Available online at http://www.journalijdr.com

International Journal of
DEVELOPMENT RESEARCH

ISSN: 2230-9926

International Journal of Development Research
Vol. 06, Issue, 11, pp.10364-10366, November, 2016

Full Length Research Article

NONINVASIVE CARDIAC OUTPUT MONITORING BASED ON THORACIC IMPEDANCE

***Jong Hae Kim**

Department of Anesthesiology and Pain Medicine, School of Medicine, Catholic University of Daegu, Daegu, Republic of Korea

ARTICLE INFO

Article History:
Received 22nd August, 2016
Received in revised form
14th September, 2016
Accepted 29th October, 2016
Published online 30th November, 2016

Key Words:

Cardiac output,
Electric impedance,
Physics,
Stroke volume.

ABSTRACT

The maintenance of optimal cardiac output is mandatory to reduce the incidence of postoperative complications and length of hospital stay. Despite the advantages of cardiac output monitoring, most of the modalities to measure cardiac output had been invasive thereby preventing their liberal use. However, nowadays, cardiac output can be measured noninvasively using a thoracic bioimpedance technique. Assuming that the human thorax is a cylinder consisting of resistor and capacitor, the periodic change (in accordance with a cardiac cycle) in the thoracic impedance generated by low-amplitude alternating current can be measured. The maximal rate of change in the magnitude of thoracic impedance is correlated with stroke volume by which heart rate multiplied is cardiac output. However, the accuracy of cardiac output measured by the magnitude of thoracic impedance is significantly influenced by several factors, such as electrode positioning, electrocautery, or static fluids in the thorax. In contrast, the phase angle of thoracic impedance is not affected by those factors and the maximal rate of its change is also correlated with stroke volume. Therefore, the phase angle of thoracic impedance is more useful for the noninvasive cardiac output monitoring than the magnitude of thoracic impedance.

INTRODUCTION

The maintenance of optimal cardiac output by titrating fluid administration is mandatory to reduce the incidence of postoperative complications and length of hospital stay (Gan *et al*., 2002; Hamilton, 2011; Lopes, 2007; Noblett, 2006; Polonen, 2000 and Wakeling, 2005), because excessive fluid resuscitation is associated with the increased complications and length of stay (Boyd, 2011; Maitland, 2011; de-Madaria *et al*., 2011 and Rosenberg, 2009). As a criterion standard method of measuring cardiac output, thermodilution measurements using a pulmonary artery catheter had been accepted (Rajaram, 2013). However, the use of the pulmonary artery catheter carries significant risks, such as pulmonary artery rupture, thrombosis and hemorrhage, knotting of the catheter, right atrial thrombosis, atrial and ventricular arrhythmia, electromechanical dissociation, catheter-related bloodstream infection and right-sided endocarditis, and internal jugular/subclavian vein stenosis or thrombosis (Marik, 2013). Furthermore, the benefit from its use was not clearly verified (Sandham, 2003 and Richard *et al*., 2003; Harvey *et al*., 2005; Binanay, 2015 and Harvey, 2006), and the hemodynamic data provided by the pulmonary catheter is not accurate (Dhingra *et al*., 2002 and Phillips *et al*., 2012). Therefore, many less invasive or noninvasive modalities for cardiac output monitoring have developed (carbon dioxide rebreathing, esophageal Doppler, pulse contour analysis, thoracic bioimpedance and bioreactance, vascular unloading, pulse wave transit time, radial artery applanation tonometry, echocardiography, etc.) (Marik, 2013 and Saugel *et al.,* 2015). Among them, the measurement of cardiac output using thoracic impedance will be discussed in this review.

****Corresponding author: Jong Hae Kim,***
Department of Anesthesiology and Pain Medicine, School of Medicine, Catholic University of Daegu, Daegu, Republic of Korea.

Fundamental physics of an electric circuit consisting of resistor and capacitor upon receipt of alternating current

By hindering electric current in an electric circuit, a resistor creates electrical resistance. The electric resistance is proportional to electric voltage and is inversely proportional to electric current in a direct current electric circuit according to Ohm's law.

R (electric resistance) = V (electric voltage) / I (electric current)

The Ohm's law also applies to an alternating current electric circuit including a resistor, in which an electric generator produces alternating voltage and its corresponding current that are based on the trigonometric sine function. However, the alternating voltage and current per time should be averaged to a root mean square.

v (instantaneous voltage) = V_m*sin(2πft)
V_m: maximum voltage, f: frequency of an alternating current, t: time

I (root mean square of current) = $I_m / 2^{1/2} = 0.707*I_m$
V (root mean square of voltage) = $V_m / 2^{1/2} = 0.707 * V_m$
I_m: maximum current, V_m: maximum voltage

R (electric resistance) = V (root mean square of voltage) / I (root mean square of current)

In an electric circuit including a capacitor, the effect of hindering the flow of alternating electric current can be assessed using capacitance reactance. When the electric current starts to flow through the electric circuit, there is little electric charge in the capacitor. Hence, the movement of the electric charge is not hindered and then high electric current would be detected in the capacitor. However, as the electric current flows continuously, the accumulation of the electric charge in the capacitor hinders the flow of the electric current, which increases the electric voltage. At a quarter of the cycle, the direction of the electric current that decreased from the initiation of the electric current becomes opposite rendering the electric voltage reach a maximum point with its subsequent decrease. In this way, the phase of the electric voltage changes 90 degrees later than that of the electric current unlike an electric circuit including a resistor, in which the electric voltage and current have the same phase. Therefore, the capacitance reactance can be expressed by the following equation:

X_c (capacitance reactance) = 1 / 2πfC
f: frequency of an alternating current, C: capacitance

If an electric circuit has both resistor and capacitor simultaneously, there would exist two factors which prevent electric current through the circuit, i.e. resistance and capacitance reactance. Due to the difference in phase angle of voltage between resistor and capacitor, the resistance and capacitance reactance also have the same difference in phase angle between them. Therefore, the combined effect of resistance and capacitance reactance cannot be assessed appropriately by arithmetically adding the values of the two variables. When considering the difference of 90 degrees in phase angle, the value of impedance representing the combined effect of the two components can be obtained using the Pythagorean theorem in the two-dimensional Cartesian plane with the horizontal and vertical axes for resistance and capacitance reactance, respectively.

Z (impedance) = $(R^2 + X_c^2)^{1/2}$

The phase angle (φ) is defined as the angle between the axis for resistance and the direction of the impedance.

The application of electrical physics to the measurement of cardiac output

To measure cardiac output using electrical physics, there should be an assumption that the human thorax is a cylinder perfused with fluid (blood) functioning as an electric circuit with resistor and capacitor which produce the thoracic impedance (Z_o) and phase angle (φ) when a high-frequency low-amplitude alternating current is applied across the thorax (Marik, 2013). Because blood (150 ohm/cm) and plasma (63 ohm/cm) have lower impedance than cardiac muscle (750 ohm/cm), lungs (1,275 ohm/cm), and fat (2,500 ohm/cm), (Baker, 1989) the electric current is primarily distributed to the blood and extracellular fluid. Interestingly, the periodic contraction of the heart causes the dynamic changes in the amount and distribution of the blood and plasma, in accordance with which the changes in the Z_o and φ ensue because the pulsatile ejection of blood from the left ventricle modifies the values of R and X_c. During systole, the ejection of the blood from the heart to the aorta and its branches decreases the Z_o, whereas the Z_o returns to the baseline during diastole. In contrast, the blood volume in the capillary and venous systems is relatively constant due to the absence of pulsatility. Consequently, stroke volume is correlated with maximal rate of change in Z_o (dZ_o/dt_{max}) and φ ($d\varphi/dt_{max}$) and ventricular ejection time. Thoracic bioimpedance uses dZ_o/dt_{max} to calculate the value of cardiac output. However, several limitations of the thoracic bioimpedance exist. The amplitude of Z_o is significantly affected by electrode positioning, electrical interference from electrocautery, fluids in the thorax, (e.g., pleural effusion, pericardial effusion, and pulmonary edema) (Critchley, 2000), change in peripheral vascular resistance (Critchley, 2005), variations in patient body size, patient’s age and gender (Sathyaprabha, 2008), cardiac arrhythmias, body motion artifacts (Chamos, 2013), and change in electrical conductivity between the skin and electrode (e.g., temperature and humidity). To overcome the limitations of thoracic bioimpedance, bioreactance technology has developed. It used φ/dt_{max} to obtain the value of cardiac output rather than dZ_o/dt_{max}. Phase (φ) shift is not affected by noise and occurs only in response to pulsatile flow. Because majority of the thoracic pulsatile flow is originated from the aorta, the phase shift is mainly created by the aortic flow which constitutes majority of cardiac output. Moreover, the change in non-pulsatile and static thoracic fluids does not induce the phase shift.

The noninvasive cardiac output measurement system (NICOM, Cheetah Medical, Portland, OR, USA) induces a high-frequency (75 kHz) low-amplitude alternating current in the bilateral sides of the thorax and then receives the returning voltage using the four sensors, each of which has two electrodes for injecting the alternating current and detecting the returning voltage, respectively. The four sensors are placed in the bilateral upper and lower regions of the thorax. The outer electrodes of the two paired sensors placed in the same side deliver the electric current from the generator and their inner electrodes record the returning voltage. Then, the NICOM device detects the phase shift during a cardiac cycle and creates the corresponding NICOM signal where each point represents a specific phase shift at a specific time. By deriving the NICOM signal in time, $d\varphi/dt_{max}$ is obtained in the maximum point of the derived graph. Ventricular ejection time is also measured between the first and second zero points of $d\varphi/dt$ on the time axis. Stroke volume and cardiac output are calculated as follows

Stroke volume = C * VET * $d\varphi/dt_{max}$

C: a constant of proportionality, VET: ventricular ejection time
Cardiac output = Stroke volume * heart rate

Conclusion

By comprehensive understanding of underlying electrical physics, its application to the measurement of cardiac output and potential limitations of the measurement modalities, anesthesiologists can appropriately interpret the value of cardiac output calculated based on the thoracic impedance or its phase shift and consequently manage patients in an appropriate way.

REFERENCES

Baker, L.E. 1989. Principles of the impedance technique. *IEEE Eng Med Biol Mag.,* 8:11-15.

Binanay, C., Califf, R.M., Hasselblad, V., *et al*. 2005. Evaluation study of congestive heart failure and pulmonary artery catheterization effectiveness: the ESCAPE trial. JAMA. 294:1625-1633.

Boyd, J.H., Forbes, J., Nakada, T.A., Walley, K.R., Russell, J.A. 2011. Fluid resuscitation in septic shock: a positive fluid balance and elevated central venous pressure are associated with increased mortality. *Crit Care Med.,* 39:259-265.

Chamos, C., Vele, L., Hamilton, M., Cecconi, M. 2013. Less invasive methods of advanced hemodynamic monitoring: principles, devices, and their role in the perioperative hemodynamic optimization. Perioper Med (Lond)., 2:19.

Critchley, L.A., Calcroft, R.M., Tan, P.Y., Kew, J., Critchley, J.A. 2000. The effect of lung injury and excessive lung fluid, on impedance cardiac output measurements, in the critically ill. *Intensive Care Med.,* 26:679-685.

Critchley, L.A., Peng, Z.Y., Fok, B.S., James, A.E. 2005. The effect of peripheral resistance on impedance cardiography measurements in the anesthetized dog. *Anesth Analg.* 100:1708-1712.

de-Madaria, E., Soler-Sala, G., Sanchez-Paya J, *et al*. 2011. Influence of fluid therapy on the prognosis of acute pancreatitis: a prospective cohort study. *Am J Gastroenterol.* 106:1843-1850.

Dhingra, V.K., Fenwick, J.C., Walley, K.R., Chittock, D.R., Ronco, J.J. 2002. Lack of agreement between thermodilution and fick cardiac output in critically ill patients. *Chest.,* 122:990-997.

Gan, T.J., Soppitt, A., Maroof, M. *et al*. 2002. Goal-directed intraoperative fluid administration reduces length of hospital stay after major surgery. *Anesthesiology.* 97:820-826.

Hamilton, M.A., Cecconi, M., Rhodes, A. 2011. A systematic review and meta-analysis on the use of preemptive hemodynamic intervention to improve postoperative outcomes in moderate and high-risk surgical patients. *Anesth Analg.,* 112:1392-1402.

Harvey, S., Harrison, D.A., Singer, M., *et al*. 2005. Assessment of the clinical effectiveness of pulmonary artery catheters in management of patients in intensive care (PAC-Man): a randomised controlled trial. Lancet., 366:472-477.

Harvey, S., Young, D., Brampton, W., *et al*. 2006. Pulmonary artery catheters for adult patients in intensive care. *Cochrane Database Syst Rev.,* CD003408.

Lopes, M.R., Oliveira, M.A., Pereira, V.O., Lemos, I.P., Auler, J.O., Jr., Michard, F. 2007. Goal-directed fluid management based on pulse pressure variation monitoring during high-risk surgery: a pilot randomized controlled trial. *Crit Care.,* 11:R100.

Maitland, K., Kiguli, S., Opoka, R.O. *et al*. 2011. Mortality after fluid bolus in African children with severe infection. *N Engl J Med.,* 364:2483-2495.

Marik, P.E. 2013. Noninvasive cardiac output monitors: a state-of the-art review. *J Cardiothorac Vasc Anesth.,* 27:121-134.

Marik, P.E. 2013. Obituary: pulmonary artery catheter 1970 to 2013. *Ann Intensive Care*. 3:38.

Noblett, S.E., Snowden, C.P., Shenton, B.K., Horgan, A.F. 2006. Randomized clinical trial assessing the effect of Doppler-optimized fluid management on outcome after elective colorectal resection. *Br J Surg.,* 93:1069-1076.

Phillips, R.A., Hood, S.G., Jacobson, B.M., West, M.J., Wan, L, May, C.N. 2012. Pulmonary Artery Catheter (PAC) Accuracy and Efficacy Compared with Flow Probe and Transcutaneous Doppler (USCOM): An Ovine Cardiac Output Validation. *Crit Care Res Pract.*, 2012:621496.

Polonen, P., Ruokonen, E., Hippelainen, M., Poyhonen, M., Takala, J. 2000. A prospective, randomized study of goal-oriented hemodynamic therapy in cardiac surgical patients. *Anesth Analg.,* 90:1052-1059.

Rajaram, S.S., Desai, N.K., Kalra, A., *et al*. 2013. Pulmonary artery catheters for adult patients in intensive care. *Cochrane Database Syst Rev.,* CD003408.

Richard, C., Warszawski, J., Anguel, N., *et al*. 2003. Early use of the pulmonary artery catheter and outcomes in patients with shock and acute respiratory distress syndrome: a randomized controlled trial. JAMA., 290:2713-2720.

Rosenberg, A.L., Dechert, R.E., Park, P.K., Bartlett, R.H., Network, N.N.A. 2009. Review of a large clinical series: association of cumulative fluid balance on outcome in acute lung injury: a retrospective review of the ARDSnet tidal volume study cohort. *J Intensive Care Med.,* 24:35-46.

Sandham, J.D., Hull, R.D., Brant, R.F., *et al*. 2003. A randomized, controlled trial of the use of pulmonary-artery catheters in high-risk surgical patients. *N Engl J Med.*, 348:5-14.

Sathyaprabha, T.N., Pradhan, C., Rashmi, G., Thennarasu, K., Raju, T.R. 2008. Noninvasive cardiac output measurement by transthoracic electrical bioimpedence: influence of age and gender. *J Clin Monit Comput.* 22:401-408.

Saugel, B., Cecconi, M., Wagner, J.Y., Reuter, D.A. 2015. Noninvasive continuous cardiac output monitoring in perioperative and intensive care medicine. *Br J Anaesth.*, 114:562-575.

Wakeling, H.G., McFall, M.R., Jenkins, C.S., *et al*. 2005. Intraoperative oesophageal Doppler guided fluid management shortens postoperative hospital stay after major bowel surgery. *Br J Anaesth.,* 95:634-642.

****