

Measurement Method and Principle for Thoracic Impedance Graph

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Abstract. Thoracic impedance graph is an impedance change curve measured on the surface of the human chest. It reflects indirectly the volume change of the heart and large vessels in the thorax, and it includes rich information about physiological activities and pathological changes. Thoracic impedance graph is measured using the four-electrode method in this article. Thoracic impedance change is transformed to the voltage change by means of the high frequency current I_0 , with a constant root-mean-square (rms) current. The voltage change which is directly proportional to thoracic impedance change can be obtained through the amplification, detection and calibration. The direct proportional relationship between the thoracic impedance change and volume change of the blood vessels is deduced by means of the thoracic parallel impedance model.

1 Introduction

Thoracic impedance graph, also known as Impedance cardiograph, is the impedance change curve measured on the chest surface. Because the thoracic impedance graph indirectly reflects the volume changes of the heart and large vessels within the thorax, thus it is closely related to the cardiovascular physiological activity and pathological changes, it carries rich information on the cardiovascular activity. The valuable measurement results for the clinical diagnosis and treatment can be obtained by using the thoracic impedance graph. It is widely used to measure the cardiac function and to monitor the hemodynamic changes clinically[1-4]. This article will discuss the measurement method and principle of thoracic impedance graph through the aspect of electricity.

2 Measurement method of the thoracic impedance graph

Thoracic impedance graph is generally measured using the four-electrode method. There are two ways for the placement of electrodes: Kubicek's four-ring electrode method and Sramek's eight-point electrode method^[5-6].

2. 1 Kubicek's four-ring electrode method

As shown in Fig.1, where I_1 and I_2 are the current electrodes, E_1 and E_2 are the voltage detection electrodes, which are all thin silver-plated copper ring or disposable aluminum foil. E_1 is located at lower neck, and E_2 is located at the lower edge of the thoracic xiphoid. The inner distance between the current and voltage electrodes is greater than 3.0 cm. The high frequency current I_0 , with

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a constant root-mean-square (rms) current, is fed into the body through I_1 and I_2 , and the voltage signal between E_1 and E_2 is sent to the impedance detection circuit.

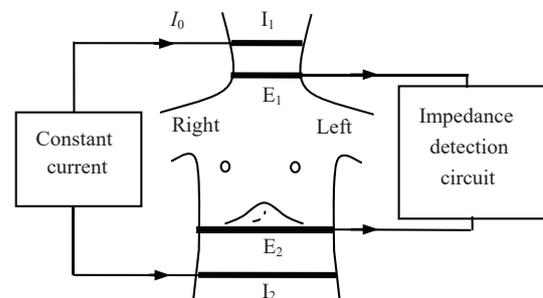


Fig.1. Kubicek's four-ring electrode method

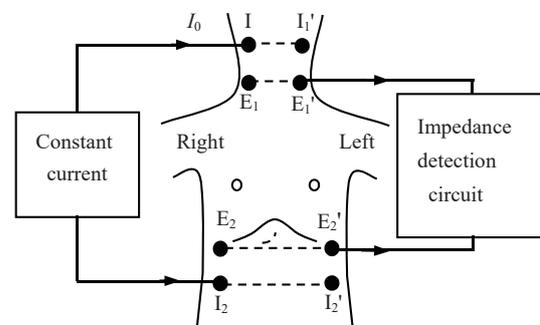


Fig.2. Sramek's eight-point electrode method

2. 2 Sramek's eight-point electrode method

From the above, we can see that the ribbon ring electrodes need to go around the neck and chest in

Kubicek's method. In the case of long-term monitoring, the patient will feel uncomfortable, and it is not suitable for monitoring the chest and stomach during the surgery. Thus Sramek proposed the eight-point electrode method to measure the thoracic impedance graph, and its method of electrode placement is shown in Fig. 2.

The eight-point electrode method is actually another form of the four-electrode method. I_1, I_1', I_2, I_2' are the current electrodes, among which I_1 and I_1' are connected, and I_2 and I_2' are connected. The high frequency current I_0 , with a constant root-mean-square (rms) current, is fed into the human chest through I_1, I_1', I_2, I_2' . E_1, E_1' and E_2, E_2' are the voltage detection electrodes, among which E_1 and E_1' are connected, and E_2 and E_2' are connected. These dot electrodes are disposable Ag/AgCl electrodes. Among which E_1 and E_1' are located at the lower neck, and E_2 and E_2' are located at the lower xiphoid, and E_2', I_2' and E_2, I_2 are located in the front left and right axillary position of the chest, respectively. The inner distance between the current and voltage electrodes is greater than 3.0 cm.

3 Block diagram of circuit composition of measuring the thoracic impedance graph

Fig. 3 is the block diagram of the circuit for measuring the thoracic impedance graph. It mainly includes the high frequency oscillator, constant current output circuit, four ring electrodes, high frequency amplifier, linear peak detection, low frequency amplifier and differential circuit. The high frequency current I_0 is fed into the human chest through current electrodes I_1 and I_2 . The voltage signals corresponding to the basic impedance (Z_0), impedance change (ΔZ), impedance differential (dZ/dt) can be obtained, respectively, after the impedance modulation signal generated between E_1 and E_2 is processed through the high frequency amplifier, linear peak detection, low frequency amplifier and differential circuit.

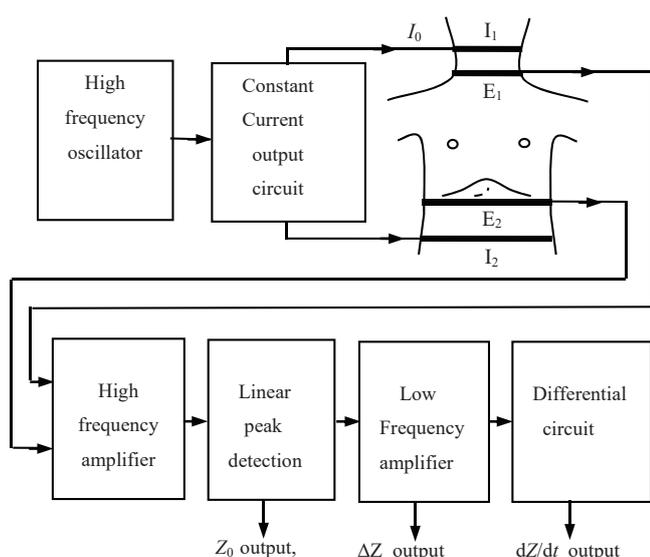


Figure 3. The block diagram of the circuit composition of measuring the thoracic impedance graph

4 Transform of the thoracic impedance change into the voltage change

The human thorax is a volume conductor which shows certain impedance towards the high frequency current, in which the constant part is the basic impedance (Z_0). The blood volume of the blood vessels in thorax will change constantly with the intermittent ejection of the heart, and a corresponding impedance change (ΔZ) will occur at the chest surface. As shown in Fig.1, when the high frequency current I_0 passes through the thorax, a high frequency voltage U is generated between the detection electrodes (E_1 and E_2), i.e.

$$U = U_0 + \Delta U \quad (3-1)$$

Where U_0 reflects the base impedance (Z_0), and ΔU reflects the impedance change (ΔZ). It is assumed that the total impedance (Z) between the detection electrodes (E_1 and E_2) can be expressed as

$$Z = Z_0 + \Delta Z \quad (3-2)$$

Since the root-mean-square (rms) current (I_0) fed into the chest is the constant in the measurement, the voltage U between E_1 and E_2 can be expressed as

$$U = I_0 (Z_0 + \Delta Z) = I_0 Z_0 + I_0 \Delta Z = U_0 + \Delta U \quad (3-3)$$

From Equation (3-3), we can lead to respectively:

$$U_0 = I_0 Z_0 \quad \Delta U = I_0 \Delta Z \quad (3-4)$$

The above equations show that U_0 is proportional to the base impedance (Z_0), and ΔU is proportional to thoracic impedance change (ΔZ). Thus the U_0 and ΔU can reflect the basic impedance and thoracic impedance change, respectively.

5 Thoracic parallel impedance model

Suppose that the human thorax is a cylindrical volume conductor [Fig. 4(a)], and the aorta is a flexible duct, which is located in the center of thorax. Fig. 4(b) shows the equivalent parallel circuit of thoracic impedance [7].

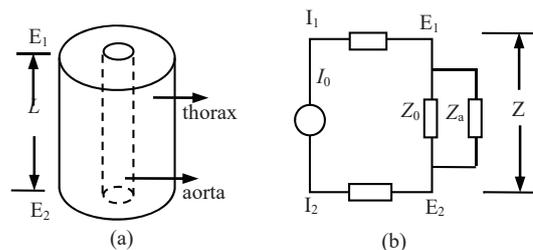


Figure4. Thoracic parallel impedance model

It is assumed that the L is the distance between the voltage electrodes (E_1 and E_2), S_{a0} is the cross-sectional area of the aorta in the basic state, and Z_0 is the thoracic impedance excluding the aorta. Z_{a0} is the impedance of the aorta in the basic state. The total impedance (Z_1) between E_1 and E_2 is the total impedance of Z_0 and Z_{a0} in parallel, that is

$$Z_1 = \frac{Z_0 Z_{a0}}{Z_0 + Z_{a0}} \quad (4-1)$$

When the heart ejects the blood and the volume of the aorta expand, the impedance of the aorta changes from Z_{a0} to Z_a , then the total impedance becomes

$$Z_2 = \frac{Z_0 Z_a}{Z_0 + Z_a} \quad (4-2)$$

From equations (4-1) and (4-2), the impedance change (ΔZ) before and after the expansion of the aorta can be obtained,

$$\begin{aligned} \Delta Z = Z_2 - Z_1 &= \frac{Z_0 Z_a}{Z_0 + Z_a} - \frac{Z_0 Z_{a0}}{Z_0 + Z_{a0}} \\ &= \frac{Z_0^2 (Z_a - Z_{a0})}{(Z_0 + Z_a)(Z_0 + Z_{a0})} \end{aligned} \quad (4-3)$$

Since $Z_0 \ll Z_{a0}$, $Z_0 \ll Z_a$, the above equation (4-3) can be approximated into

$$\Delta Z \approx \frac{Z_0^2 (Z_a - Z_{a0})}{Z_a Z_{a0}} = Z_0^2 \left(\frac{1}{Z_a} - \frac{1}{Z_{a0}} \right) \quad (4-5)$$

According to the law of resistance, Z_{a0} and Z_a in the above equations can be expressed as, respectively

$$Z_{a0} = \frac{\rho L}{S_{a0}} = \frac{\rho L^2}{S_{a0} L} = \frac{\rho L^2}{V_{a0}} \quad (4-6a)$$

$$Z_a = \frac{\rho L}{S_a} = \frac{\rho L^2}{S_a L} = \frac{\rho L^2}{V_a} \quad (4-6b)$$

The ρ in the above equations is the resistivity of the blood. $V_{a0} = S_{a0} L$, $V_a = S_a L$, which are the volumes of the aorta before and after the expansion, respectively. Substituting the equation (4-6) into the equation (4-5), after rearranging we can get

$$\Delta Z = -\frac{Z_0^2}{\rho L^2} \Delta V \quad \text{or} \quad \Delta V = -\frac{\rho L^2}{Z_0^2} \Delta Z \quad (4-7)$$

The above equation is called Nyboer's Impedance Change Equation^[7]. In this equation, $\Delta V = V_{a0} - V_a$, because the volume (V_{a0}) of the aorta before the expansion is smaller than the volume (V_a) after the expansion, the negative sign is introduced in the equation (4-7), which is indicating that the impedance decreases when the volume of the blood vessel expands. It can be shown from the equation (4-7) that the impedance change of the blood vessel is numerically proportional to its volume change, that is, the impedance change of the blood vessel can indirectly reflect the law of its volume change. Thus this lays the theoretical basis for the measurement of the thoracic impedance graph.

6 Relation between the thoracic impedance change and chest circumference

Suppose that U_0 and U_1 are the voltages of the aorta in the basal and expanded state respectively, and j_b is the current density of the blood. The currents of the blood vessel in the basal and expanded state can be denoted respectively as:

$$I_{b0} = j_b S_{b0}, \quad I_b = j_b S_{b1}$$

In terms of Ohm's law ($Z = U/I$), the impedances (Z_{a0}) and (Z_a) of the aorta in the basal and expanded states can also be expressed respectively as

$$Z_{a0} = U_0 / j_b S_{a0}, \quad Z_a = U_1 / j_b S_{a1}$$

Substituting them into the equation (4-5) yields

$$\Delta Z = \frac{Z_0^2 \cdot j_b}{U_1 U_0} \cdot (U_1 S_{b0} - U_0 S_{b1}) \quad (5-1)$$

Here $U_1 \approx U_0$. Substituting it into equation (5-1) obtains

$$\Delta Z \approx \frac{Z_0^2 \cdot j_b}{U_0} \cdot (S_{b0} - S_{b1}) \quad (5-2)$$

Suppose that ρ_t and j_t are the average resistivity and current density of the thoracic tissue, respectively. The blood current density j_b can be expressed as $j_b = \rho_t j_t / \rho_b$ ^[8]. Substituting it into equation (5-2) yields

$$\Delta Z = -\frac{\rho_t}{\rho_b} \cdot \frac{Z_0^2 \cdot j_t}{U_0} \cdot \Delta S \quad (5-3)$$

Where $S_{b0} - S_{b1} = -\Delta S$. U_0 can be denoted as $U_0 = I_0 Z_0$ (I_0 is the frequency current I_0 injecting into the thorax). Substituting it into the equation (5-3) obtains

$$\Delta Z = -\frac{\rho_t}{\rho_b} \cdot \frac{Z_0 \cdot j_t}{I_0} \cdot \Delta S \quad (5-4)$$

The numerator and denominator in the equation (5-4) both are multiplied by the length L ,

$$\Delta Z = -\frac{\rho_t}{\rho_b} \cdot \frac{Z_0 \cdot j_t}{I_0 L} \cdot \Delta S L \quad (5-5)$$

Here $\Delta S L = \Delta V$. Substituting it into equation (5-5) yields

$$\Delta Z = -\frac{\rho_t}{\rho_b} \cdot \frac{Z_0 \cdot j_t}{I_0 L} \cdot \Delta V \quad (5-6)$$

It shows that thoracic impedance change ΔZ is directly proportional to the current density j_t in the thorax.

If S_t denotes the cross-sectional area of the thorax, the average current density in the thorax can be expressed as $j_t = I_0 / S_t$. Substituting it into equation (5-6) gives

$$\Delta Z = -\frac{\rho_t}{\rho_b} \cdot \frac{Z_0}{S_t L} \cdot \Delta V \quad (5-7)$$

Where the S_t can be denoted as $S_t = C_t^2 / 4\pi$ (C_t is the chest circumference). Substituting it into equation (5-7) obtains

$$\Delta Z = -\frac{4\pi \rho_t}{\rho_b} \cdot \frac{Z_0}{C_t^2 L} \cdot \Delta V \quad (5-8)$$

According to Sramek's formula^[6], the distance L between two voltage electrodes (E_1 , E_2) on the chest surface can be approximately expressed as $L = 0.168H$ (H is the body height). Substituting it into the equation (5-8) yields

$$\Delta Z \approx -\frac{24\pi \rho_t}{\rho_b} \cdot \frac{Z_0}{C_t^2 H} \cdot \Delta V \quad (5-9)$$

This is an equation of the thoracic impedance change including the chest circumference^[8]. The equation (5-9) shows that the thoracic impedance change (ΔZ) is directly proportional to the volume change ΔV of the blood vessel, and to the ratio (Z_0/H) of the basal impedance to the body height, while it is inversely proportional to the square of the chest circumference (C_t^2).

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