessary to derive absolute values, based on an initial cohort of patients [3]:

$$SV = VET \times dZ / dt_{max} \times CF$$

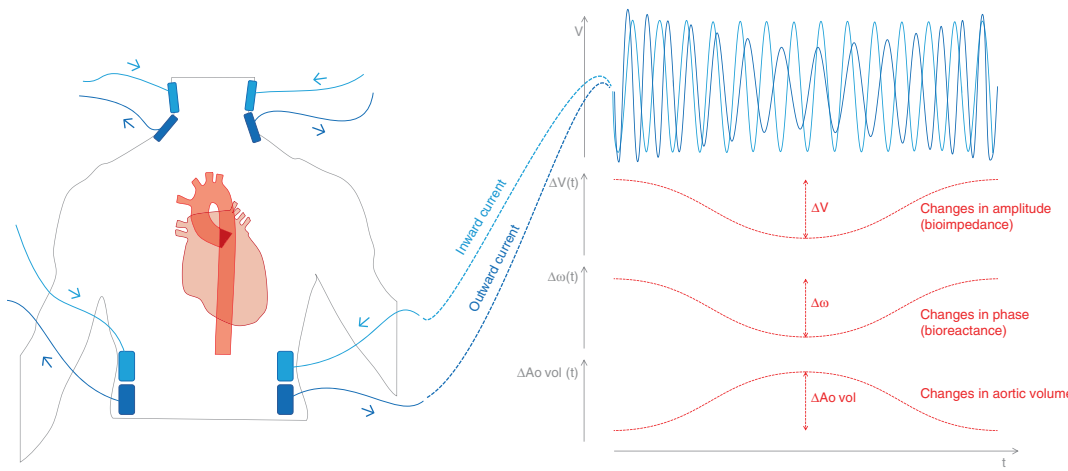

Fig. 11.1 Schematic functioning of thoracic electrical bioimpedance and bioreactance. At each heartbeat, the change in amplitude (ΔV, measured for bioimpedance) and in phase ($\Delta\omega$, measured for bioreactance) of the outward current compared to the inward current applied through the thorax by skin electrodes are used to estimate the increase in aortic volume (ΔAo vol), and thus stroke volume (partially adapted from [3], with permission)

Cardiac output is estimated from SV, and a moving average of the beat-to-beat values of CO is calculated over a period that depends upon the constructor.

Thoracic bioimpedance is used in many commercial devices: NCCOM (Bomed Medical, Irvine, CA, USA), BioZ (Cardiodynamics, San Diego, CA, USA), NICCOMO (MEDIS, Limenau, Germany), ICON (Osypka Cardiotronic, Berlin, Germany), ICG (Philips Medical Systems, Andover, MA, USA), NICOMON (Larsen and Toubro Ltd., Mumbai, India), the CSM3000 (Cheers Sails Medical, Shenzhen, China), and PHYSIOFLOW (Manatec Biomedical, Paris, France). The NICaS system (NI Medical, Petah-Tikva, Israel) uses the same principles but applied to the whole body [3]. The ECOM device (ECOM; ConMed, Utica, NY, USA) is the only one using endotracheal bioimpedance [4].

11.2.2 Advantages and Limitations

The main advantage of thoracic bioimpedance, which simply derives CO from electrodes pasted on the skin, is that it is one of the least invasive techniques for the continuous monitoring of CO. The devices are affordable and simple to use. Also, the bioimpedance measurement of CO is continuous and, provided that the period over which SV is automatically averaged is not too long, it is able to detect its short-time changes.

Nevertheless, thoracic bioimpedance suffers from several limitations. First, it is considerably affected by electrical noise, created by movements of the patient and surrounding electrical devices such as the ventilator or electrocautery [5]. It is to circumvent these limitations that endotracheal bioimpedance has been developed [4].

Second, many situations prevent the validation of assumptions on which the operation of the technique is based. Stroke volume must be associated with aortic deformation during systole. When it is not the case (aortic dissection or prosthesis), the effectiveness of bioimpedance is drastically reduced [3]. Other much more common conditions, such as obesity, low hematocrit, high blood pressure, or dehydration, may also limit or alter the principles on which the CO estimation is based [3].

11.2.3 Validation

Dozens of validation studies investigated the reliability of the measurement of CO through bioimpedance in a large variety of settings, from ambulatory patients at home to the intensive care unit (ICU) and the operating room. Results are equivocal [6–9]. Interestingly, the most positive studies were conducted outside from the ICU setting, perhaps because the latter increases the risk of electrical interference caused by the number of electrical devices surrounding the patient [3]. Confirming previous ones [8, 9], the most recent meta-analysis included 13 studies in adults (620 patients) and 11 studies in pediatrics (603 patients) evaluating thoracic bioimpedance [6]. The percentage error was 48% in adults and 42% in children, while values below 30% are usually judged as clinically acceptable [10]. Endotracheal bioimpedance has been less evaluated, but the available results are not better [4]. Overall, these results explain that bioimpedance is consensually not considered as reliable enough, at least in ICU patients [3, 5, 6, 11].

11.3 Bioreactance

11.3.1 Operating Mode

As described above, traditional bioimpedance uses the modulation of amplitude to estimate SV. With thoracic bioreactance, the hypotheses supporting the estimation of SV are the same, but the signal which is used for this purpose is the modulation of phase rather than of amplitude (Fig. 11.1). The advantage of the frequency modulation over the amplitude modulation, as for

radiobroadcasting, is that the signal-to-noise ratio is largely increased. In theory, this may circumvent many limitations of bioimpedance.

The NICOM (Starling SV in its new version) is the only available bioreactance device. It has been developed by Cheetah Medical (Centre St, MA), which has now joined Baxter International Inc.

11.3.2 Validation

Compared to bioimpedance, most recent bioreactance has been more scarcely investigated. The percentage error compared to the reference method ranged from 26% [12] to 145% [13] in these studies. As for bioimpedance, the worst results were obtained in studies conducted in the ICU [13, 14].

A limitation of the former NICOM device was that it averaged CO on a rather long time period and it refreshed the value displayed on the device screen every 30 s only. The new Starling SV device has been modified to shorten the latency to CO changes. In spite of a limited ability to measure absolute values of CO, the Starling SV was shown to reliably detect its changes during a passive leg-raising test, whose effects of CO occur within less than a minute [15].

A randomized trial included patients with sepsis admitted at the emergency room and distributed them between usual care and hemodynamic evaluation with the passive leg-raising test monitored by the bioreactance device. Although there was no difference in survival between groups, patients monitored with bioreactance demonstrated lower net fluid balance and reductions in the risk of renal and respiratory failure [16].

Practical Advice
Bioreactance essentially provides a continuous measurement of cardiac output. The last version allows the assessment of quite rapid changes, like during a passive leg-raising test, for instance.

11.3.3 Indications

To determine the potential indications for bioreactance, two elements must be taken into account. The first is that, as we have seen, the reliability of the system appears to be better outside the ICU than inside. The second element is that the system provides only CO as exploitable hemodynamic information. Therefore, like other non- or minimally invasive hemodynamic monitoring systems (esophageal Doppler, uncalibrated pulse contour analysis, volume clamp), this system is mainly intended for the perioperative context in the operating room. Its ease of implementation and ease of use make it a good candidate for prehospital monitoring or in the emergency medicine department, if continuous cardiovascular monitoring is deemed necessary.

Practical Advice
Bioreactance is better indicated in the operating room than in the intensive care unit.

However, it should not be used in ICUs. In the most severe patients, we should instead turn to the pulmonary arterial catheter or transpulmonary thermodilution, which are more reliable systems and which provide a large amount of hemodynamic information, even if they are more invasive and more expensive [11, 17].

11.4 Conclusion

Bioimpedance and bioreactance base their estimation of CO on the changes in impedance and reactance, respectively, of an electric current applied through the thorax during the cardiac cycle. Bioreactance should be seen as an improvement in bioimpedance, notably having a better signal/noise ratio.

Systems validation studies have shown variable results, more favorable with bioreactance, but possibly poorer in the ICU setting than in other ones. These systems are indicated in the

context of the operating theater, the prehospital medicine or the emergency department, but not in the ICU, where more reliable and informative systems are indicated.

Keynotes

- Bioreactance and bioimpedance are techniques that estimate cardiac output and are totally noninvasive.
- Bioreactance likely has a higher signal-to-noise ratio than bioimpedance. It is likely less sensitive to electrical interferences.
- Bioreactance and bioimpedance only provide cardiac output and the variables that can be inferred from it, like the peripheral arterial resistance.
- Bioreactance is likely less reliable in critically ill patients than in the operating room. The last version of the commercially available device is more reactive to rapid changes in cardiac output.

References

1. Nyboer J. Plethysmography, impedance. In: Glasser O, editor. Medical physics, vol. 2. Chicago, IL: Yr. Book. Pub.; 1950. p. 736–43.
2. Kubicek WG, Karnegis JN, Patterson RP, Witsoe DA, Mattson RH. Development and evaluation of an impedance cardiac output system. Aerosp Med. 1966;37(12):1208–12.
3. Nguyen LS, Squara P. Non-invasive monitoring of cardiac output in critical care medicine. Front Med (Lausanne). 2017;4:200.
4. Fellahi JL, Fischer MO. Electrical bioimpedance cardiography: an old technology with new hopes for the future. J Cardiothorac Vasc Anesth. 2014;28(3):755–60.
5. Saugel B, Cecconi M, Hajjar LA. Noninvasive cardiac output monitoring in cardiothoracic surgery patients: available methods and future directions. J Cardiothorac Vasc Anesth. 2019;33(6):1742–52.
6. Sanders M, Servaas S, Slagt C. Accuracy and precision of non-invasive cardiac output monitoring by electrical cardiometry: a systematic review and meta-analysis. J Clin Monit Comput. 2020;34(3):433–60.
7. Raaijmakers E, Faes TJ, Meijer JM, Kunst PW, Bakker J, Goovaerts HG, Heethaar RM. Estimation of non-cardiogenic pulmonary oedema using dual-frequency electrical impedance. Med Biol Eng Comput. 1998;36(4):461–6.
8. Peyton PJ, Chong SW. Minimally invasive measurement of cardiac output during surgery and critical care: a meta-analysis of accuracy and precision. Anesthesiology. 2010;113(5):1220–35.
9. Joosten A, Desebbe O, Suehiro K, Murphy LS, Essiet M, Alexander B, Fischer MO, Barvais L, Van Obbergh L, Maucort-Boulch D, et al. Accuracy and precision of non-invasive cardiac output monitoring devices in perioperative medicine: a systematic review and meta-analysis dagger. Br J Anaesth. 2017;118(3):298–310.
10. Critchley LA, Critchley JA. A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. J Clin Monit Comput. 1999;15(2):85–91.
11. Teboul JL, Saugel B, Cecconi M, De Backer D, Hofer CK, Monnet X, Perel A, Pinsky MR, Reuter DA, Rhodes A, et al. Less invasive hemodynamic monitoring in critically ill patients. Intensive Care Med. 2016;42(9):1350–9.
12. Doherty A, El-Khuffash A, Monteith C, McSweeney L, Breatnach C, Kent E, Tully E, Malone F, Thornton P. Comparison of bioreactance and echocardiographic non-invasive cardiac output monitoring and myocardial function assessment in primagravida women. Br J Anaesth. 2017;118(4):527–32.
13. Fagnoul D, Vincent JL, Backer DD. Cardiac output measurements using the bioreactance technique in critically ill patients. Crit Care. 2012;16(6):460.
14. Kupersztych-Hagege E, Teboul JL, Artigas A, Talbot A, Sabatier C, Richard C, Monnet X. Bioreactance is not reliable for estimating cardiac output and the effects of passive leg raising in critically ill patients. Br J Anaesth. 2013;111(6):961–6.
15. Galarza L, Mercado P, Teboul JL, Girotto V, Beurton A, Richard C, Monnet X. Estimating the rapid haemodynamic effects of passive leg raising in critically ill patients using bioreactance. Br J Anaesth. 2018;121:567–73.
16. Douglas IS, Alapat PM, Corl KA, Exline MC, Forni LG, Holder AL, Kaufman DA, Khan A, Levy MM, Martin GS, et al. Fluid response evaluation in Sepsis hypotension and shock: a randomized clinical trial. Chest. 2020;158(4):1431–45.
17. Cecconi M, De Backer D, Antonelli M, Beale R, Bakker J, Hofer C, Jaeschke R, Mebazaa A, Pinsky MR, Teboul JL, et al. Consensus on circulatory shock and hemodynamic monitoring. Task force of the European Society of Intensive Care Medicine. Intensive Care Med. 2014;40(12):1795–815.