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Tools for assessment of mechanical properties of tissue with lymphedema. Application of methods: indentation with a membrane model and air plethysmography

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Purpose of research:

The aim of the dissertation is to propose and test two measurement devices: the indentation method with a membrane model and air plethysmography, developed to support the diagnosis of edema diseases - especially lymphoedema.

The model of pressing the indenter into a membrane with a layer of incompressible liquid may be an accurate approximation of the indentation examination carried out on the limb of a person affected by the early stage of lymphoedema. In this context, a model of this kind has not been considered before and it is worth checking its usefulness.

Air plethysmography was previously used at possibly low pressures (below 10 mmHg), minimizing the impact of the pressure itself on the examined limb. The paper proposes a high-pressure version (up to 120 mmHg), which is to combine the effect of pneumatic pressure with the examination of the properties of the compressed tissue. Research work included the design of the device, construction of prototypes and verification of its measurement capabilities.

The work puts forward the following research hypotheses:

1. The membrane model can be the basis for determining the Young's modulus of a thin shell, stretched over an incompressible body, whose Young's modulus is much lower (this is an approximation of the skin model on the fluid-filled subcutaneous tissue);
2. It is possible to construct a device that performs plethysmographic measurement of volume changes at pressures appropriate for compression therapy (up to 120 mmHg).

Tests carried out:

The paper formulates a mathematical model of the membrane, derived from the equations of continuum mechanics. A special case of the problem (a membrane with an incompressible liquid underneath subjected to the pressure of an indenter putting into a certain depth) was solved by numerical methods in the Matlab environment using the Runge-Kutta algorithm. Two versions of the boundary condition for the contact between the membrane and the indenter were involved: ideal slip and no slip (membrane adjacent to the indenter). Neo-Hookean material was adopted for the membrane.

To validate the obtained results, two measuring stations were made:

- one for pre-stretching the membrane;
- one for indentation tests;

and a physical model for attaching the membrane to the water tank. The research tools made it possible to measure the pressure of the membrane on the indenter and the pressure in the liquid under the membrane.

To confirm the hypothesis concerning high-pressure air plethysmography, an extensive plethysmographic measurement procedure was developed, taking into account the possibility of introducing corrections from changes in air temperature in the system and initial calibration using a compressed air container.

In accordance with the developed procedures, three prototypes of the measuring device in various configurations were prepared:

- plethysmograph with manual calibration (version 1);
- plethysmograph with classical calibration and temperature measurement (version 2);
- plethysmograph with automatic calibration (version 3).

In order to verify the measurement efficiency of the prepared prototypes, a physical model simulating a limb was prepared. The model consisted of a water tank made of flexible plastic (allowing the pressure to be transferred to the liquid), which was connected via a throttle valve to a separate tank, equipped with a scale enabling direct measurement of the volume of the squeezed liquid.

The last stage consisted of tests for the model in which the sponge represented soft tissue and for the calf of the author of the research. Based on the results of these tests, a simple procedure for estimating Young's moduli of the tested materials was proposed.

Results and conclusions:

Validation of numerical simulations for the membrane model was carried out by comparing its results with experimental results, using previously determined Young's modulus values. Validation tests showed a significant agreement of theoretical predictions with experimental results ($R^2 = 0,97$ or more).

The tests showed that the membrane model with a layer of incompressible liquid can be used in the design of diagnostic tests and the discussion of their results for edematous tissues - especially for the initial stage of lymphedema.

It is worth developing research on the improvement of instrumentation, enabling conducting indentation tests on patients' limbs and objectivizing their results.

Plethysmographic measurements of volume change were similar to the results of direct measurements. The difference did not exceed 0.8% of the total volume under the compression cuff. Research has shown that the plethysmograph with automatic calibration (version 3 prototype) can also be used to determine the Young's modulus of the tested physical body.

The obtained results give hope that high-pressure air plethysmography will be used in the diagnosis and therapy of people suffering from lymphoedema. Further work aimed at automating the device may make it possible for the end user to perform the procedure without the help of medical staff.

It is reasonable to conduct research with cuffs of a larger and more complex design. It is also worth considering the introduction of resistance pressure sensors as a permanent element of subsequent versions of the device. These elements can increase the effectiveness of the treatment and extend the range of applications of the device.

The work was limited primarily to tests on physical models. The next stage of research should include trials involving patients affected by lymphoedema with the assistance of medical staff.

The obtained results and the formulated conclusions allow us to conclude that the hypotheses adopted in the dissertation have been confirmed.

Keywords: lymphoedema, indentation test, membrane model, air plethysmography, compression therapy