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Microprocessor-based air plethysmograph for the examination of compressed tissue of limbs

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Purpose: The aim of the article is to propose a simple microprocessor-based air plethysmograph that uses a measurement of changes in air pressure in a closed cuff to determine the changes in the volume of the compressed limb. *Methods*: The microprocessor-controlled measurement system applied pressure to the object (ultimately the limb) by pumping air into the cuff surrounding the object. Changes in pressure and air temperature in the cuff over time were recorded. The results supplemented with the calibration procedure made it possible to determine the changes in the volume of the object. *Results*: Measurement-independent calibration and temperature correction of pressure changes in the system proved to be necessary components of the measurement procedure for volume changes. When comparing the device test results with the actual changes observed with the limb model, there was a discrepancy between 0.2 and 0.7 percent of the total volume under the cuff. *Conclusions*: Studies have shown that the proposed air plethysmograph is useful for assessing the changes in the volume of the limb model within the range that are expected in the diagnosis of lymphedema. The solution is a cheaper and less complicated alternative than most of the available methods of measuring changes in the volume of edema tissue under controlled pressure.

Key words: *plethysmography, volume change measurement, lymphedema, theranostics*

1. Introduction

Plethysmography is a term used to describe several test methods for measurement of volume changes [13], which differ from each other in terms of the range of application and the principle of operation. The best known of those methods are *body plethysmography*, which measures mainly changes in lung volume between inhalation and exhalation [6], as well as the standard methods used for cardiovascular diagnosis: mercury-in-silastic strain gauge plethysmography (SGP) [8], [14], air plethysmography (APG) based on large cuffs covering a half of the limb [3], [5], chamber plethysmography with sealed chamber with rigid walls where the limb is placed [2], [22] and segmental plethysmography where smaller compression cuffs are used [2], [21]. Videoplethysmography, to measure volume changes from video recording [18], [20], or laser plethysmography using noncontact laser displacement sensors [7] are novel methods in this group.

In the context of the study of long-term changes in the volume of limbs affected by lymphedema, plethysmography is often referred to as a method based on the measurement of the amount of water displaced by a submerged part of the body [1]. On the other hand, measurements of changes in limb circumference with lymphedema as a result of pneumatic massage are performed with the help of SGP [16], which is typically used for blood flow monitoring.

Lymphedema is a disorder where too much lymphatic fluid is accumulated in a limited part of the soft tissues of the human body [11]. According to the current knowledge on lymphedema, its diagnosis by measurement of the properties of the subcutaneous tissue and selection of the parameters of effective compression therapy through the use of cuffs, sleeves,

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stockings, bandages or mixed methods require an assessment of tissue stiffness and its susceptibility to lymphatic fluid removal [17]. Publications on this subject matter contain descriptions of various methods of measurement of changes in the volume of the body, not necessarily related to the problems of swelling [4], [10], [19].

The simplest of these methods is a measurement of the circumference, which is used mainly for limbs and makes it possible to determine the volume on the assumption that the limb is cylindrical or conical. The accuracy of this method is between +/–8% and +/–6% of the measured volume, depending on the number of planes in which the circumference is measured and the method of approximation of the volume based on the measured circumference [4]. Slightly better accuracy can be achieved using controlled immersion of the limb in water and measurement of the volume of liquid that has been displaced. The accuracy of the measurement is between +/–2% of the measured volume in the case of lower parts of legs and +/–8% in the case of fingers [4], [10]. A group of volume measurement methods that have been developing rapidly is techniques based on optoelectronic measurements. They are characterized by accuracy of +/–2% of the measured volume and lower dependence of the result on the researcher's experience compared to measurements of the circumference or water plethysmography [4]. Other technically advanced methods of volume measurement include 3D Ultrasonography (US), Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). US methods, due to divergence of wave beam, have poor resolution (about 5 mm) compared to CT, which reaches up to 0.2 mm spatial resolution, and MRI for which the resolution is approx. 1 mm [4]. The above-mentioned methods of measurement of limb volume or volume changes include techniques that are simple and cheap (circumference measurement, immersion method) but are characterized by significant inaccuracy, as well as more precise methods which, however, require expensive, specialized and not commonly available diagnostic equipment (SGP, Ultrasonography, CT, and MRI equipment).

Current knowledge on limb lymphedema indicates that systematic and long-term compression massages can be an effective tool for inhibiting its development [16]. Due to the nature of such treatment of lymphedema, in affluent countries, patients have adequate massage equipment at home at their disposal, which allows them to conduct massage sessions by themselves and at the appropriate frequency. An important drawback of this situation is the lack of tools to control the effects of home therapy in the form of a simple to use and safe plethysmograph, with which the patient could independently assess the changes in the properties of the tissue. Given the fact that the optimal solution would be an apparatus that could be combined in one system with compression therapy equipment, an attractive candidate for such a plethysmograph is an air plethysmograph. Air and segmental plethysmographs are usually perceived as devices that support the diagnosis of the condition of the circulatory system [5], [9], [15], [21], whereas, in this paper, we consider the use of a similar tool to diagnose lymphedema.

This paper aims to describe a microprocessor air plethysmograph that can be used for measuring changes in the volume of limbs under pressure. The key idea of the measurement is using thermodynamic relationships for a closed system with a cuff wrapped around a limb, measuring changes in pressure and temperature. In addition to a description of the apparatus, the method of tests, the tests results, and a discussion of the capacities and limitations of the proposed system are presented. A significant advantage of the presented plethysmographic method is the combination of compression and measurement of the changes in the volume occurring as a result.

2. Materials and methods

In this section, the details of the construction of the measuring device, the test and calibration algorithm, the mathematical model necessary for data interpretation and the methodology of the device validation on the limb model are presented.

2.1. Device description

The block diagram of the measurement system of the plethysmograph is shown in Fig. 1. The system consists of a pneumatic and electronic subsystem. The arrows in the diagram illustrate the flows of electricity, compressed air mass and information (on/off and data signals) within and between subsystems. The pneumatic subsystem consists of an air pump (type JQB2428003), a valve (solenoid valve 6VDC) that closes and opens the outlet of air from the system, a pressure cuff (Erk Green Cuff) used to examine the object, a rigid air tank, and a calibration syringe that allows for controlled changes in the volume of the pneumatic system.

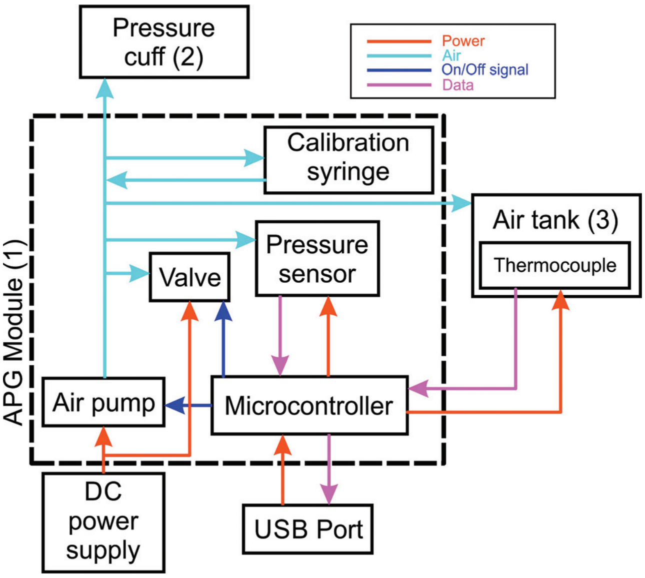


Fig. 1. The block diagram of the measuring system and connections between its elements: (1) Air Plethysmograph Module, (2) pressure cuff and (3) air tank, distinguishing between flows of electricity, gas mass and information

The central element of the electronic subsystem is a microcontroller (Arduino Leonardo) which converts the signals from the pressure sensor (P51-03-G-UC-I36-4.5V-000-000) and the temperature sensor (type K thermocouple) into information about the status of the pneumatic circuit. This information is used by the microcontroller program to turn on or off the power of individual components (air pump, valve). In order to limit the role of the non-uniform temperature field, the temperature sensor was placed at a considerable distance from the walls inside the rigid steel tank. The microcontroller enables the transmission of measurement data in digital form to a computer via USB port.

2.2. Algorithm of operation

The algorithm of the plethysmograph is the sum of what the operator of the device does and what the microcontroller program performs and can be divided into the following four stages:

- the initial stage – when the device is switched on, the microcontroller waits for the procedure to be started;
- the cuff inflation stage – when air is simultaneously pumped and the pressure level is controlled until the desired limit is reached;
- the measurement stage – starts after the completion of the air pumping process and continues until the pressure and temperature stabilize;
- the calibration stage – provides data for interpreting the measurement results. After that, the device can be manually turned off.

The microcontroller's program operates in a loop, providing measurement results at a selected frequency (normally limited to 4 measurements per second). The developed air plethysmograph uses an air bladder cuff, similar to that used to measure blood pressure. The position of the pressure cuff bladder and its effect on the test object (ultimately on the soft tissue of the limb) are shown schematically in Fig. 2a. The cuff is placed on the test object and the cuff is pumped with an air pump to a physiologically acceptable pressure (max. 120 mmHg). Then the air pump is turned off and, thanks to its internal structure, air is not released from the system by the pump. While maintaining a constant mass (number of moles) of air in the system, pressure and temperature are recorded as a function of time. Due to the high tensile stiffness and slight deformation of the fabric on the outer surface, the changes in volume and pressure in the cuff bladder are mainly the result of a reduction in the volume of the object compressed by the cuff. After the pressure and temperature have stabilized, controlled changes in the system volume are made and the pressure is measured for calibration. The entire procedure is shown schematically in Fig. 2b.

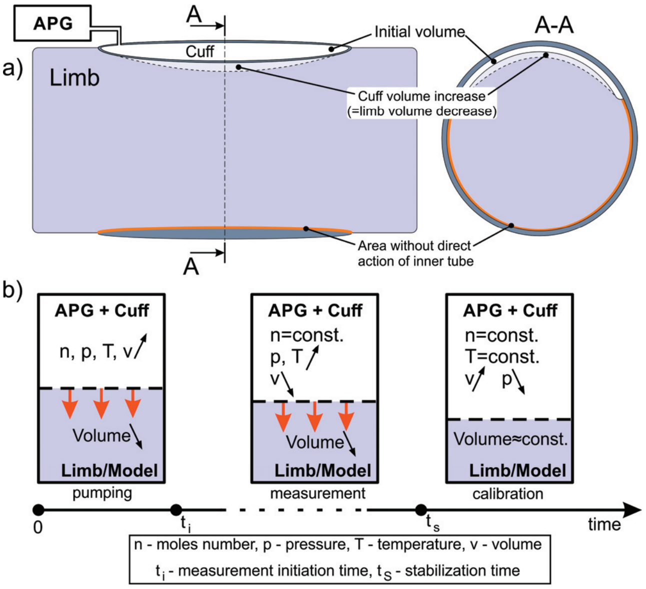


Fig. 2. Test procedure: (a) diagram illustrating the position of the inflatable cuff and its effect on the limb, (b) measurement scheme

2.3. Interpretation tools

The data collected from the test and calibration can be used in the interpretation process with the help of a simple mathematical model. It is assumed that the test begins with a relatively rapid injection of air into the system (including the cuff) during which pressure, volume, mass of air and air temperature increase over time. After reaching the maximum assumed pressure, the pump is turned off and the actual test begins. During this process, the air mass does not change, but there are changes in the air volume (v) in the system due to the deformation of the object subjected to the cuff pressure. The changes in volume are accompanied by changes in absolute pressure (p) and temperature (T), which are recorded values. The ideal gas equation is used as the basis for the interpretation of the test results

$$pv = nRT\,, \tag{1}$$

where n denotes the number of moles and R is the gas constant.

Depending on the rheological properties of the tested object (ultimately the soft tissue of the limb), after a certain time of the test duration, changes in the volume under the chamber cease. As a result of heat exchange with the environment, the temperature stabilizes at the level which we denote as T_s and assume that this is the end of the test. The expression on the right side of Eq. (1) then takes the constant value C, i.e.,

$$nRT_s = C\,. \tag{2}$$

Calibration (the last stage of the proposed procedure) is aimed at determining the C parameter. It is assumed that the calibration process takes place while maintaining the temperature at the T_s level and with the same amount of air in the system. To ensure these conditions, the calibration should be performed on the same object as the test. Changes in air volume controlled with a calibration syringe and recorded changes in pressure in the chamber for isothermal conditions for ideal gas are described by Boyle–Mariotte law

$$pv = p(v_0 + \Delta v) = C\,, \tag{3}$$

where v_0 denotes the initial volume inside the pneumatic system at the beginning of calibration, Δv is the small volume change inside the pneumatic system driven by the syringe, and p is the total pressure in the system, equal to the reading of the sensor.

As p and Δv change but are registered transforming Eq. (3) to the form

$$p\Delta v = -v_0 p + C \tag{4}$$

we receive the linear equation with p as independent variable and product $p\Delta v$ as the dependent variable, while v_0 and C can be determined using linear regression. Given the value of C for a known and constant temperature T_s from Eqs. (1) and (2), it is possible to eliminate the number of moles n and find the dependence of the volume of air in the system on temperature and pressure

$$v = \frac{C}{T_s}\frac{T}{p}\,, \tag{5}$$

where T and p are quantities varying with time and measured in the test.

2.4. Test, calibration and method validation

The complete prototype of the measurement system with an artificial object (model) simulating a limb is shown in Fig. 3.

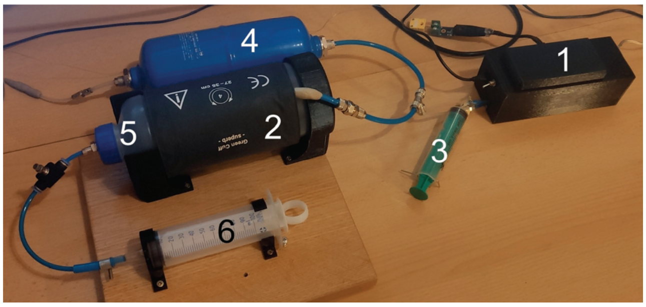


Fig. 3. The prototype of the measuring system: 1 – APG module, 2 – compression cuff, 3 – calibration syringe, 4 – air tank with a thermocouple inside, 5 – the bottle simulating a limb, 6 – graduated syringe

The APG module (1 in Fig. 3) includes a microcontroller, an air pump, a pressure sensor and a solenoid valve. The test object (limb model) was a one-liter, thick-walled high-density polyethylene (PE-HD) bottle. The bottle (5 in Fig. 3) was filled with water and closed with a screw cap with a sealed polyurethane hose connecting the bottle with the syringe. The graduated syringe (6 in Fig. 3) shows the amount of water dispensed from the bottle if the manually controlled needle valve on the hose is open.

During the test of the measuring system, water from the bottle under the cuff flowed into the syringe, the plunger of which was initially blocked, and, after unblocking, it moved under the influence of liquid pressure. After making the test, a calibration procedure is needed (the explanation is given in the part describing the model). Calibration should be performed on the same object for which the test is performed. With the help of a calibration syringe

(Fig. 1), short-term, controlled changes in air volume are forced and changes in pressure in the chamber are recorded.

The course of the syringe plunger movement during the test was recorded with a camera in order to establish the time dependence of its movement, corresponding to the amount of water flowing from the reservoir from under the cuff. This data is then used for method validation including checking accuracy and repeatability.

3. Results

In this section, the results of an example test and calibration with the use of the described plethysmograph on the limb model (a bottle filled with water) and the method validation are presented. The volume changes under the cuff were caused by the flow of water from the bottle through the open valve into a graduated syringe. Independently registered changes in the volume in the syringe by the camera were used to assess the accuracy and repeatability of the measurements with the proposed plethysmograph (method validation components).

3.1. Sample measurement and calibration

In Figure 4, the results of an exemplary measurement of relative pressure p_R (the difference between absolute pressure and atmospheric pressure) and temperature performed with the proposed plethysmograph on a limb model are shown. The model is a bottle-shaped tank filled with water (details of the measuring system and methods are discussed in the previous section). The results include test and calibration, combined. The time after which the cuff is inflated (when the maximum pressure is recorded), marked as t_i, is the start of the data vector used to determine the change in the volume of the object under the cuff. Time t_s signifies the end of the test and the beginning of the calibration stage. The calibration points were determined in six steps, each time increasing the volume of the pneumatic system by another 5 ml, which gave a total range of 30 ml. This volume was determined on the basis of the real changes that occur in the limb affected by lymphoedema after pneumatic massage [23]. It is worth paying attention to the fact that in the initial phase of the test, the temperature changes significantly and then its value stabilizes. During the calibration phase (after time t_s) the temperature remains approximately constant. This confirms the correctness of the assumptions of the models adopted for the interpretation of the results in both stages of the test.

The measurement results obtained in the calibration (pressure and temperature for $t > t_s$) and the Eq. (4) were used to determine the *C* parameter using the linear regression method. In Figure 5, the measurement points and the approximation line which is the result of the regression are shown.

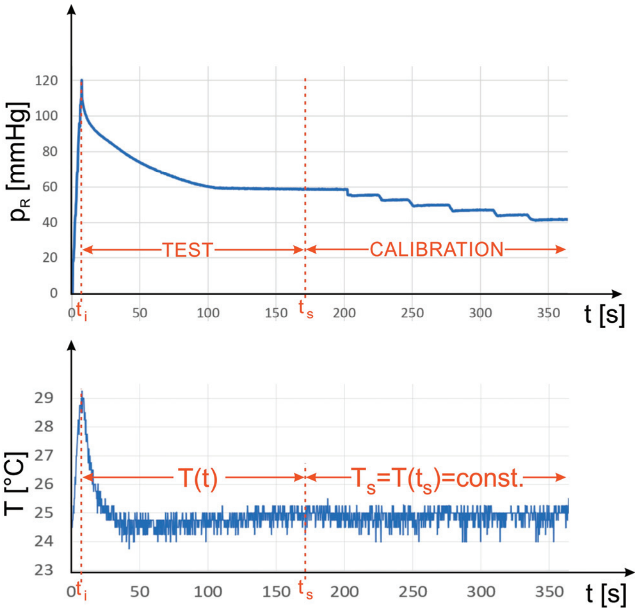


Fig. 4. The results of an exemplary test and calibration for a limb model: relative pressure and temperature versus time

3.2. Volume changes from plethysmograph and accuracy check

The changes in the volume under the cuff were determined on the basis of the Eq. (5) using the measurements of pressure and temperature and the parameter *C* obtained from the calibration. In order to check the accuracy of the measurement with the plethysmograph, the flow of water from the squeezed reservoir to the connected syringe was recorded independently by means of a video from which the instantaneous volumes were read (recording stopping every second). The comparison of the measurement results from plethysmography and those obtained from video recording is shown in Fig. 6.

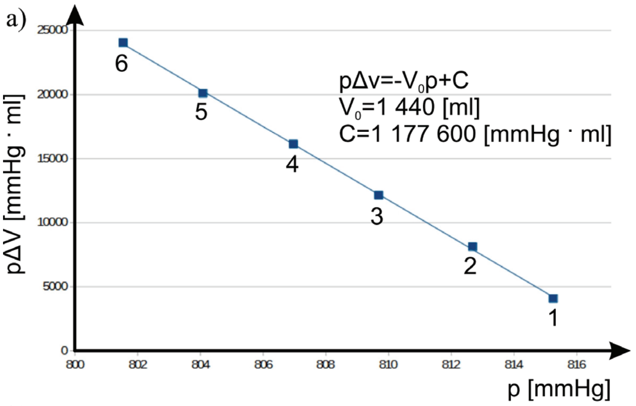
The relative measurement error δ_V was determined by the volume changes measured by plethysmograph

Δv_p and determined from video recording of syringe volume increase Δv_v:

$$\delta_v = \frac{|\Delta v_p - \Delta v_v|}{v_B} \cdot 100\% , \tag{6}$$

where the volume of water in bottle under the cuff was taken as the reference value ($v_B \approx 700$ ml). In the presented example, the average value of δ_v was about 0.26%.

The results obtained for the limb model reducing its volume in a continuous manner indicate that there is a convergence between the independently observed changes of the volume of the model and the obtained results of plethysmographic measurements.



b)

no.	Δv [ml]	p [mmHg]	pΔv [mmHg·ml]
1	5	815.25	4076.25
2	10	812.68	8126.80
3	15	809.69	12145.35
4	20	806.97	16139.40
5	25	804.08	20102.00
6	30	801.54	24046.20

Fig. 5. Determination of the parameter *C*:
a) regression line, b) coordinates of the points

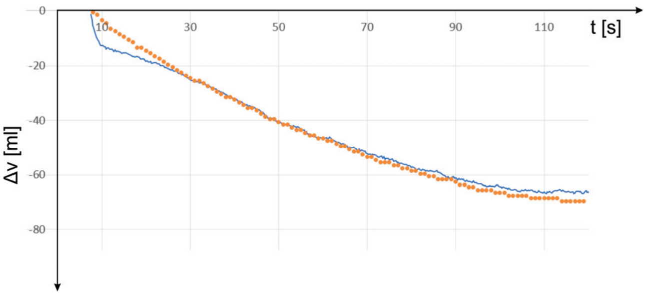


Fig. 6. Comparison of the results of measuring the volume changes from a plethysmograph (blue solid line) and video recording (orange dots) during an experiment simulating the actual measurement on a limb

3.3. Repeatability

The test was repeated several times to ensure that random factors (such as the effect of friction or the position of the cuff) did not have a significant effect on the reported accuracy of the measurement.

To assess the repeatability and, consequently, the reliability of the method under consideration, 8 repetitions of the tests were carried out in succession. For the 60-second test, the values of relative error were determined every 10 seconds.

From these data (for 8 repetitions of the test) the maximum and average values of the δ_v coefficient were determined for individual moments of time and the results are summarized in Fig. 7. The obtained results show that the average values of the δ_v coefficient are at the level of 0.2% and the maximum values are about twice as high. Both the maximum and average differences of volume changes measured by plethysmograph and determined from video recording at the beginning and end of the tests are higher than in the central part, which is confirmed by the result of volume change measurement seen for the single test run, shown in Fig. 6.

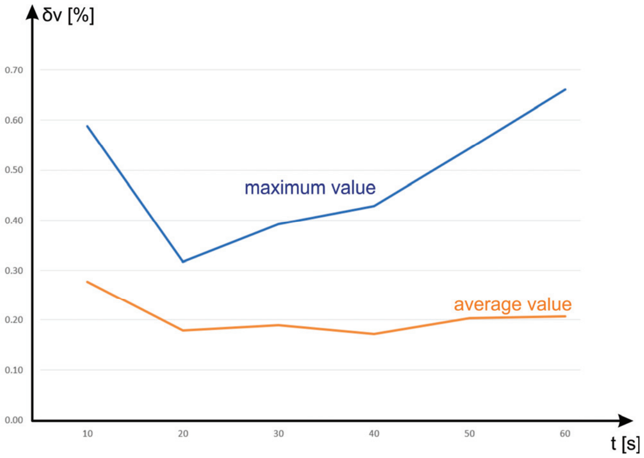


Fig. 7. Maximum and mean relative differences in volume changes measured by plethysmograph and determined from video recording obtained on the basis of 8 repetitions of the test

4. Discussion

In this paper, it was demonstrated that an important element in the interpretation of air plethysmography results, particularly the relatively rapid air pressure changes occurring during cuff inflation, is the coupled process of temperature changes. Accounting for the effects of this coupling on the determination of volume changes has been accomplished in this paper through the proposed calibration procedure, which occurs as an additional test step performed on the same object. The pressure changes realized in the calibration are small and do not generate significant temperature changes. The tests conducted in this work were limited to tests on a model at room temperature. Application of the developed method to limb tests requires taking care of proper thermal insulation of the cuff or temperature correction of volume change results.

The cuff used in the plethysmography method being developed is identical to that used for measuring blood pressure. The air bladder of such a cuff has a dimension that does not guarantee bladder pressure around the entire circumference of the limb model or the limb itself. However, this enables the proposed solution to be successfully applied to limbs of different dimensions and does not require cuff changes. Taking into account the observation that in the part of the cuff where there is no bladder the fabric also exerts pressure on the object under the cuff in the basic version of the interpretation of plethysmography results, it can be assumed that the stress distribution and volume changes are distributed approximately homogeneously around the circumference. In further testing of the solution, it is worth checking what are the effects of the limited bladder dimension on the precise implementation of the volume change measurement.

As a comparative test to evaluate the role of limb temperature or the limited size of the air bladder cuff, one can consider testing with a chamber method that applies compression therapy solutions and uses mercury plethysmography [23]. This method does not require the effects of temperature changes to be taken into account because the assessment of volume changes uses sensors mounted directly on the limb. The pressure chamber, on the other hand, covers the entire circumference. An additional difficulty in accurate plethysmographic measurements to diagnose subcutaneous tissue may be other processes of limb volume change under pressure – including those related to blood circulation and muscle contractions. Isolation of these effects requires the participation of an experienced diagnostician.

In the proposed method of air plethysmography, some technical limitations arise from the non-automatic (manual) conduct of the calibration process. In the next, more advanced and easier to use version of the device, automation of the calibration process can be introduced by adding an actuator to realize precise piston movement of the calibration syringe and extending the function of the microcontroller that controls this actuator with simultaneous acquisition of pressure changes.

A factor that may lead to a wider interest in air plethysmography methods may be the fact that this diagnostic technique can be combined with compression therapy using appropriate hardware solutions. Such a solution would be in line with the method of the so-called teranostics. It is an approach that assumes a combination of therapeutic and diagnostic solutions in search of optimal methods (parameters) of treatment and constant observation of the progress of therapy while minimizing the number of procedures [12].

The plethysmograph presented herein can be an alternative to the methods used so far to measure changes in limb volume. It can be particularly useful for patients with lymphedema. Information on changes in the volume of a limb affected by lymphedema under a given pressure is crucial to determination of appropriate compression therapy parameters and to evaluation of the effectiveness of this treatment. The device is simple, safe and inexpensive. It can be operated by a patient at home, in a similar way as a blood pressure monitor. The ability to perform measurements under a load and the automation of the measurement provided by the microcontroller reduce the inaccuracies associated with the impact of pressure on the sensors (this is the case with mercury strain gages). It is also possible to repeat the tests several times and to digitally record and archive the measured data.

Further development of the measuring apparatus and procedure towards the controlled and faster inflation of the cuff (e.g., from the gas tank) and optimization of the chamber properties and pneumatic elements (to reduce the phenomenon of creep of the cuff tube or tubing materials) may contribute to the increased accuracy of the device. In the next step, clinical trials will also be necessary, in which, unlike model tests, body temperature and its effect on cuff pressure may play a role. In the next stage of work on the device, such a version of the device is going to be prepared that could work independently of the computer (without data transmission from the controller to the computer during the test).

5. Conclusions

The aim of the work was to present a diagnostic device that works as an air plethysmograph and to carry out tests showing its usefulness for the assessment of changes in the volume of an object (model, limb) affected by pressure. The presented research was carried out on a test stand with a model simulating a limb. This made is possible to control the volume changes under the cuff by video recording of the outer graduated reservoir, thanks to which it was possible to determine the accuracy of the measurements performed by the prototype. Registered changes in the measured increment of the volume were similar to the actual changes measured with the camera. Differences may result from errors of the plethysmograph itself as well as from imperfect reading of changes recorded by the camera.

The obtained results give hope that the discussed method can find application in the diagnosis and therapy of people suffering from lymphedema. Further work aimed at greater automation of the device may make it so user-friendly that the patient could be able to perform the procedure without the help of medical personnel.

It is also justified to conduct research with larger and more complex structure cuffs, which may additionally increase the effectiveness of the procedure and expand the range of applications of the device.

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