VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Zyta KUZBORSKA

RESEARCH OF BLOOD FLOW AND STRESSES IN THE PATHOLOGICAL BLOOD VESSELS

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

Topicality of the problem

Cardiovascular diseases are the main reason of human's disability and death in the world and Lithuania. Academic literature indicates that every third person in the world die of cardiovascular dysfunction.

Recently scientists of various specialties – medics, biologists, biochemists, biomechanics, and mechanics pay attention to increased circulatory system diseases spread, pay more attention to circulatory system diseases etiology and pathogenesis, to explain circulatory system phenomenon.

Main cardiovascular system diseases are progressive atherosclerosis, arterial hypertension, pathological arteries torsions and more common aneurisms. Mentioned pathological are changing blood vessel diameter, wall thickness and length in various ways. Depending on occurred pathology type and size vary blood flow rate and pressure to the blood vessels wall. When there is particular blood vessels wall geometry variation, local blood pressure increase because of flow variation in the blood vessel. This affects blood vessel wall and cause critical stresses what could lead to blood vessel cracks. Academic literature mostly studies laminar blood flow, blood is taken as Newtonian fluid, physical load and age influence to cardiovascular system is valued.

Blood flow velocity, local blood pressure and stresses values in the blood vessels, when there is particular pathology degree, are important to estimate human working efficiency.

Object of the research

The object of this work – disease pathological blood vessel (atherosclerosis, aneurysm) and blood flow processes in it that depend on physical load, pathology degree and type, age, gender and blood vessel mechanical characteristics.

Aim and tasks of the work

The aim of this work is to examine blood flow characteristics, local blood pressure, stress distribution in the pathological blood vessels dependent physical load assessing blood vessels mechanicals properties variation due to age, gender, blood vessel pathology type; to make simplified human efficiency evaluation methodology.

To achieve aim of the work, these tasks must be solved:

1. To make blood vessel model that let to investigate local blood pressure, stresses in blood vessel pathological places assessing turbulent phenomenon and blood Newtonian fluid features.

2. To explore physical load, blood vessels pathological, age and gender influence to blood pressure and stresses increase in the blood vessels pathological places.

3. Experimentally determine blood flow rates changes in pathological blood vessels assessing age and gender (with different load).

4. Additionally investigate blood pressure and heart rate characteristics variations during set physical load and human working age range.

5. To make an approximate evaluation of efficiency methods.

Methodology of research

To achieve set aims in the dissertation work, analytical, experimental, digital and statistical research methods were used. Blood flow and stresses in the pathological blood vessels modeling was made with finite elements method ANSYS software package.

Scientific novelty

Work novelty is in these main scientific propositions, regularities and summations:

1. Pathological blood vessel model was made assessing geometrical, turbulent blood flow and local blood pressure changes in the pathological places and blood Newtonian fluid features.
2. Physical load, blood vessels pathology degree, age and gender influence dependences to blood pressure and stresses increase were set.
3. Local blood pressure and stresses increase in the pathological blood vessels places evaluation is important to evaluate blood vessels cracks and human efficiency possibilities.
4. Made efficiency evaluation criterions and blood pressure and heart rate interdependences evaluation hodographs are also important assessing human possibilities to specialize to set load.
5. An approximate efficiency evaluation methodology was made.

Practical value

Made work results practical value is shown in these main statements:

1. Made hodographs let according summarized methodology to value physical load, warming up and others factors influence to the humans efficiency.

2. Made criterions let approximately to value human ability to perform set physical work estimating load size and work time.
3. Blood vessels strength dependence on age was established, that let to value human efficiency degree reduction when age is increasing.
4. To have more precise human efficiency evaluation depending on blood vessels pathology degree, age, gender and physical load, human efficiency evaluation methodology was made.

Defended propositions

1. The human efficiency evaluation criterions show two main indexes: working duration and signs of the initial fatigue.
2. Arterial blood pressure and heart rate interdependence hodographs allow determining warming-up's influence for physical work and symptoms of human's health problems.
3. Blood vessels are bursting in case of higher case of local blood pressure's stenosis (atherosclerosis), it determines local blood pressure becomes few times higher than systolic blood pressure.

The scope of the scientific work

The scientific work consists of the general characteristic of the dissertation, 4 chapters, conclusions, list of literature, list of publications and addenda. The scope of the dissertation – 116 pages, 86 pictures and 2 addenda.

1. Cardiovascular System Mechanical Characteristics Research Methods Analysis

This chapter is literature's review. There are scientific works, analysis of blood vessel's injuring influence to parameters of blood flow, injured location's stress and analysis of strength characteristics changes. At the end of the chapter there are written conclusions and adjusting of thesis tasks.

2. Blood flow in the elastic blood vessel model

To have exactly pathological blood vessel processes evaluation, improved and specified elastic blood vessel model was made: considering mechanical arteries features (blood vessel diameter, length, wall thickness, blood vessel pathology level and others), evaluating turbulence phenomenon and Newtonian fluid properties. Thoracic aorta was used for the research.

After analyzing foreign and Lithuanian scientific works, these main blood vessels geometrical shapes groups were chosen:

1. cylindrical shape healthy blood vessel;
2. local blood vessel dilatation (aneurism);
3. symetrical and asymetrical blood vessel diamater stenosis (atherosclerosis);
4. single and dual ("S" shape) blood vessel deflections.

Blood vessel's with one stenosis diameter is D=0.02 m, blood vessel wall thickness – h=0.001 m, total length L=0.11 m, healthy blood vessel length L_S=0.06 m, pathological one length L_P=0.01 m, stenosis diameter $D_P(p)$ from 25 % to 95 % (Fig. 1 a).

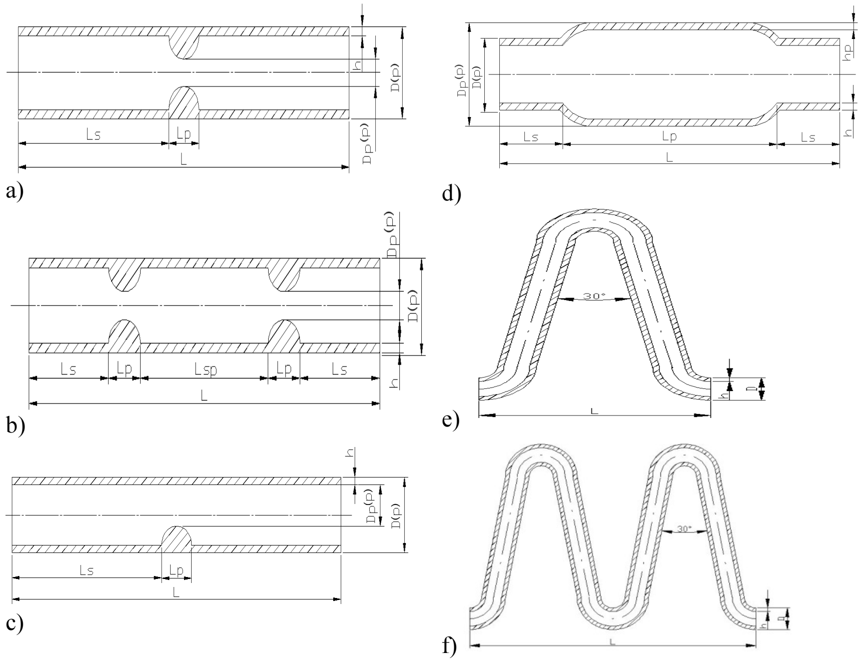


Fig. 1. Model of a blood vessel: a – with one stenosis; b – with two stenosis; c – with single-sided stenosis; d – aneurysm; e – with one deflections; f – with dual deflections

Blood vessels with two stenosis healthy blood vessel length L_S=0.03 m, healthy blood vessel length between pathology locations L_{SP}=0.03 m, pathological one length L_P=0.01 m, stenosis diameter $D_P(p)$ from 25 % to 95 % (Fig. 1 b). Blood vessels with single-sided stenosis healthy blood vessel length L_S=0.05 m, pathological one length L_P=0.01 m, stenosis diameter $D_P(p)$ from

25 % to 95 % (Fig. 1 c). Healthy blood vessel diameter D=0.02 m, aneurysm diameter D_P=0.05 m, healthy blood vessel wall thickness – h=0.001 m, aneurysm wall thickness – h_P=0.0005 m, blood vessel total length L=0.11 m, healthy blood vessel length L_S=0.02 m, aneurysm length L_P=0.07 m (Fig. 1 d). Blood vessels with one deflection (Fig. 1 e) and two deflections (Fig. 1 f) diameter is D=0.02 m, blood vessel wall thickness – h=0.001 m, blood vessel length L=0.11 m, deflecyion angle 30°.

Blood vessels models volumes was made using finite elements method and divided into rectangular elements. The research was performed using two-dimensional healthy and pathological artery model, which is made from two components – flowing blood and elastic blood vessel wall, exposed to blood pressure and velocity variation, when blood vessel pathology form and size are varying; mentioned parameters influence to blood vessel wall was investigated.

These assumptions will be used in the work:

1. Blood Newtonian, blood dynamic viscosity μ=const (Mandal 2005).
2. When there is laminar blood flow, Reynolds number Re=1700, turbulent blood flow – Re=7800 (Ethier *et al.* 2007).
3. Blood temperature is constant t=const.
4. Blood vessel has linear elasticity characteristic E=const (Milnor 2009).
5. Stationary blood flow in the segment is not pulse like, because blood system almost always is pulse like (Long 2001).
6. Chosen blood vessels is without mechanical defects, wall thickness is the same.
7. There is normal stress in the blood vessel wall and shear stress is second and is not evaluated.

Navier-Stokes (1), elastic body equations (4 and 5) have been solved in this study using finite elements method ANSYS software package.

Turbulent blood flow in the pathological blood vessels locations was chosen making blood flow model, blood Newtonian, blood flow velocity v=0.5 m/s, blood dynamic viscosity μ=0.0035 kg/ms, blood density ρ=1060 kg/m^3, blood medium temperature t=37 °C, blood vessel diameter D=0.02 m, length L=0.11 m. Extreme limits of research in blood vessel were set so every calculation impulses of arterial pressure are consistently increased $p \in [16, \ldots, 27]$, kPa ($p \in [120, \ldots, 200]$, mmHg).

The blood flow was examined by solving Navier-Stokes equations for equilibrium form Newtonian fluids (Ethier *et al.* 2007):

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\eta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right),$$
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial x}+\eta\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right), \tag{1}$$
$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial x}+\eta\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right).$$

Continuous flow equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\,\cdot \tag{2}$$

Whereρ, η – fluid density; u – blood floe velocity; ∂ – differentiation operator; p – pressure; u, v, w – velocity components along x, y and z axis.

Blood flow elastocity module E=4.66 MPa, Puason rate ν=0.49, blood vessels walls density ρ_2=1100 kg/m^3.

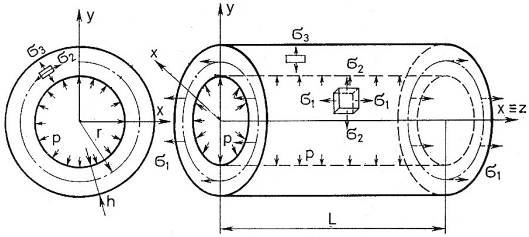


Fig. 2. Elastic blood vessel

Figure 2 shows stress that occur in the blood vessel wall segment, where r – cross-section radius, m; h – blood vessel wall thickness, m; σ_1 – longitudinal stress, Pa; σ_2 – circular stress, Pa; σ_3 – radial stress, Pa; P – pressure, Pa. Von-Mises stress – σ_i were calculated according equation:

$$\sigma_i=\frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}\,. \tag{3}$$

The main finite elements elastic body matrix equations (4) and (5) are :

$$[M_S]\{\ddot{U}\}+[K_S]\{U\}=\{F_S\}+[R]\{P\}, \tag{4}$$

$$[M_f]\{\ddot{P}\}+[K_f]\{U\}=\{F_f\}+\rho_0[R]^T\{\ddot{U}\}, \tag{5}$$

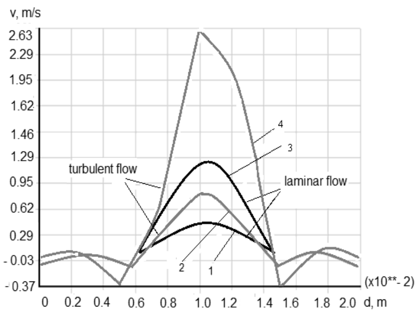
where $[M_s]$, $[M_f]$ – elasticity matrixs; $[K_s]$, $[K_f]$ – tightness matrixs; $\{P\}$, $\{\ddot{P}\}$ – first and second rows pressure variation matrixs; $[R]$ – connection matrix; $[R]^T$ –

transpose connection matrix; $\{F_s\}$, $\{F_f\}$ – forces variation matrix; ρ_0 – dencity; P – pressure, $\{U\}$ir $\{\ddot{U}\}$ – first and second rows displacements variation matrixs.

Summarizing this chapter, the conclusion is – improved and specified blood flow in the elastic blood vessel mathematical model was made. This model allow to value flow turbulence phenomenon and blood as Newtonian fluid properties.

3. Blood vessels modeling with finite elements method results and their analysis

Blood flow dynamics in healthy and pathological blood vessels, local blood pressure influence to blood vessel wall and stresses distribution in it were analyzed. Healthy blood vessel with deflections and pathology with aneurysm atherosclerosis models were made using finite elements methods. It was find out that local pressure, blood vessels wall stresses and blood flow velocity variation dynamic is depend on not only pathology size, but also on pathology type. Obtained research results could be used evaluating human efficiency.

a) 

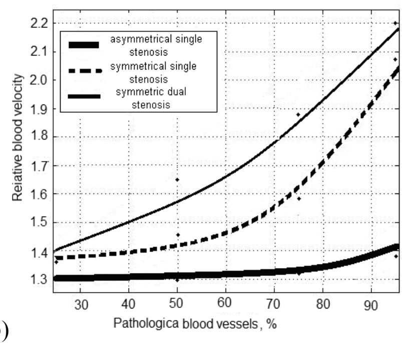
b) 

Fig. 3. Relative blood velocity dependence of the degree of pathology

The research was made using two-dimensional and three-dimensional arterial blood vessels models. Blood flow velocity and local pressure variations in the blood vessels pathological locations were researched with mentioned investigation method. Also was explored mentioned parameters influence to blood vessel wall. Blood vessels modeling allow forecasting critical cases when blood vessels crack. During investigation blood vessels diameter pathology value was changed from 25 % to 95 %, systolic blood pressure varied $p\in[16,$

…, 27], kPa, steps Δp=3 kPa. Navier-Stokes (1), elastic body (4) equations were solved during research, using finite elements method ANSYS software package.

When blood vessels pathology degree differ, relative blood velocity also varies (Fig. 3). Blood velocity increase from 1.3 to 1.38 times, when there is single-sided asymetric stenosis (Fig. 3 a, curves 1^{st} and 2^{th}). When there is one symetrical stenosis, relative blood velocity is increased from 1.38 to 2.2 times (Fig. 3 b). Mentioned relative blood velocity is bigest and dangerous. When pathological dagree is increasing, blood velasity also increase and when there is maximal stenosis (95 %), it is 2.6 m/s (Fig. 3 a, 3^{th} and 4^{th} curves).

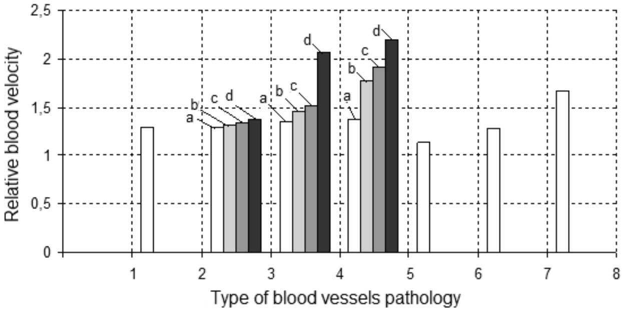


Fig. 4. Relative blood velocity dependence on the type of blood vessel pathology

Blood vessels geometrical shape pathological are shown in the figure 9. The figure shows how many times blood velocity increase when there is turbulence phenomenon and which case is the most dangerous. Performed researches show, that in the healthy blood vessel blood velocity is increased 1.3 times (Fig 4 1^{st} column), when there is single deflection blood velocity increase 1.13 times (Fig. 4 5^{th} column), with dual deflection – 1.28 times (Fig.4 6^{th} column). When there is aneurysm blood flow increase to 1.67 times (Fig 4 7^{th} column). When there is asymetric single-sided stenosis relative blood velocity increase $v_{sant} \in [1.3, ..., 1.38]$ times with blood vessel diameter pathology from 25 % to 95 % (Fig. 4 2^{nd} case, columns: a, b, c, d). In the blood vessel with one symetric stenosis, when there is maximal reduction of the diameter to 95 %, blood velocity increase 2.1 times (Fig. 4 3^{rd} case, *d* column). With dual symetric stenosis, when blood vessel's diameter is decreases to 50 %, blood velocity increase to 1.8 times (Fig. 4 4^{th} case, *b* column), respectively when 75 % stenosis – to 1.9 times (Fig. 4 4^{th} case, *c* column), when 95 % stenosis – 2.2 times (Fig. 4 4^{th} case, *d* column).

Performed investigations show that different blood flow velocity is determined by blood vessel shape pathological; the most dangerous pathological – symetrical dual stenosis and symetrical single stenosis.

Figures 5 and 6 show obtained local blood pressure (p_{lok}) values. Investigating local blood pressure in the pathological locations, output pressure (systolic blood pressure – p_{sist}) vary $p_{sist} \in [16, \dots, 27]$, kPa, steps ∇p=3 kPa. Exploring different blood vessels types, we could see that there is different local pressure distribution in the pathological locations. In all cases, when blood vessel diameter stenosis is to 50 %, local pressure change is not significant, increase 1.2 times. When blood vessel diameter contracts to 95 % with nonsymmetrical stenosis ($p_{sist} \in [16, \dots, 27]$, kPa,) $p_{lok} \in [44, \dots, 72]$ kPa increase from 2.58 to 2.8 times (Fig. 4); when there is symmetrical contraction with one stenosis – $p_{lok} \in [47, \dots, 75]$, kPa increase from 2.68 to 2.95 times (Fig. 3.13); when there is symmetrical contraction with two stenosis – $p_{lok} \in [50, \dots, 80]$, kPa increase from 3.12 to 3.44 times (Fig. 6).

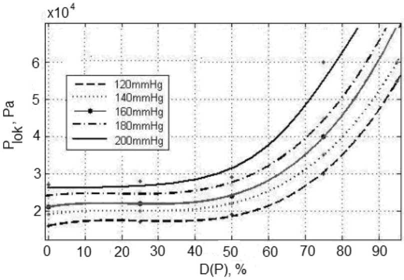


Fig. 5. Distribution of local pressure in the blood vessel with two symmetrical stenosis

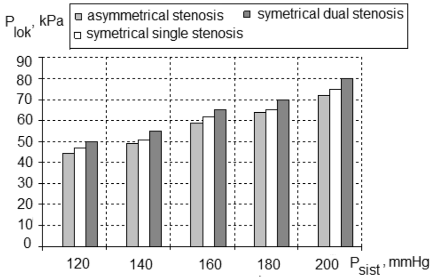


Fig. 6. Distribution of maximal local pressure in the pathological blood vessel

We could see, that dangerous is symmetrical dual stenosis and aneurism; maximal stresses values when $p_{sist} \in [16, \dots, 27]$ kPa are $\sigma_{max} \in [17, ..., 64,9]$ kPa and $\sigma_{max} \in [39, ..., 58]$ kPa, and stresses increase 1.7 times (Fig. 7). Also dangerous is symmetrical stenosis $\sigma_{max} \in [11.6, ..., 58]$ kPa, which increase 1.48 times. Less dangerous is asymmetric stenosis $\sigma_{max} \in [26, ..., 43.7]$ kPa.

Assessing most dangerous cases, the characteristic pathological blood vessels deformations are given in figures 7 and 8.

Given analysis show, that when there is aneurysm, maximal displacements $u_{max} \in [0.0019, \dots, 0.0032]$ m when $p_{sist} \in [16, \dots, 27]$ kPa (Fig. 8) are noticed. When there is symmetrical dual and single stenosis – $u_{max} \in [0.00064, \dots,$

0.001] m, they are 3 times less than aneurysm displacements. When there is asymmetry $u_{max}\in[0.00054, \ldots, 0.0009]$ m, they are 3.6 times less than aneurysm and 1.11 times less than symmetric displacements.

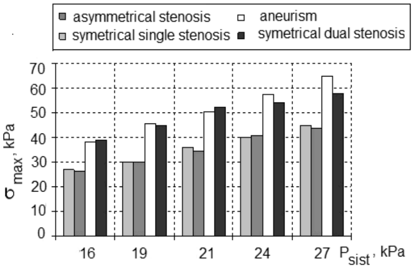


Fig. 7. Maximal stresses distribution in the pathological blood vessel

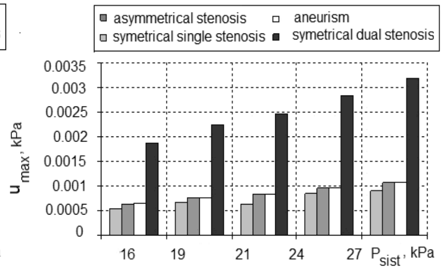


Fig. 8. Maximal displacements distribution in the pathological blood vessel

In the conclusion, we could say, that the most dangerous pathology type is stenosis. That's why it is important to pay attention not only to pathology size, but also to type. It was find out, that the most dangerous dual stenosis symmetric case, because local blood pressure and stresses values are maximal. It was evaluated, that blood vessels crack because of local blood pressure size. That's why it is important to determine real local blood pressure in the pathological locations and to value caused blood vessels cracks.

4. Load size, age and gender influence to blood pressure investigation and human efficiency evaluation methodology formation

In this chapter is given load size influence to arterial blood pressure, heart rate investigation and blood vessels strength dependences from age analysis, performance methodology, means and methods.The researches were made for different age and genders human goups with jump and constant load with different load duration. Experimantal veloergometry method was used during reasearch – heart rate and arterial blood pressure were recorded during investigation. For that computerized "Siemens" and "SpaceLabs Medical" monitoring and data processing system were used. It was find out, that heart rate and arterial blood pressure functional dependences from load duration have characteristic points, where functions fluxions values are $\frac{\partial P(t)}{\partial t} = 0$ and $\frac{\partial S(t)}{\partial t} = 0$.

First critical point shows human adaptation to set load (Fig. 16, 1st point). Second critical point shows, that certain variations occurin the human organism and person starts to feel fatigue (Fig. 9, 2nd point). First point and second point fatigue beginning features (t_{PN}) were chosen, when adaption beginning is (t_A). Heart rate and arterial blood pressure dependences are described with this expressions: $S(t) = f_1(Q,t)$ and $P(t) = f_2(Q,t)$; where $S(t)$ – heart rate functional dependence on load and time, $P(t)$ – arterial blood pressure functional dependence on load and time, Q – load, t – time. Than fatigue beginning conditions are: $\frac{\partial S(t)}{\partial t} = \frac{\partial f_1(Q,t)}{\partial t} = 0$ and $\frac{\partial P(t)}{\partial t} = \frac{\partial f_2(Q,t)}{\partial t} = 0$.

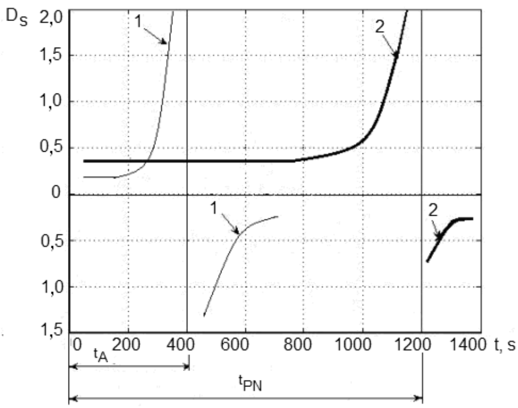


Fig. 9. Heart rate dependence of the time at a constant load of 50 W

Arterial blood pressure dependences on heart rate hodograms were made for different loads, gender and age. These hodograms allow evaluating maximal arterial blood pressure and heart rate values and their extremes disagreement during set load; also human health condition ability to adapt for chosen load and initial warming up importance for preparing to physical load.

Blood vessels system mechanical characteristics variations were explained, cardiovascular system adaptation to physical load was evaluated, human efficiency evaluation parameters and methodology was made. Approximately efficiency evaluation methodology is illustrates in the figure 10 nomogram.

Given methodology shows us, that important influence have human age to blood vessels strength and efficiency. Gender does not show significant differences.

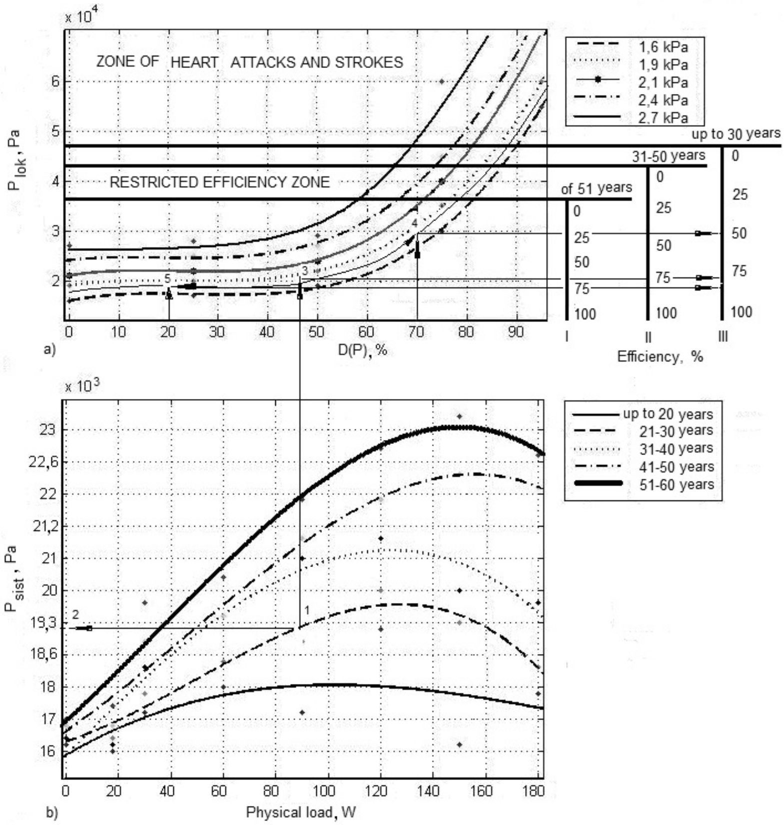


Fig. 10. Human efficiency evaluation methodology for male groups in the blood vessels with two symmetrical stenosis

Summarized research results show us, that given methodology allows determining local blood pressure in the pathological locations and efficiency level depending on load value, blood vessels pathology degree. Also allow to assess blood vessel pathology type influence to human working level.

General Conclusions

1. Blood vessel model was made assessing turbulence phenomenon and blood Newton fluid features in the blood vessels pathological and deflections places. This model allows determining:

- Blood flow rate in the pathological blood vessel location could be 1.4–2.2 times bigger than in the healthy blood vessel depended on blood pressure, physical load, pathology degree.
- Dual symmetrical blood vessel stenosis is mostly dangerous for cracks, because stresses in the pathological locations are increased to 13.8 times, blood pressure – 3.4 times.
- evaluating blood flow turbulence phenomenon was determined that maximal pressure in the pathological blood vessels location is approximately 1.8 times bigger than without evaluation of turbulence. Thus chosen model allowed exactly to value blood flow variations in the pathological blood vessels places.

2. Was find out that when blood vessels pathology degree is to 50 %, local blood pressure and stresses increase is not significant; when 50–95 %, in dependence on pathology type, local blood pressure could increase 2.1–3.4 times and stresses 2.7–13.8 times. Therefore blood vessels cracks reason is not systolic blood pressure, but increased local blood pressure in the pathological location.

3. It was determined that the biggest influence to local blood pressure have blood vessel pathology degree. It is shown that most dangerous is symmetrical dual stenosis.

4. It is shown that arterial blood pressure and heart rate functional dependence on time have two characteristic points where fluxion value according time is equal zero. First point shows human adaption to set physical load duration, second – signs of the initial fatigue.

5. Using arterial blood pressure and heart rate diagrams characteristic points, two efficiency evaluation criterions were made. Mentioned criterions show adaption to set physical load duration and working capacity time.

6. Made arterial blood pressure and heart rate interdependence hodograph allow:

- to determine physical load, blood vessel pathology and warming up value to adaption when load is set;
- showed that for the same blood pressure during time could be two heart rate values and opposite – to same heart rate during time could be two blood pressure values; allow to determine person physical state;
- it was found out that in the hodogram heart rate maximal value is achieved earlier than arterial blood pressure maximal value during time. That's why human initial fatigue features could be noticed analyzing heart rate.

7. It was determined that in human efficiency limit from 21 year to 60 year blood vessel strength could decrease to 1.6 times; over 81 year group to 9 times.

8. Approximately human efficiency evaluation methodology was made which allows determining human working capacity considering age, physical load value and local blood pressure calculation results.

List of Published Works on the Topic of the Dissertation
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Mariūnas, M.; Kuzborska, Z.; Jarmalienė, E. 2007. Kraujagyslių mechaninių charakteristikų tyrimas, *10-osios Lietuvos jaunųjų mokslininkų konferencijos „Lietuva be mokslo – Lietuva be ateities“, įvykusios Vilniuje 2007 m. balandžio 19–20 d., medžiaga: mechanika, medžiagų inžinerija, pramonės inžinerija ir vadyba / VGTU. Vilnius: Technika*, p. 75–82. ISBN 978-9955-28-214-3.

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KRAUJO TĖKMĖS IR ĮTEMPIŲ PAŽEISTOSE KRAUJAGYSLĖSE TYRIMAS

Mokslo problemos aktualumas

Širdies ir kraujagyslių ligos yra pagrindinės žmonių nedarbingumo ir mirties priežastys pasaulyje ir Lietuvoje. Mokslo literatūroje nurodoma, kad kas trečias žmogus pasaulyje miršta nuo širdies ir kraujagyslių sistemos funkcijų sutrikimų.

Pastaruoju metu įvairių specialybių mokslininkai – medikai, biologai, biochemikai, biomechanikai, mechanikai – atkreipė dėmesį į spartėjantį kraujotakos sistemos ligų plitimą, tad vis daugiau dėmesio skiria kraujotakos sistemos ligų etiologijai ir patogenezei, kraujotakos reiškiniams išaiškinti.

Pagrindiniai širdies ir kraujagyslių sistemos kraujagyslių susirgimai – tai progresuojanti aterosklerozė, arterinė hipertenzija, įvairūs arterijų susisukimai bei vis dažniau pasitaiko aneurizmos. Šie pažeidimai įvairiai keičia kraujagyslės spindį, sienelės storį ir ilgį. Priklausomai nuo susidariusios pažeidimo formos ir dydžio kinta kraujo tėkmės greitis, kraujo spaudimas ir įtempiai pažeistose kraujagyslių vietose. Esant tam tikriems kraujagyslės sienelės geometrinės formos nuokrypiams dėl tėkmės pokyčių kraujagyslėje didėja lokalinis kraujo spaudimas ir įtempiai. Tai veikia kraujagyslės sienelę ir sukelia joje kritinius įtempius, dėl kurių kraujagyslė gali plyšti. Mokslo šaltiniuose dažniausiai nagrinėjama laminarinė kraujo tėkmė, kraujas traktuojamas kaip niutoninis skystis, vertinama fizinio krūvio ir amžiaus įtaka širdies ir kraujagyslių sistemai.

Nustatant žmogaus darbingumą ypač svarbu žinoti realų kraujo tėkmės greitį, lokalinį kraujo spaudimą ir įtempių reikšmes kraujagyslėse, susidarančias esant tam tikram pažeidimo laipsniui.

Tyrimų objektas

Darbo tyrimų objektas – ligos pažeista kraujagyslė (aterosklerozė, aneurizma) ir joje vykstantys kraujo tėkmės procesai, priklausantys nuo fizinės apkrovos, pažeidimo laipsnio ir rūšies, amžiaus, lyties ir kraujagyslių mechaninių savybių.

Darbo tikslas ir uždaviniai

Tikslas – ištirti kraujo tėkmės charakteristikas, lokalinį kraujo spaudimą, įtempių pasiskirstymą ligos pažeistose kraujagyslėse priklausomai nuo fizinio krūvio, įvertinant kraujagyslių mechaninių savybių pokytį dėl amžiaus, lyties, kraujagyslės pažeidimo rūšies bei sudaryti supaprastintą darbingumo vertinimo metodiką.

Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Sudaryti kraujagyslės modelį, kuriuo remiantis galima būtų tirti lokalinį kraujo spaudimą, įtempius pažeistose kraujagyslių vietose, vertinant turbulentiškumo reiškinius ir kraujo kaip niutoninio skysčio savybes.
2. Ištirti fizinės apkrovos dydžio, kraujagyslių pažeidimų laipsnio, amžiaus bei lyties įtaką kraujo spaudimui ir įtempių padidėjimui pažeistose kraujagyslių vietose.
3. Eksperimentiniu būdu nustatyti kraujagyslių mechaninių savybių pokytį įvertinant amžių, lytį (keičiant fizinės apkrovos dydį).
4. Papildomai ištirti kraujo spaudimo ir širdies susitraukimų dažnio charakteristikų pokyčius nustatytame fizinio krūvio ir žmogaus darbingo amžiaus intervale.
5. Sudaryti apytikslę darbingumo vertinimo metodiką.

Tyrimų metodika

Užsibrėžtiems tikslams pasiekti disertacijoje taikyti analitiniai, eksperimentiniai, skaitiniai ir statistinio tyrimo metodai. Kraujo tėkmės ir įtempių pažeistose kraujagyslėse modeliavimas atliktas naudojantis baigtinių elementų metodu ANSYS programiniu paketu.

Mokslinis naujumas

Darbo naujumas išdėstytas šiuose pagrindiniuose mokslo teiginiuose, dėsningumuose ir apibendrinimuose:

1. Pasirinktas pažeistos kraujagyslės modelis, įvertinantis patologijos sukeltus geometrijos pokyčius, turbulentinės kraujo tėkmės ir lokalinio kraujo spaudimo pokyčius pažeidimo vietose bei kraujo kaip niutoninio skysčio savybes.

2. Nustatyta fizinio krūvio, kraujagyslių pažeidimo laipsnio, amžiaus ir lyties įtaka kraujo spaudimui ir įtempių padidėjimui.
3. Lokalinio kraujo spaudimo ir įtempių padidėjimo pažeistose kraujagyslių vietose nustatymas turi svarbią reikšmę vertinant kraujagyslių plyšimo ir žmogaus darbingumo galimybes.
4. Sudaryti darbingumo vertinimo kriterijai ir pateikti kraujo spaudimo bei širdies susitraukimų dažnio tarpusavio priklausomybių vertinimo hodografai taip pat turi svarbią reikšmę vertinant žmogaus galimybes prisitaikyti prie nustatyto fizinio krūvio dydžio.
5. Sudaryta apytikslė darbingumo vertinimo metodika.

Praktinė vertė

Darbo rezultatų praktinė reikšmė atspindi šiuose pagrindiniuose teiginiuose:

1. Sudaryti hodografai leidžia pagal supaprastintą metodiką vertinti fizinio krūvio, apšilimo ir kitų faktorių įtaką žmogaus darbingumui.
2. Sudaryti kriterijai leidžia apytiksliai vertinti žmogaus gebėjimą atlikti užduotą fizinį darbą vertinant apkrovos dydį bei darbingumo trukmę.
3. Nustatyta kraujagyslių stiprumo priklausomybė nuo amžiaus, kuri leidžia vertinti žmogaus darbingumo laipsnio praradimą jam (amžiui) didėjant.
4. Siekiant tiksliau įvertinti žmogaus darbingumą priklausomai nuo kraujagyslių pažeidimo laipsnio, amžiaus, lyties ir fizinio krūvio dydžio sudaryta žmogaus darbingumo vertinimo metodika.

Ginamieji teiginiai

1. Darbingumo vertinimo kriterijai atskleidžia du pagrindinius rodiklius: darbingumo trukmę ir pirminio nuovargio požymius.
2. Kraujo spaudimo ir širdies susitraukimo dažnio hodografai leidžia nustatyti apšilimo įtaką fiziniam krūviui ir žmogaus sveikatos sutrikimo požymius.
3. Kraujagyslės plyšimą susiaurėjimo (aterosklerozės) vietoje sąlygoja lokalinio kraujo spaudimo padidėjimas keletą kartų daugiau už sistolinį kraujo spaudimą.

Darbo apimtis

Disertaciją sudaro įvadas, keturi skyriai ir bendrosios išvados. Taip pat yra du priedai. Darbo apimtis yra 116 puslapių, 86 paveikslai ir 2 priedai.

Įvadiniame skyriuje aptariama tiriamoji problema, darbo aktualumas, aprašomas tyrimų objektas, formuluojamas darbo tikslas bei uždaviniai, aprašoma tyrimų metodika, mokslinis darbo naujumas, praktinė darbo rezultatų reikšmė, ginamieji teiginiai. Įvado pabaigoje pristatomos disertacijos tema autorės paskelbtos publikacijos ir pranešimai konferencijose bei disertacijos struktūra.

Pirmasis skyrius skirtas literatūros apžvalgai. Jame aptarti mokslo darbai, kuriuose analizuojama kraujagyslių pažeidimo įtaka kraujo tėkmės parametrams, įtempiams pažeistose vietose ir mechaninių savybių pokyčiams. Skyriaus pabaigoje formuluojamos išvados ir tikslinami disertacijos uždaviniai. Antrajame skyriuje pateiktas tamprios kraujagyslės modelis, aprašantis kraujo tėkmę ir tamprųjį kūną, pažeidimo rūšis, taip pat čia formuluojamos prielaidos, išvados. Trečiajame skyriuje pateikiami kraujagyslių modeliavimo baigtinių elementų metodu rezultatai ir jų analizė. Formuluojamos skyrių išvados. Ketvirtajame skyriuje pateikiami apkrovos dydžio, amžiaus ir lyties įtakos kraujo spaudimui tyrimo rezultatai ir apytikslė darbingumo vertinimo metodika. Formuluojamos skyrių išvados.

Bendrosios išvados

1. Sudarytas kraujagyslės modelis, vertinant turbulentinius reiškinius ir kraujo kaip niutoninio skysčio savybes, kraujagyslių pažeidimų ir įlinkių vietose leido nustatyti, kad:

- kraujo tėkmės greitis pažeistoje kraujagyslės vietoje, priklausomai nuo kraujo spaudimo, fizinio krūvio, pažeidimo dydžio, gali būti nuo 1,4 iki 2,2 karto didesnis negu sveikoje kraujagyslėje;
- pavojingiausias, sukeliantis didžiausią plyšimo riziką atvejis yra dvigubas simetrinis kraujagyslės susiaurėjimas, nes įtempiai pažeistose vietose padidėja iki 13,8, spaudimas – 3,4 karto;
- vertinant kraujo tėkmės turbulencijos reiškinius nustatyta, kad didžiausias spaudimas pažeistoje kraujagyslės vietoje yra apie 1,8 karto didesnis negu jų nevertinant. Tad pasirinktas modelis leido 1,8 karto tiksliau įvertinti kraujo tėkmės pokyčius pažeistose kraujagyslės vietose.

2. Nustatyta, kad, esant kraujagyslių pažeidimo laipsniui iki 50 %, lokalinis kraujo spaudimas ir įtempiai padidėja nežymiai, nuo 50 % iki 95 %, priklausomai nuo pažeidimo rūšies, lokalinis kraujo spaudimas gali padidėti nuo 2,1 iki 3,4 karto, o įtempiai nuo 2,7 iki 13,8 karto. Todėl kraujagyslės plyšta ne dėl sistolinio kraujo spaudimo, o dėl padidėjusio lokalinio kraujo spaudimo pažeidimo vietoje.

3. Nustatyta, kad didžiausią įtaką lokaliniam kraujo spaudimui turi kraujagyslės pažeidimo laipsnis. Parodyta, kad pavojingiausias yra simetrinis dvigubo susiaurėjimo atvejis.

4. Parodyta, kad arterinio kraujo spaudimo ir širdies susitraukimų dažnio funkcinėse priklausomybėse nuo laiko yra po du būdinguosius taškus, kuriuose išvestinės reikšmė pagal laiką lygi nuliui. Pirmasis taškas parodo žmogaus

prisitaikymo prie nustatyto fizinio krūvio trukmę, antrasis – pirminio nuovargio požymius.

5. Remiantis arterinio kraujo spaudimo ir širdies susitraukimų dažnio grafikų būdingaisiais taškais buvo sudaryti du darbingumo vertinimo kriterijai, kurie parodo prisitaikymo prie tam tikro fizinio krūvio trukmę ir darbingumo laiką.

6. Sudarytas arterinio kraujo spaudimo ir širdies susitraukimų dažnio tarpusavio ryšio hodografas leido:

- nustatyti fizinio krūvio, kraujagyslės pažeidimo ir apšilimo reikšmę adaptacijai prie nustatytos apkrovos;
- parodė, kad tam pačiam kraujo spaudimui kintant laikui gali būti dvi širdies susitraukimų dažnio reikšmės ir atvirkščiai – tam pačiam širdies susitraukimų dažniui kintant laikui gali būti dvi kraujo spaudimo reikšmės;
- nustatyti žmogaus fizinę būklę;
- nustatyta, kad hodogramoje didžiausia vertė pagal širdies susitraukimų dažnį pasiekiama anksčiau negu didžiausia arterinio kraujo spaudimo vertė kintant laikui. Tai rodo, kad žmogaus pirminio nuovargio požymius galima pastebėti analizuojant širdies susitraukimų dažnį.

7. Nustatyta, kad žmogaus darbingo amžiaus metu nuo 21 m. iki 60 m. kraujagyslių stiprumas gali sumažėti iki 1,6 karto, o daugiau nei 81 m. amžiaus grupėje – iki 9 kartų.

8. Sudaryta apytikslė žmogaus darbingumo vertinimo metodika, kuria remiantis ir atsižvelgiant į amžių, fizinio krūvio dydį ir lokalinio kraujo spaudimo skaičiavimo rezultatus galima nustatyti žmogaus darbingumą.

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RESEARCH OF BLOOD FLOW AND STRESSES
IN THE PATHOLOGICAL BLOOD VESSELS

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)

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KRAUJO TĖKMĖS IR ĮTEMPIŲ
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