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Virtual ankle-brachial index – can the immediate outcome of femorodistal bypass surgery be predicted?

Virtuelni brahijalni indeks gležnja – može li se predvideti neposredni ishod femorodistalne bajpas hirurgije?

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Abstract

Background/Aim. The best treatment for the occlusion of the largest artery in the thigh is a femorodistal (FD) bypass. Ankle-brachial index (ABI) and multidetector computed tomographic (MDCT) angiography are the gold standards for diagnosing peripheral arterial occlusive disease. The finite element analysis (FEA) method can help measure the quantity of blood flow and arterial pressure in the arteries in the leg. The aim of this study was to examine the possibility of using the FEA method in predicting the outcome of FD bypass surgery. **Methods.** The study involved 45 patients indicated for FD arterial reconstruction from December 1, 2021, to March 31, 2023. Each patient underwent pre- and postoperative MDCT angiography of the arteries of the lower extremities, on the basis of which, with the use of FEA, models were made for measuring ABI. All patients had their ABI measured preoperatively and postoperatively using the Doppler ultrasound and sphygmomanometer. Based on the findings of the preoperative MDCT angiography, postoperative virtual surgical models were created using the FEA method, on which ABI were also measured. The values of ABI were divided into five groups: ABI measured preoperatively (ABI pre-op), ABI measured postoperatively (ABI post-op), ABI measured on FEA models based on the MDCT findings [ABI (sim) pre-op], ABI sim post-op, and ABI measured on virtual surgery model [ABI sim post-op (virtual)]. The ABI of the models were statistically compared with preoperative and postoperative measurements done on patients. **Results.** The values based on the virtual ABI model did not show significant differences compared to the values obtained on patients and values obtained with the FEA method using MDCT angiography ($p < 0.001$). A strong statistically significant correlation was shown between the virtual ABI and the values obtained by the other two methods, measured on the postoperative MDCT angiography model and virtual postoperative model ($p < 0.001$). **Conclusion.** Virtual simulation based on the MDCT angiography parameters of peripheral blood vessels can be successfully used to predict the immediate outcome of the FD bypass surgery.

Key words:
arterial occlusive diseases; ankle brachial index; computed tomography angiography; finite element analysis; image interpretation, computer-assisted; leg; prognosis; ultrasonography.

Apstrakt

Uvod/Cilj. Najbolji način lečenja okluzije površne femoralne arterije je femorodistalni (FD) bajpas. Brahijalni indeks gležnja (BIG) i angiografija primenom metode multidetektorske kompjuterizovane tomografije (MDKT) predstavljaju „zlatni standard” u dijagnostici periferne okluzivne bolesti arterija. Analiza konačnih elemenata (AKE) može pomoći u merenju količine protoka krvi i arterijskog pritiska u arterijama donjih ekstremiteta. Cilj rada bio je da se ispita mogućnost korišćenja AKE u predviđanju ishoda FD bajpas hirurgije. **Metode.** Istraživanjem je

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obuhvaćeno 45 bolesnika kojima je indikovana FD arterijska rekonstrukcija u periodu od 01. decembra 2021. do 31. marta 2023. godine. Svakom bolesniku je preoperativno i postoperativno urađena angiografija arterija donjih ekstremiteta primenom MDKT, na osnovu koje su, uz korišćenje AKE, napravljeni modeli na kojima su mereni BIG. Svim bolesnicima su mereni BIG preoperativno i postoperativno, korišćenjem Doppler ultrazvuka i sfigmomanometra. Na osnovu preoperativne MDKT angiografije, korišćenjem metode AKE, napravljeni su postoperativni virtuelni hirurški modeli, na kojima su takođe mereni BIG. Vrednosti BIG raspoređene su u pet grupa: BIG meren preoperativno (BIG *pre-op*), BIG meren postoperativno (BIG *post-op*), BIG meren na modelima konačnih elemenata dobijenim primenom MDKT [BIG (*sim*) *pre-op*], BIG *sim post-op*, i BIG dobijen merenjem na virtuelnom hirurškom modelu [BIG *sim post-op* (*virtual*)]. Statistički su upoređivane vrednosti BIG dobijene na modelima sa vrednostima dobijenim merenjem na bolesnicima. **Rezultati.** Vrednosti dobijene na osnovu virtuelnih BIG modela nisu pokazale značajnu razliku u poređenju sa vrednostima dobijenim merenjem na bolesnicima i vrednostima dobijenim primenom AKE uz MDKT angiografiju ($p < 0,001$). Značajna statistička korelacija pokazana je između vrednosti virtuelnih BIG i vrednosti dobijenih primenom druge dve metode, merenim na postoperativnom modelu MDKT angiografije i na virtuelnom postoperativnom modelu ($p < 0,001$). **Zaključak.** Virtuelna simulacija parametara dobijenih primenom MDKT angiografije perifernih krvnih sudova može se uspešno koristiti za predviđanje neposrednog ishoda FD bajpas hirurgije.

Ključne reči:
arterije, okluzione bolesti; brahijalni indeks gležnja; angiografija, tomografska, kompjuterizovana; analiza konačnih elemenata; kompjuterski asistirano tumačenje slika; noga; prognoza; ultrasonografija.

Introduction

The blockage of the largest artery in the thigh caused by peripheral arterial occlusive disease (PAOD) of the lower limbs affects 12–14% of the general population, and the prevalence increases with age [1]. Nowadays, the best treatment is femoropopliteal or femorocrural bypass, where the blocked portion of the artery is bypassed by adding a piece of great saphenous vein or a synthetic vascular graft [2]. The diagnostic assessment of PAOD is based on the measurement of the ankle-brachial index (ABI), i.e., the ratio of the systolic pressure measured at the ankle and the systolic pressure measured at the brachial artery (BA). To calculate ABI_{ATP}, systolic pressure is measured in the *arteria tibialis posterior* (ATP), and to calculate ABI_{ADP}, it is measured in the *arteria dorsalis pedis* (ADP). Multidetector computed tomographic (MDCT) angiography is becoming more popular because of the increased speed of imaging acquisition and the volume of coverage, decreased contrast dose, and improved spatial resolution [3]. Finite element analysis (FEA) is used to divide the fluid domain in an arterial blood vessel into many small, finite elements. For each of these elements, it is possible to accurately calculate the flow *per* unit of time using mathematical equations and measuring the corresponding physical quantities [4–6].

Our previous study proposed using computationally derived ABI – a virtual ABI [7, 8], as a non-invasive procedure that could assist clinicians in finding the optimal bypass strategy for a particular patient. The key contribution of the study was a novel approach to prescribing boundary conditions (BC) by combining non-invasive preoperative measurements and medical imaging. The validation of the study showed the high reliability of the proposed approach to prescribing BC by combining clinical measurements of blood pressure and blood flow rates with the values obtained using computational fluid dynamics.

The aim of the study was to examine existing procedures for computing the ABI (virtual ABI) to predict the outcome of femorodistal (FD) bypass surgery.

Methods

The observational study with mathematical modeling based on data obtained by measurements was carried out at the Clinic for Vascular and Endovascular Surgery of the Military Medical Academy and University Clinical Center of Serbia in Belgrade, Serbia from December 1, 2021, to March 31, 2023.

The study was approved by the Ethics Committee of the Military Medical Academy, at the meeting held on November 1, 2021 (Decision No. 25/2021).

It involved 45 patients with PAOD with recommended FD arterial reconstruction. The MDCT angiography of the arteries of the lower extremities was performed both preoperatively and postoperatively (third or fourth day after surgery), based on which FEA models were made (preoperative and real surgery model) (Figure 1).

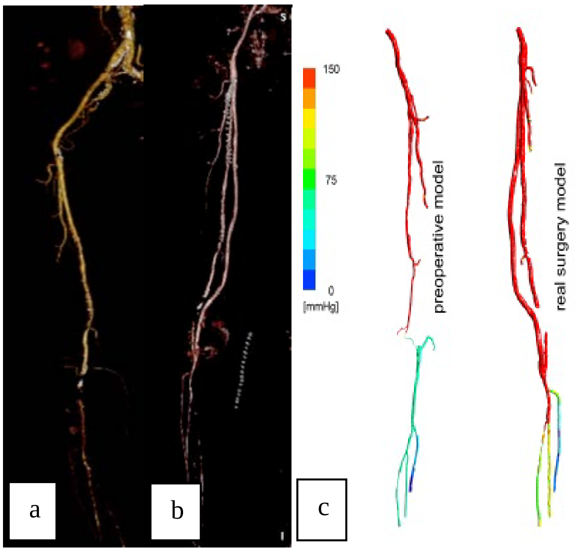

Fig. 1 – a) Preoperative multidetector computed tomographic (MDCT) angiography; b) Postoperative MDCT angiography; c) Finite element analysis models.

All patients had their ABI measured daily preoperatively and on the third or fourth day after the surgery (ATP pre-op, ATP post-op, ADP pre-op, ADP post-op). The ABI was measured on preoperative and postoperative FEA models based on the MDCT findings (ATP sim pre-op, ATP sim post-op, ADP sim pre-op, ADP sim post-op). Based on the findings of the preoperative MDCT angiography, a postoperative model was made using the FEA (virtual surgery model), and the ABI was calculated (ATP sim post-op virtual, ADP sim post-op virtual) (Figure 2). In the virtual surgical model, the same diameter and length of the graft were used as in the surgery. Where a vein graft was used, the vein was measured at 2 cm distal to the proximal anastomosis, and this size was used for the virtual bypass.

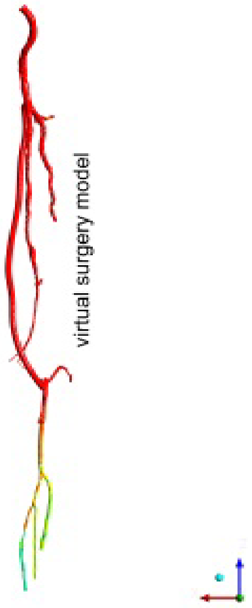

Fig. 2 – Postoperative finite element analysis model based on the findings of the preoperative multidetector computed tomographic angiography.

The ABI values measured on models were statistically compared with the values measured on patients preoperatively and postoperatively. A sphygmomanometer and a stethoscope were used to measure the pressure of the BA to calculate the ABI. The pressure in the ankle joint area was measured using Doppler sonography (Esaote MyLabGamma 4790) and a sphygmomanometer, and Atys medical BASIC 3.4. Then, the quotient was calculated, and the ABI values were obtained [9]. The MDCT angiography was performed using the Toshiba Prime Aquilion (CGGT-032A and CGGT 030A, Toshiba Medical System Corporation, Japan).

The FEA models were based on three-dimensional MDCT angiography imaging. The blood flow was calculated using the Navier-Stokes equation with the set initial and BC obtained through measurement.

A virtual bypass was created based on a preoperative model using the Solidworks 2018 software. To achieve adequate mesh density, the models were discretized into unstructured 3D finite elements using TetGen mesh parameters [10]. The "dfemtoolz" software was used to generate the hexahedral mesh and impose the BC [11].

All patients older than 18 years who were recommended FD arterial reconstruction due to PAOD with preserved renal function and who had signed informed consent for the research were included in the study. Patients who were excluded from the study were the ones who were recommended FD arterial reconstruction due to other conditions (aneurysms of peripheral arteries), who had had operations on the iliac or other arteries of the lower extremities, a bypass surgery on the arteries of the lower extremities, endovascular procedures on the aorta, iliac or lower limb arteries, patients diagnosed with malignancy, patients with renal insufficiency, and patients who did not sign a consent for the research.

Statistical analysis

The research defined two groups of data. The first was the values of ABI obtained by the FEA method based on preoperative and postoperative MDCT angiography, as well as by the FEA method of virtual surgery using only preoperative MDCT angiography, while the second group of data was the same data but obtained by experimental measurement on patients. For comparison, these two data group *t*-test independent samples were used. These two groups of data were measured before and after surgery. Student's *t*-test for dependent samples was used to compare the same group before and after intervention. The computer software SPSS version 26.0 (IBM, USA, 2019) was used for statistical data processing. The Kolmogorov-Smirnov test was used to test the normality of the data distribution. A value of $p < 0.05$ was considered significant during all analyses.

Results

The ABI was significantly higher after surgery compared to the preoperative value. In both cases, it was measured using Doppler sonography and MDCT angiography (Tables 1 and 2, Figures 1 and 2).

Virtual ABI was simulated for each patient. The values based on the virtual ABI model did not show significant differences compared to the values measured using Doppler sonography and MDCT angiography (Tables 1 and 2, Figures 3 and 4).

There was a strong, statistically significant correlation between the virtual ABI values and the values obtained using the other two methods (Table 3). There was a strong positive correlation between the ATP sim post-op virtual, the ATP post-op (Pearson correlation $r = 0.912$, $p < 0.001$), and the ATP sim post-op (Pearson correlation $r = 0.925$, $p < 0.001$). Furthermore, there was a strong positive correlation between the ADP sim post-op virtual, the ADP post-op (Pearson correlation $r = 0.900$, $p < 0.001$), and the ADP sim post-op (Pearson correlation $r = 0.987$, $p < 0.001$).

Table 1

The ankle-brachial index (ABI) in the *arteria tibialis posterior* (ATP) before and after surgery

Parameter	mean ± SD	*p*-value
ATP pre-op	0.406 ± 0.211	< 0.001
ATP post-op	0.782 ± 0.205	
ATP sim pre-op	0.416 ± 0.213	< 0.001
ATP sim post-op	0.788 ± 0.193	
ATP sim post-op virtual	0.782 ± 0.196	
ATP post-op vs. ATP sim post-op virtual		1.000
ATP sim post-op vs. ATP sim post-op virtual		0.569

ATP pre-op – ABI preoperative value on ATP measured on the patient; ATP post-op – ABI postoperative value on ATP measured on the patient; ATP sim pre-op – ABI preoperative value on ATP measured on preoperative finite element analysis (FEA) models based on the multidetector computed tomographic (MDCT) findings; ATP sim post-op – ABI postoperative value on ATP measured on postoperative FEA models based on the MDCT findings; ATP sim post-op virtual – ABI postoperative value on ATP measured on virtual surgery model; SD – standard deviation.
The Paired Samples *t*-test was applied.

Table 2

The ankle-brachial index (ABI) of the *arteria dorsalis pedis* (ADP) before and after surgery

Parameter	mean ± SD	*p*-value
ADP pre-op	0.393 ± 0.193	< 0.001
ADP post-op	0.759 ± 0.198	
ADP sim pre-op	0.397 ± 0.194	< 0.001
ADP sim post-op	0.744 ± 0.193	
ADP sim post-op virtual	0.749 ± 0.197	
ADP post-op vs. ADP sim post-op virtual		= 0.461
ADP sim post-op vs. ADP sim post-op virtual		= 0.232

ADP pre-op – ABI preoperative value on ADP measured on patient; ADP post-op – ABI postoperative value on ADP measured on patient; ADP sim pre-op – ABI preoperative value on ADP measured on preoperative finite element analysis (FEA) models based on the multidetector computed tomographic (MDCT) findings; ADP sim post-op – ABI postoperative value on ADP measured on postoperative FEA models based on the MDCT findings; ADP sim post-op virtual – ABI postoperative value on ADP measured on virtual surgery model; SD – standard deviation.
The Paired Samples *t*-test was applied.

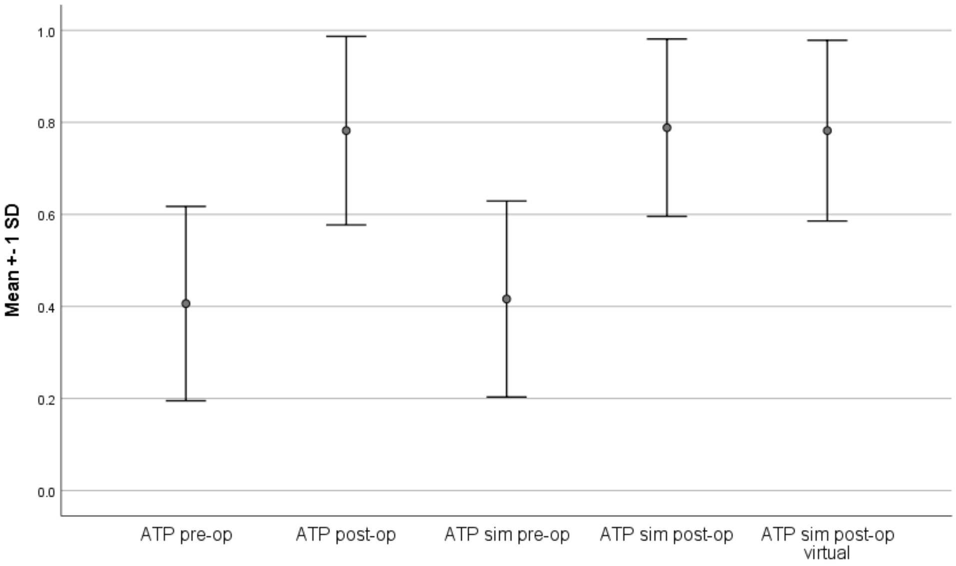

Fig. 3 – The average values of the ankle-brachial index (ABI) in the *arteria tibialis posterior* (ATP) before and after surgery, measured using Doppler, multidetector computed tomographic angiography, and virtual ABI.
SD – standard deviation; For other abbreviations, see Table 1.

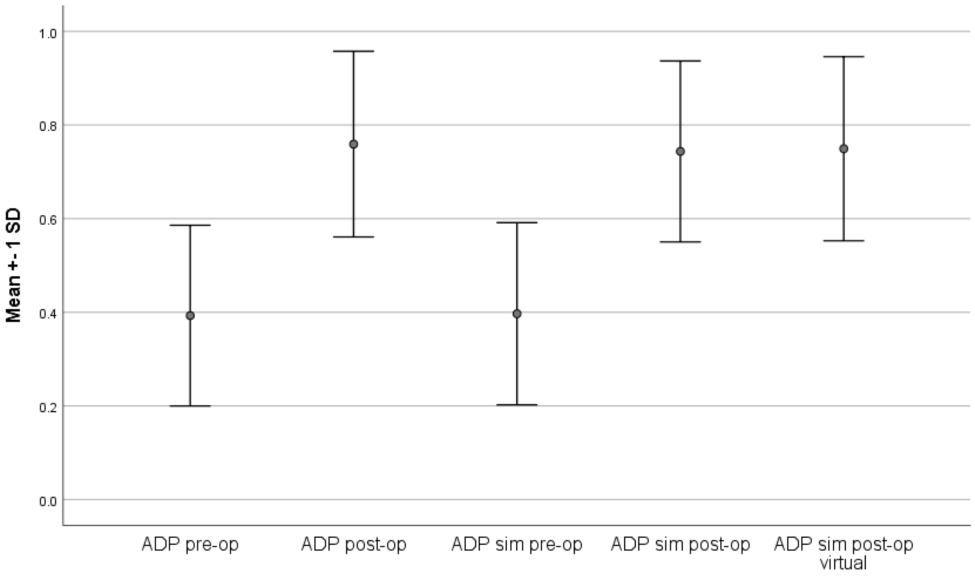

Fig. 4 – The average values of the ankle-brachial index (ABI) of the *arteria dorsalis pedis* artery (ADP) before and after surgery, measured using Doppler, multidetector computed tomographic angiography, and virtual ABI.
SD – standard deviation; For other abbreviations, see Table 2.

Table 3

Correlation of the ankle-brachial index (ABI) of the *arteria tibialis posterior* (ATP) and the *arteria dorsalis pedis* (ADP) before and after surgery

Parameter		ATP pre-op	ADP pre-op	ATP post-op	ADP post-op	ATP sim pre-op	ADP sim pre-op	ATP sim post-op	ADP sim post-op	ATP sim post-op virtual	ADP sim post-op virtual
ATP pre-op	r	1									
	p										
ADP pre-op	r	**0.489**	1								
	p	**0.001**									
ATP post-op	r	**0.508**	0.179	1							
	p	**< 0.001**	0.239								
ADP post-op	r	-0.021	**0.302**	**0.336**	1						
	p	0.891	**0.044**	**0.024**							
ATP sim pre-op	r	**0.971**	**0.498**	**0.462**	0.001	1					
	p	**< 0.001**	**< 0.001**	**0.001**	0.993						
ADP sim pre-op	r	**0.461**	**0.982**	0.181	**0.327**	**0.493**	1				
	p	**0.001**	**< 0.001**	0.233	**0.028**	**0.001**					
ATP sim post-op	r	**0.520**	0.161	**0.986**	**0.320**	0.499	0.168	1			
	p	**< 0.001**	0.291	**< 0.001**	**0.032**	< 0.001	0.269				
ADP sim post-op	r	-0.009	**0.322**	**0.328**	**0.920**	-0.054	**0.333**	0.277	1		
	p	0.953	**0.031**	**0.028**	**<0.001**	0.727	**0.025**	0.065			
ATP sim post-op virtual	r	**0.478**	0.099	**0.912**	**0.305**	**0.455**	0.103	**0.925**	0.267	1	
	p	**0.001**	0.516	**< 0.001**	**0.041**	**0.002**	0.500	**< 0.001**	0.076		
ADP sim post-op virtual	r	-0.061	**0.330**	0.277	**0.900**	-0.100	**0.338**	0.229	**0.987**	0.233	1
	p	0.692	**0.027**	0.066	**< 0.001**	0.511	**0.023**	0.130	**< 0.001**	0.124	

For abbreviations, see Tables 1 and 2. Statistically significant values are bolded (Pearson correlation was applied).

Discussion

The key result of this study is that the measurement properties for the Virtual ABI method compared to the Doppler and MDCT angiography simulation techniques were generally good. The precision of the virtual ABI measurement was also markedly good. There was a strong correlation between the virtual ABI and the values obtained using the other two methods.

The basic diagnostic procedure for PAOD is Color Doppler, which provides direct visualization of stenoses and arterial plaques, as well as the indirect analysis of the Doppler signal proximal and distal to the stenosis, which can determine the degree of stenosis [12]. The basic diagnostic screening method is the calculation of the ABI. In our study, the ABI was measured on real models (patients) using Doppler, and it was compared with the models based on the MDCT angiography findings.

The ABI is a sensitive and inexpensive method defined as a quotient of the systolic pressure at the level of the ankle joint (ADP and ATP) and the systolic pressure measured at the level of the BA. The ABI values between 0.4 and 0.9 indicate a mild to moderate PAOD, while the ABI values lower than 0.4 indicate significant PAOD [13]. However, this method cannot be used in patients with severely calcified arteries because the ABI cannot be adequately measured [14]. MDCT angiography or magnetic resonance of the blood vessels of the lower extremities is useful in diagnosing the site of significant stenosis on the arterial blood vessel [15, 16].

Today, efforts are being made to find different virtual models for assessing ABI as an indicator of PAOD. Diagnosis of PAOD is largely based on the recorded ABI. The equipment that automatically determines the ABI could facilitate diagnosing PAOD [17]. In our previous study, the measurement properties of an automated oscillometric ABI measuring device were tested against reference ABI values measured manually in patients with and without PAOD [7]. Generally, the automated device tended to overestimate lower ABI values while underestimating the higher ones, potentially leading to underdiagnosing PAOD. Using the FEA method, other physical quantities can be measured: shear stress, oscillatory shear stress, particle tracking, and velocity [18–20]. These physical quantities were not examined in this study, but they were published in our earlier study [21]. The focus of this study was on arterial pressure values, i.e., ABI, which we also use in clinical practice, and the immediate outcome of FD bypass surgery. In the following studies, these unused values could be measured for the purpose of testing long-term patency or reasons for the failure of the FD bypass surgery.

Our previous study proposed using computationally derived ABI – a virtual ABI [7], as a non-invasive procedure that could assist clinicians in finding the optimal bypass strategy for a particular patient. The validation of the study indicated the high reliability of the proposed approach.

Conclusion

The study showed that the virtual simulation based on the MDCT parameters of peripheral blood vessels could be successfully used to predict the outcome of the disease. However, considering the relatively small cohort available for this study, a larger study group is needed before the virtual ABI could be established as a diagnostic procedure.

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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