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A REVIEW OF RHEOGRAPHY: THE NONINVASIVE VASCULAR MONITORING IN MEDICINE

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ABSTRACT

Peripheral arterial disease is becoming more common worldwide. In Vietnam, its prevalence is rising due to increasing cases of diabetes and high blood pressure. Rheography is a non-invasive method used to diagnose peripheral arterial disease, but it is not widely used in healthcare centers, especially in the Mekong Delta. This study aims to summarize current rheography knowledge and suggest future research directions. Rheography measures changes in electrical resistance (impedance) in body tissues as blood flow changes. This technique, also known as impedance plethysmography, helps assess blood circulation in the limbs. At Can Tho University of Medicine and Pharmacy Hospital, a rheometer with six electrodes is used to measure these changes. The rheography procedure starts with healthcare professionals explaining the procedure to patients, then body measurements are taken, and the electrodes are positioned based on the examined blood vessels. The results appear as waveforms, which help assess vascular tone (the state of blood vessels) and blood flow intensity, which correspond to different phases of the heartbeat. Rheography is useful in diagnosing blood vessel problems such as peripheral arterial disease, deep vein thrombosis, and cardiac autonomic neuropathy. However, the effectiveness of rheography depends on the expertise of the reader. In addition, certain conditions, such as calf thrombi or non-occlusive proximal clots, are harder to diagnose because these conditions only partially block the blood vessels. Future research should focus on the use of rheography in combination with other diagnostic methods and the effectiveness of this combination in disease scanning.

Keywords: *rheography, impedance plethysmography, peripheral arterial disease, diabetes, atherosclerosis.*

I. INTRODUCTION

Peripheral arterial disease (PAD) is becoming more prevalent worldwide. Globally, 1.8% of the world population reported suffering from PAD [1]. In Vietnam, the number of PAD patients has increased with the increase of diabetes mellitus, arteriosclerosis, and high cholesterol. According to the Vietnamese Ministry of Health, in 2023, about 10.5% of Vietnamese citizens were reported to have diabetes [2], putting them at a two- to seven-fold higher risk of developing PAD [3]. Similarly, in 2022, the Vietnamese Ministry of Health reported that half of the Vietnamese urban citizens were diagnosed with high blood cholesterol [4]; these people were faced with a five-fold increased risk of PAD compared to the general population [5].

PAD is a group of diseases that cause the narrowing or blockage of peripheral arteries, especially in the lower extremities. The primary cause of this is primarily caused by fatty plaque in the peripheral arteries [6]. Patients with this condition suffer from

insufficient blood flow in the thigh and calf muscles, leading to pain in the affected area when walking [7]. In addition, other complications include chronic ulcers and sores as well as cold or numbness of the toes. If left untreated, patients run the risk of developing an infection leading to limb amputation. Furthermore, due to the systematic nature of vascular conditions, patients with PAD have a 96% increased risk of cardiovascular mortality and are 1.35 times more likely to develop other cerebrovascular diseases [8]. More importantly, in Vietnam, most patients get their PAD diagnosis after experiencing symptoms of pain. This delayed medical attention greatly contributes to a worse prognosis.

Developed as an alternative to venography in the 1980s, this method was used before the development of the Doppler and duplex ultrasound, but it has since been largely replaced by ultrasonography in many health facilities around the world [9]. Despite this, numerous tests involving rheography establish sensitivity rates of 86% to 90% and specificity rates of 94% to 96% [10]. The predictive value of an abnormal test was recorded to be 89% [11]. In Vietnam, rheography is still seen as an unfamiliar testing method that is mostly performed in major health facilities. Therefore, this test remains inaccessible to many of the patients who may benefit from it.

Therefore, we conduct this review with the main aim to summarize current knowledge of rheography, including the mechanism, necessary equipment, and technique, as well as the analysis of rheography test results in some common vascular illnesses.

II. CONTENT

2.1. Biophysical basis

The human body can produce electrical currents given suitable conditions, thanks to the number of ion particles in bodily tissues. The extent of this phenomenon depends on the number of ions. Thus, each type of tissue varies in the amount of current it produces. In terms of electrical resistance, objects that can produce more electrical current have lower electrical resistance. Among all bodily tissues, blood generates the highest amount of electrical current and therefore has the lowest resistance. In the body during a relatively short period, the resistance of tissues is constant. However, due to the pulsing nature of the blood vessels, the base resistance of every part of the human body alters slightly by 0.05% to 0.1% with every heartbeat. The changes in resistance of a body part due to blood volume alteration (RΔ) are proportional to the change in volume of blood (ΔV) and the square of the base resistance. In contrast, RΔ is inversely proportional to the blood's resistivity as well as the square of the length of the tested body area. This relationship can be shown in the Nyboer Equation [11].

$$\Delta = \frac{\Delta V}{\rho\left(\frac{L}{Ro}\right)^2}$$

Impedance, measured in Ohms, represents the total resistance of an object against the electrical current passing through it. It is comprised of resistance R and reactance X. Reactance is composed of capacitance C and inductance L, with the latter being negligible in the body. In addition, reactance X is affected by the angular frequency of the applied current [12]: $Z = (R^2 + X^2)^{\frac{1}{2}}$; X= $\omega L - \frac{1}{\omega C}$.

Theoretically, the changes in the impedance of a limb segment depend on the natural resistance of the tissues in question. In the human body, it depends on the resistance of the cells, the interstitial space, and the resistance of the blood content. The two former

components have little change over short periods. Primarily, changes were made thanks to the ever-changing nature of the blood flowing through the blood vessels. In addition, the flow of fluid, blood, in this case, alters the resistance of an area. Since the resistivity of blood decreases as the speed of blood flow increases, the measured area experiences a slight increase in resistance during systole and a slight decrease in resistance during diastole. However, according to Liebman *et al.,* this change contributes only about 0.4% to 0.8% of the total resistance, a negligible change in the context of disease screening [12].

Due to the changes in tissue polarization and the appearance of additional charges, an alternating excitation current is used instead of a direct current [12]. In addition, to ensure the evenness of the current density, the modern rheometer utilizes a current system of multiple electrodes. As the electrodes emit an excitation current with the frequency F0, the altering resistance of the examined area results in an altering voltage U. The difference in ΔU is then measured. To process this minor change of Voltage ΔU, it goes through a selective differential amplifier and then a low-pass filter. Furthermore, these signal high-pass filters are employed to extract variable impedance ZΔ(t) from base impedance (Z0). The resulting rheography shows the changes in ΔR over time [11].

2.2. Equipment

At Can Tho University of Medicine and Pharmacy Hospital, the Vasoscreen 5000 rheometer (Medis GmbH, Ilmenau, Germany) was used to measure rheoencephalography as well as rheography in patients. The layout of the device is described in Figure 1. This model is capable of measuring both the rheography in the head as well as the extremities (legs and arms). This equipment is equipped with 6 electrodes (2 emitters and 4 receivers), each made of round aluminum with a diameter of 2 cm. The rheography impedance has a measuring current of 1.5mA ±1%, 85 kHz with the basic impedance of 0-200 Ohm ±1%, 0-1.5 Hz, and impedance change of ±6.25 Ohm ±2%, 0-1.5 Hz. The pulse wave is ±500 mOhm ±2%, 0.2-120 Hz, and the noise is <1 mOhm. An electrocardiogram channel had the maximum input voltage of ±10 mV, 0.2-120 Hz alternating current (AC), common-mode rejection ratio (CMMR) >90 dB, noise voltage <10 μV, and a test signal (1 mV). The main supply was set with 115-230 V ±10%, 50-60 Hz, and 60 VA [13]. The electrodes are arranged based on color, with the red ones on the right and the yellow ones on the left.

2.3. Measuring technique

2.3.1. Patient positioning

Before taking the measurement, doctors provide patients with all the necessary information to understand the process of measuring rheography. Then each patient is taken for anthropometric measurements (weight, height). This information can help to provide a more complete picture of the patient's overall health and can be useful in interpreting the results of the rheography measurements. For the examination of the lower extremities, the patient lies in a relaxed position. By changing the position of the measuring electrodes, the doctors can measure different sections. The positioning should be made symmetrically on both legs. Figure 2 illustrates possible electrode positions on the right leg [14].

It is essential to consider that the cross-sectional area of a limb changes along the extremity when using impedance plethysmography (IPG) for limb blood flow studies. This is of great importance because it impacts the accuracy of the measurement. To prevent an underestimation of the blood flow value, it is crucial to carefully select the actual measurement site as well as the interelectrode distance [15].

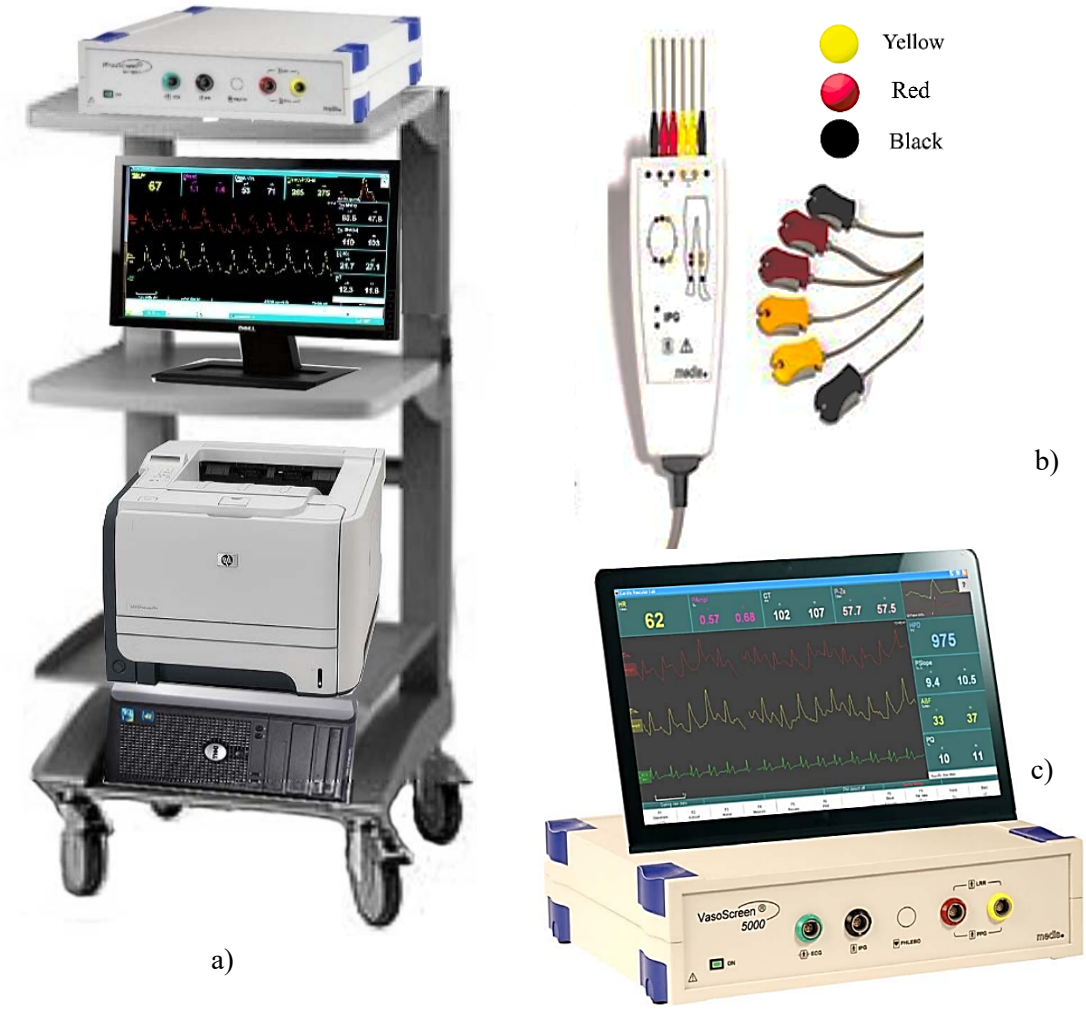


Figure 1. Types of equipment used for measuring rheography. (a) Input and output of the monitoring device, (b) System of electrodes, and (c) VasoScreen 5000 device.

This figure was reorganized from the brochure of VasoScreen. (Company Medis Medizinische Messtechnik GmbH Brochure, Angiologic Diagnostic System, Diagnostic support manual, 2012 [14]).

Clinicians should consider the patient electrically as a combination of resistance and capacitive reactance, as proposed by Schaefer in 1940. To measure these parameters, the vascular section of the patient is connected to one arm of the device, and then the button is pressed to initiate the measurement of either the patient's capacitive reactance or resistance. The resulting values provide important information about the volume of blood flow in the vascular section being examined, especially when a peripheral rheogram is being recorded. By carefully monitoring these values and using them to guide treatment decisions, healthcare professionals can effectively diagnose and treat various vascular conditions [16].

2.3.2. Method of measuring

This method is based on the measurement of the electrical resistance of a selected body segment. Four electrodes were used to measure the fluctuations in resistance for blood flow in arteries. The impedance of blood flow is calculated by a rheographic method, from

which the pulse rate can be evaluated. Once the pulse rate is calculated, systolic and diastolic pressure can be evaluated as well. The method involves the application of four electrodes to the body surface, typically in a line. The two outer electrodes, also known as current electrodes, are used to pass a very low and constant alternating current (1.5 mA, 86 kHz) through the body segment. This current is imperceptible to the patient and does not cause any physiological reaction. The two inner electrodes, known as measuring electrodes, are placed between the two current electrodes and measure the voltage generated when the current flows through the body segment. This voltage corresponds to the impedance of the body segment, which changes depending on venous and arterial blood volume variations. The positioning of the measuring electrodes defines the segment that is analyzed, which is between both electrodes. To ensure a more homogeneous current dispersion in the measuring segment, the current electrodes should be placed as far as possible from the measuring electrodes (greater than 10 cm) [11], [17].

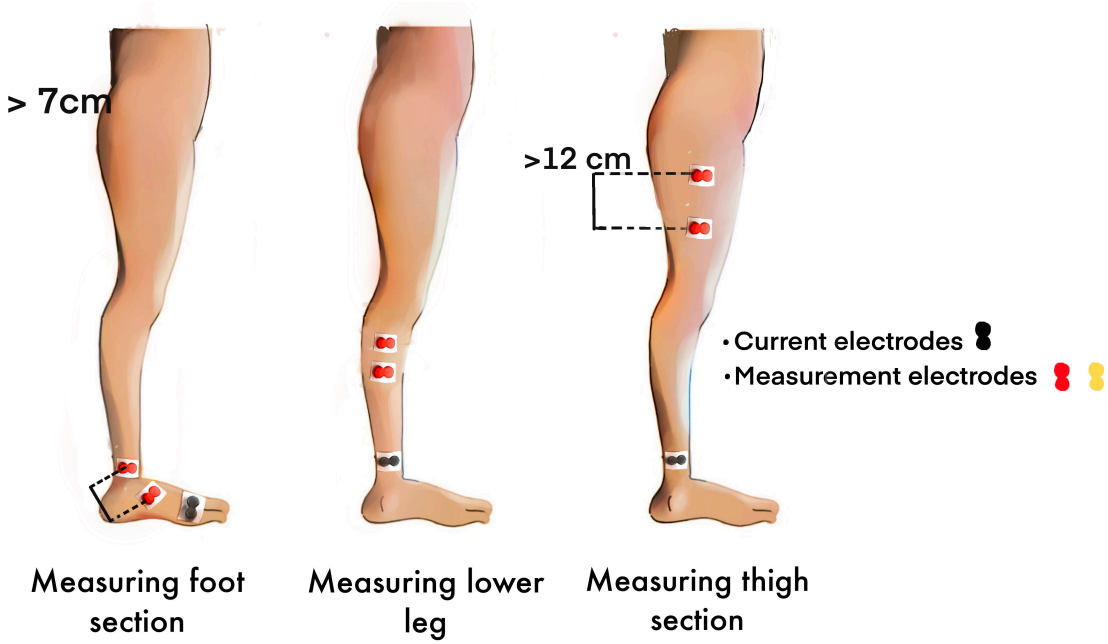


Figure 2. Possible electrode locations for measurements on lower extremities
This figure was redrawn from the brochure of VasoScreen.
(Company Medis Medizinische Messtechnik GmbH Brochure, Angiologic Diagnostic System, Diagnostic support manual, 2012 [14]).

There should be a minimum distance between the current electrodes and the next set of measurement electrodes for two main reasons. Firstly, within a distance of approximately 3 cm around the current electrode, the electrical field becomes highly unpredictable, which could result in significant measurement errors. Secondly, the measuring current requires ample space to evenly disperse across the entire cross-section of the measurement segment. Without this, the measuring electrodes would only cover a portion of the measurement segment [14].

This process has to be started by entering the patient's name and selecting "Pulse wave analysis". It is important to check the values of the basic impedances shown on the

measurement instrument after positioning the impedance electrodes as previously indicated. Less than 150 Ohms should be valued. If they are higher, the distance should be reduced between the measuring electrodes (red and yellow electrodes, respectively). There may be edema or inadequate electrode-skin contact if the electrodes are symmetrically positioned on both sides and the side difference between basic impedances is greater than twice. If a -E- appears in place of a number, either there is not enough contact between the electrode and the skin, or there is too much space between the current electrodes, then place the electrocardiogram (ECG) electrodes. After that, it is necessary to wait until the computer screen displays curves free of artifacts, click the "Calculation" button to determine the parameters, and stop the measurement. The curves are now examined and shown once more. If doctors want to measure the pulse wave at different locations, the measurement needs to be saved. Besides, they need to reposition the electrodes and begin the measuring process [14].

2.4. Parameter analysis

The examination is typically evaluated in two steps: firstly, by examining the shape of the pulse wave to assess its quality, and secondly, by analyzing the automatically calculated parameters to measure the results. When examining the lower extremities, it's also feasible to identify pathological processes through repeated measurements at various sites such as the foot, calf, and thigh. Analyzing the pulse wave's shape enables rapid identification of pathological changes, as arterial diseases frequently induce characteristic alterations in the pulse wave's shape [14].

Waveforms have distinctive characteristics in terms of peak waves (sharp, obtuse, domed) and sub waves (clear, blurred, absent). Normally, the curve has sharp peaks and clear sub-waves. The assessment of vascular tone during a cardiac cycle involves the evaluation of several points. The A-wave marks the onset of the systolic wave and denotes the atrial depolarization. The B-wave is crucial in determining the opening of the aortic valve. The C-wave signifies the first peak of the systolic wave and is used to measure the maximum systolic flow rate. The X and Y points represent the closing of the aortic and pulmonary valves, respectively. The segment between the end of the B-wave and the onset of the X-wave is known as the left ventricular ejection time (LVET) segment, which denotes the duration of systole, or the period during which blood is ejected into the systemic circulation. The ideal signal in the extremities exhibits clear systolic and diastolic waves, and the amplitude of particular points with noticeable changes in their value can be utilized to determine vascular tone.

Six parameters, which are used to evaluate vascular tone and the intensity of blood flow, are presented in Table 1. Crest time (CT) and crest width (CW) represent two of the main parameters for evaluating vascular tone. Additionally, conduction time and elastic index alpha/T serve as other potential indicators. Conduction time (ms) represents the time from the starting point of the QRS complex of the electrocardiogram to the beginning of the appearance of the blood flow wave. Short conduction time increases vascular tone, and vice versa. The elasticity index reflects the elastic properties of the arterial vessel wall, calculated as the percentage between the ascending branch time and the duration of a peak wave cycle. The elasticity index increases when blood vessel elasticity decreases or blood vessel tone increases. Furthermore, parameters related to the intensity of blood flow can be assessed. The slope percentage, also known as the angle of the tangent line to the ascending branch, indicates the ratio between the steepest slope of the ascending branch and the background impedance.

This measure can be used to assess vascular tone. The impedance ratio is calculated as the ratio of the received wave amplitude to the reference amplitude. Alternating blood flow reflects the amount of blood pumped during a heartbeat and helps assess PAD, though it doesn't measure actual blood flow. Similarly, harmonic content, derived from Fourier coefficients, indicates vascular conditions but is sensitive to poor signal quality. Both parameters serve as useful diagnostic tools but have limitations in accuracy [14].

Table 1. Main parameters on blood flow results.

(Company Medis Medizinische Messtechnik GmbH Brochure, Angiologic Diagnostic System, Diagnostic support manual, 2012) [14]

Parameters	Definition	Unit	Normal	Pathological	Remarks
Crest time	CT is the time from the first starting point to the maximum pulse point of the REC wave in seconds.	ms	<150 ms	Larger >200 ms	This parameter represents the time delay of the maximum of the pulse curve and is increased in case of compensated occlusions and stenoses.
Crest width	CW is the time delay between two curve points on either side of the curve, maximum at a level of 95% of the amplitude.	ms	<80 ms	Larger >90 ms	This parameter represents the shape of the maximum of the pulse curve and is increased in case of well-compensated occlusions; no changes in cases of stenosis or arteriosclerosis.
Impedance quotient	Impedance is the ratio of amplitude and basic impedance; very often called the rheographic quotient.	p.m	>0.7 p.m	Smaller <0.5 p.m	This parameter represents the size of the pulse wave, but it depends on a range of factors, resulting in potential variations.
Slope quotient	Slope quotient is the ratio of the maximal slope and the basic impedance.	mOhm/Ohm/s = p.m/s	>9 p.m/s	Smaller <6 p.m/s	This parameter represents the systolic slope of the pulse curve and is decreased in the case of proximal and well-compensated occlusions and stenoses.
Alternating blood flow	This parameter is an expression for the amount of	%/min	22%/min	Smaller < 18%/min	This parameter is used to evaluate the severity of peripheral

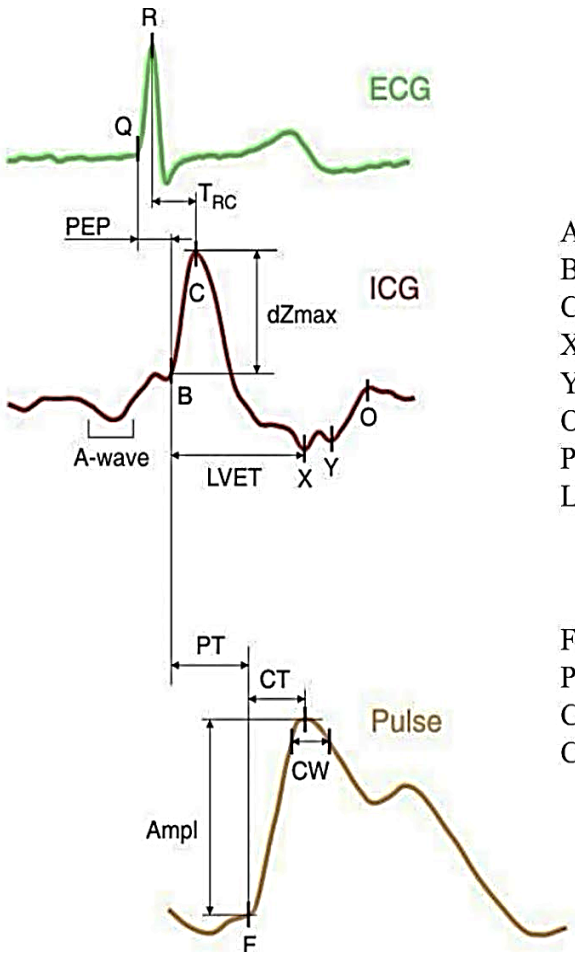
Parameters	Definition	Unit	Normal	Pathological	Remarks
	blood pumping through the measuring segment during a heartbeat and is calculated using the parameters amplitude, CT, heart period, and basic impedance.				obliterative arterial diseases and is very sensitive to pathological changes. However, this parameter is not an expression of the real blood flow.
Harmonic content	Harmonic content is the sum of the 2^{nd} to 6^{th} Fourier coefficients of a pulse curve, normalized to the 1^{st} harmonic (fundamental frequency), which is set to 100%.	%	> 100%	significantly below 100 %	This parameter is reduced in case of compensated occlusions and atherosclerotic changes, but is very sensitive to bad signal quality.

Figure 3 shows that the monitoring of limb operations is closely associated with breathing and ECG. Point A marks the beginning of the arterial blood wave, where the vessels begin to expand, and the bloodstream enters the small arteries and capillaries in the segment. This point is useful to normalize the baseline of the bioimpedance signal and to approximate the signal to the ideal state. In addition, waveforms must be carefully studied since they can be altered in a wide range of conditions. There are two types of peak waves (sharp waves, blunt waves, dome waves) and secondary waves (clear waves, blurred waves) that need to be considered. The ECG electrodes should be placed with the red electrode on the right wrist, the yellow electrode on the left wrist, and the black electrode on one of the wrists, near the red or yellow electrode. In most cases, the black electrode is not needed.

Almost everyone knows about electrical resistance, which is an electrical measurement of resistance between two points of a conductor when a constant potential difference of one volt (V) is applied to those points and a current of one ampere (A) is produced. In the equation $R=\frac{E}{I}$, R is called resistance and has units of ohms (Ω), I represents the electric current in amperes (A), and E represents the voltage in volts (V). Although this relationship is widely recognized, its use is limited to only one circuit element - the ideal resistor. This type of resistor has several characteristics that make it easier to work with, including consistent adherence to Ohm's Law at all current and voltage levels, resistance value that does not depend on frequency, and in-phase AC and voltage signals [18].

However, in the real world, circuit elements exhibit much more complex behavior. As a result, they have used the concept of impedance, which is a more general circuit parameter, instead of resistance. While resistance measures a circuit's ability to resist the flow of electrical

current, impedance is not limited by the simplifying properties of resistance. Electrochemical impedance is measured by applying an AC potential to an electrochemical cell and then measuring the current through the cell. Assume that they apply a sinusoidal potential excitation. The response to this potential is an AC signal. This current signal can be analyzed as a sum of sinusoidal functions (a Fourier series). In addition, electrochemical impedance is normally measured using a small excitation signal. This is done so that the cell's response is pseudo-linear. In a linear (or pseudo-linear) system, the current response to a sinusoidal potential will be a sinusoid at the same frequency but shifted in phase [18].



A- wave - the contraction of the atrium
B - Opening of the valve
C - Max systolic flow
X - Closing of the aortic valve
Y - Closing of the pulmonary valve
O - Opening of the mitral valve
PEP - Pre-Ejection Period
LVET - Left Ventricular Ejection Time

F - Foot (base point)
PT - Propagation time
CT - Crest time
CW - Crest widthAmpl - Amplitude

Figure 3. Left: Electrocardiography, impedance variation (ΔZ), and impedance cardiography signals. Right: Waves, notches, and intervals of impedance cardiography signal and corresponding events.

(Yazdanian H, Mahnam A, Edrisi M, Esfahani MA. Design and Implementation of a Portable Impedance Cardiography System for Noninvasive Stroke Volume Monitoring. J Med Signals Sens. 2016 Jan-Mar;6(1):47-56. https://pubmed.ncbi.nlm.nih.gov/27014612/) [19].

Every fundamental structure with an electrical line passing through it has resistance to the electrical line, just like other materials do. The resistance of a material is directly proportional to the resistivity and length of the conductor and inversely proportional to its area.

$$R = \frac{pL}{A}$$

In this equation, ρ is the resistivity of the conductor, L is the length of the conductor, and A is the cross-sectional area. The connection between that unit's capacitance (c) and inductance (L) creates another barrier (X). That sum can be written as follows if we call it Z: Z = R + X. And then there is the complete metamorphosis:

$$\Delta Z = \Delta R + \Delta X$$

The human body can conduct electric current. The main charge carriers in them are ions. Blood as a distinct electrolyte is characterized by the lowest resistance ($\rho \approx 1.5$ Ohm.m), while the other tissues are much higher in resistance ($\rho \approx 5.5$ Ohm). Blood impedes significantly less than other tissues, such as muscle or bone. As a result, blood volume variations in a particular body segment can lead to measurable changes in the electrical impedance. Specifically, an increase in blood volume in a body segment is associated with a decrease in impedance, which can be used to estimate blood flow [7].

2.5. Diagnosis of some diseases of the lower extremities using rheography

Rheography is utilized for diagnosing and promptly identifying arteriosclerosis, chronic or acute arterial vascular diseases, and functional circulatory issues. It is also employed in monitoring at-risk patients such as diabetics, smokers, and individuals over 50 years old, as well as for postoperative assessments following vascular surgeries. Additionally, it is used to assess the effects of pharmaceuticals on the vascular system (Figure 4) [14].

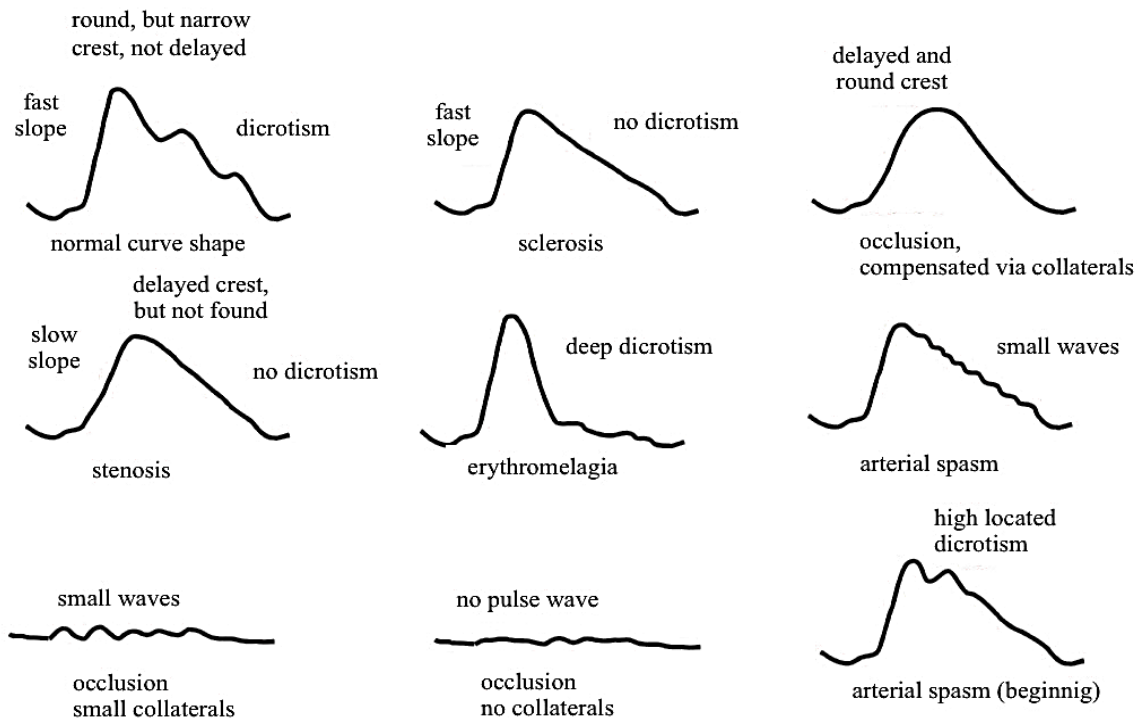


Figure 4. The pulse wave's curve shape.

(Company Medis Medizinische Messtechnik GmbH Brochure, Angiologic Diagnostic System, Diagnostic support manual, 2012 [14])

2.5.1. Peripheral arterial occlusive disease (PAOD)

In patients with normal limb blood flow, the blood flow index (BFI) remains consistent across different limb segments, and the dZ/dt waveform amplitude gradually

decreases from the thigh to the ankle due to normal circulation resistance. Diastolic pulse arrival time (DPAT) values remain within the normal range. However, in cases of arterial blockage, BFI decreases below the occlusion site, which decreases in the measuring sites further from the heart, while the dZ/dt waveform shows a sharper amplitude drop below the blockage. DPAT values begin to rise and increase in segments further from the heart, indicating delayed blood arrival [20]. Reactive hyperemia can be used to predict vascular diseases. Lower reactive hyperemia is linked to increased cardiovascular risk, especially in patients with peripheral arterial disease [21].

Reactive hyperemia is a critical measure in assessing endothelial function, as its magnitude and speed indicate vascular health. A study on cardiovascular patients (with a mean age of 76.1±9.6 years) comparing blood flow during reactive hyperemia found significantly higher peak ABF in healthy individuals (24.8 ±1.6) compared to patients with intermittent claudication (10.5 ±1.3) and those experiencing rest pain (5.3 ±0.5, $p < 0.0001$). The study also found a strong negative correlation between CT and the ankle-brachial index (ABI) ($r = -0.699$, $p < 0.001$), indicating that as arterial circulation worsens (lower ABI), CT increases. ABF and pulse amplitude (Pampl) showed moderate positive correlations with ABI, though Pampl's correlation was only observed in men. CW did not correlate with ABI, suggesting it is not a reliable diagnostic marker for PAOD [22].

2.5.2. Atherosclerosis

Atherosclerosis leads to significant changes in waveform morphology, including a pronounced flattening and reduction in amplitude, particularly in cases of severe arterial occlusion. These waveform alterations provide insight into the extent of arterial thickening and stiffness [23].

A large-scale study involving 1,741 adults aged 30-45 years assessed the relationship between bioimpedance-derived pulse wave parameters and markers of subclinical atherosclerosis. The study found that the risk score derived from selected pulse waveform parameters was the third strongest predictor of carotid intima-media thickness, suggesting that impedance-based measurements provide important insights into early arterial thickening. Additionally, the risk score was the second strongest predictor of flow-mediated dilation, highlighting a significant association between impedance-derived pulse wave parameters and endothelial function. For carotid artery distensibility, the risk score emerged as the strongest predictor, surpassing pulse wave velocity and other conventional measures. These findings underscore the potential of bioimpedance-based pulse waveform analysis as a reliable method for early detection of atherosclerosis. It provides valuable information on arterial elasticity and compliance, making it useful for cardiovascular risk assessment. The combination of IPG, impedance cardiography, and tissue IPG could enhance risk stratification beyond traditional diagnostic tools. Given its noninvasive and cost-effective nature, impedance-based testing has the potential for widespread use in large-scale cardiovascular screenings [24].

2.5.3. Cardiac autonomic neuropathy in gestational diabetes

Unlike other vascular conditions, cardiac autonomic neuropathy in gestational diabetes does not exhibit distinct IPG waveform abnormalities. However, affected individuals show reduced heart rate variability (HRV), indicating autonomic dysfunction [25].

A case-control study examined the role of IPG in detecting vascular changes and autonomic dysfunction in mothers with gestational diabetes. The study found that HRV was significantly impaired in these individuals, suggesting early dysfunction of the autonomic nervous system. Since cardiac autonomic neuropathy is a known complication of diabetes, this finding supports the hypothesis that gestational diabetes may contribute to early autonomic dysfunction, potentially increasing the risk of long-term cardiovascular complications. These findings highlight the potential of IPG as a noninvasive screening tool for detecting autonomic dysfunction in gestational diabetes. Early identification of HRV impairment could allow for timely interventions to prevent future complications. The ability to use IPG for this purpose expands its clinical utility beyond vascular assessments, offering an additional diagnostic application in the context of metabolic disorders [25].

2.5.4. Deep vein thrombosis (DVT)

The test for DVT requires a temporary artificial venous occlusion. Venous capacity is normally 4–7% (ml blood/100 ml tissue) but decreases to <2% in thrombosis due to insufficient venous emptying when legs are raised, though results vary with leg height. Volume displacement is normally positive (>0%), reflecting a decrease in venous volume after occlusion test, but this value is reduced in thrombosis due to impaired venous tone. Venous outflow is >35%/min (2s after occlusion test) and >50%/min (3s after occlusion test) in healthy veins, but drops below 35%/min in thrombosis, indicating obstruction, especially in high-leg or pelvic thromboses. Outflow time is constant after artificial occlusion is normally 2–6s, but exceeds 6s in thrombosis, indicating prolonged venous drainage. Outflow index is >40% (3s after occlusion test) and >50% (5s after occlusion test) under normal conditions but falls below 40% in thrombosis, reflecting reduced venous outflow [14].

A comparative study evaluated the diagnostic accuracy of IPG and compression ultrasonography against ascending contrast venography in hospitalized patients. The results showed that for proximal DVT, IPG had a sensitivity of 96%, specificity of 83%, positive predictive value of 82%, and negative predictive value of 97%. While contrast venography remains the most accurate method for diagnosing DVT, it was not feasible for 20% of patients in the study, making IPG a more practical alternative in many clinical settings [26].

2.5.5. Drawbacks of rheography and comparisons with other diagnostic methods

The accuracy of rheography depends greatly on the expertise of the reader. Since the results are presented as waveforms, the reliability of the diagnosis is influenced by the reader's interpretation. Additionally, rheography's accuracy varies depending on the size and placement of venous thrombi. In comparison with Doppler ultrasound, rheography performs better in diagnosing treatable thrombosis (95%) [27]. In comparison with venography, despite venography being more reliable, rheography remains a promising screening tool. IPG was positive in 77 of 79 limbs with acute deep vein thrombosis proximal to the calf. It was positive in 6 of 27 limbs with a clot isolated in the calf. Only 7 false-positive plethysmograms were found in 161 normal contrast venograms [28]. However, rheography is prone to false-positive results in cases of chronic venous insufficiency or isolated iliac vein thrombi; false-negative results are also more likely in patients with proximal vein thrombosis and small thrombi, namely clots isolated in the calf [27], [28].

III. RESEARCH PROSPECTS

Despite its advantages, rheography is still seen as an unfamiliar testing method that is only performed in a few major health facilities in Vietnam. This lack of accessibility to rheography means that many patients who may benefit from it are unable to access it. Therefore, there is a need for more awareness and education among healthcare providers and patients on the benefits of rheography in diagnosing peripheral arterial disease.

Rheography holds promise for future advancements in non-invasive medical monitoring. Research can focus on improving signal analysis to differentiate between various blood flow issues and identify specific pathologies. Researchers might explore rheography's potential in specific conditions like diabetic foot ulcers or lymphedema, potentially leading to improved monitoring and management strategies. Finally, advancements in miniaturization could pave the way for more portable and user-friendly rheography devices, expanding their clinical applications and accessibility. In addition, future research needs to determine how plethysmography and rheography techniques perform in combination with other diagnostic modalities. The question is whether their diagnostic performance is independent, adding valuable additional information at a low cost and with little inconvenience, or if they do not provide any useful additional diagnostic information.

Figure 5 summarizes the key findings of this paper, including current knowledge of the principles of rheography, six key parameters used to measure changes in blood flow, and vascular conditions assessed through rheography.

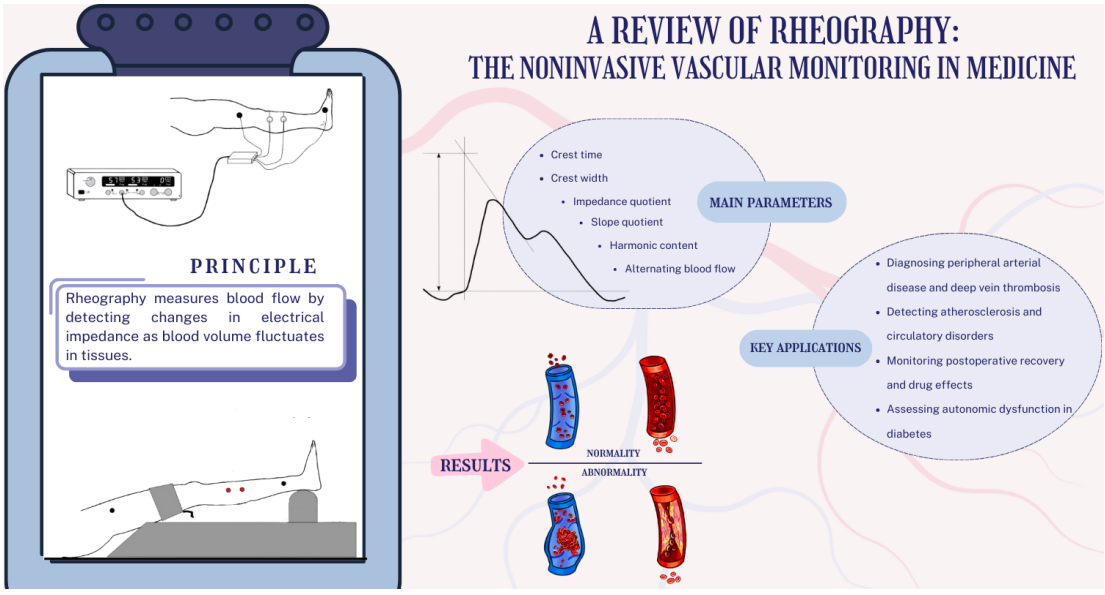


Figure 5. Graphical abstract of the usage of rheography in vascular monitoring
This figure was redrawn and summarized from the brochure of VasoScreen.
(Company Medis Medizinische Messtechnik GmbH Brochure, Angiologic Diagnostic System, Diagnostic support manual, 2012 [14]).

IV. CONCLUSIONS

In summary, rheography or IPG is a non-invasive technique for determining the extremities' blood flow. Compared to other testing methods, rheography is considered to be a more sensitive and more affordable way to diagnose PAD. Impedance analysis, which is part of the rheography process, is a method used to measure the total resistance of an object against the electrical current passing through it. More future studies are needed to explore the mechanism, necessary equipment, techniques, and the analysis of rheography test results.

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