CONTRALATERAL ARTERIAL FLOWS INTERACTION BY REFERENCE TO DOPPLER ULTRASONOGRAPHY

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SUMMARY
Objective: This research paper discusses the phenomenon of junction and interaction of contralateral arterial flows in studies of various human vessels. *Materials and methods*. The studies enrolled 2236 healthy patients. Doppler ultrasonography was used to estimate the blood flow in brachial artery (before and after tourniquet application). The contralateral arterial flows were also studied in major vessels. *Results*. In the course of this research, the multidirectional blood flow consistent with junction and interaction of contralateral arterial flows was revealed. Values of maximum velocity for orthograde and contralateral blood flows before and after tourniquet application differed significantly ($p < 0.05$). Orthograde arterial flow was indicative of systolic peaks above the baseline. Contralateral arterial flow revealed systolic peaks below the baseline. *Conclusions*. The phenomenon under study is of practical bearing for diagnosing various diffuse and local vascular pathologies. *Contribution*. The outcome of this research will contribute to quality improvement in pathology diagnostics.
Key words: cardio-vascular system; arteries; contralateral arterial flows; major vessels; multidirectional blood flow; blood rheological properties; Doppler ultrasonography; tourniquet application; flow rate; rectal stump.
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Introduction

With regard to its structure and function, cardiovascular system is very complex. The difference in values of forces controlling blood flow rate between different surface areas of vessels represents the mandatory condition for the entire blood flow. Nonetheless, blood flow through vessels is governed by other factors, such as cardiac output, elasticity of vessel walls, type and degree of interrelations between multiple vascular branches, etc. (1). Some of these factors can be subject of quantitative analysis, which helps to perceive normal physiology of blood flow, as well as its pathophysiological specifics (2).

The scientific interest as regards the research into blood flow in cardiovascular system resulted in formation of a new scientific field, i.e. blood flow biomechanics (1). In the mid-1990s, the helical blood flow was discovered in cardiovascular system of humans and animals (3, 4). Prior to that, the majority of mathematical models relied on longitudinal component of velocity assuming that the transport of particles in blood flow is of progressive mobility along the vessel axis (5, 6). It took long to study key patterns and parameters of fluid flow in elastic vessels and mesenteric arteries, but that undertaking was considered outstanding, yet challenging from the point of view of physics (7). In addition, the studies included research into advantages of pulsating perfusion during artificial flow, often associated with increased microvascular blood flow (8). It was proved, that introducing pulsating flow may enhance perfusion of micro vessels and may result in improved treatment outcome in patients subject to high-risk cardiac surgery (9).

That discovery explains early theoretic suppositions that blood flow runs towards periphery where its reflection back to heart occurs. Some researchers believed that secondary flows referred to as U-shaped swirls appeared due to small vascular curvatures and variable blood viscosity (10). Still, other authors assumed spontaneous self-oscillations in capillary blood flow caused by nonlinear rheological blood properties (11).

Nowadays, it is certain that the cause of contralateral arterial flows lies in interaction of linear blood flows of two arterial anastomoses producing the resultant force from arterial flows of the opposite directions. At the same time, the assumptions made earlier can be taken as indirect factors (12, 13).

Interaction of multidirectional arterial flows fulfills crucial biological functions. Firstly, it ensures uniformity

in blood perfusion for individual components, which means symmetric blood perfusion in hollow organs (anterior and posterior walls of stomach, small intestine and colon walls, as well as in other organs in health) (14). Secondly, it ensures compensation of energy depletion of the flow. It is known, that pulsating blood flow energy dissipates into vessels and cerebrospinal fluid (15). With arterial vessels distanced from heart, counter flows act as natural biomechanical agents, i.e. with the greater energy recovery for more distal vessel. Thus, there are different levels of compensation in response to energy depletion in arterial flow in different parts of organs and tissues. Thirdly, the phenomenon of arterial flow interaction is especially critical when performing anti-aggregation functions and maintaining normal rheological blood properties. The pulsating nature of blood flow also acts to increase hydrostatic blood pressure in vascular bed, which results in stronger filtration of mural substances and diffusion of oxygen from vascular bed into tissues (16).

Evaluation of interspecific variability quantitative indicators contributes to more profound understanding of cardiovascular system structure and function of humans, and forms the basis for blood flow biomedical modeling.

This research paper discusses the phenomenon of junction and interaction of contralateral arterial flows in studies of various human vessels employing Doppler ultrasonography. This research is of practical bearing in view of immediate determination of intravascular arterial resistance, and can form the basis for diagnosing diseases of diffuse and local pathology in various organs. In addition, the research outcome can be referred to for preventive purposes to avoid possible diagnostic errors (false positive and false negative results).

Methods

Ethical constituent

Local Ethics Committee at the Federal State Budgetary Educational Institution of Higher Education Izhevsk State Medical Academy under the Ministry of Health of the Russian Federation granted approval on all procedures (Certification No. 625).

All studies in patients were performed given their full awareness, and by virtue of their voluntary written informed consent statement pursuant to Articles 30, 31, 32, 33 on Framework Legislation of the Russian Federation on Protection of Health of the Public (approved by the Supreme Soviet of the Russian Federation 22. 7. 1993 No. 5487-1, revision 07. 12. 2011) for invasive procedures, surgical intervention or operations. The procedures were carried out on the grounds of the informed consent from patients in accordance with international ethical requirements of the World Health Organization (Good Clinical Practice) to conduct medical research studies with human subject (Geneva, 1993).

The studies were performed at Operative Surgery and Topographic Anatomy Department of the Federal State Budgetary Educational Institution of Higher Education Izhevsk State Medical Academy under the Ministry of Health of the Russian Federation with participation of the Budgetary Institution of Health in the Republic of Udmurtia Clinical Diagnostic Center under the Ministry of Health of the Republic of Udmurtia on the premises of the Budgetary Healthcare Institution Municipal Clinic No. 6 and the Budgetary Healthcare Institution Municipal Clinic No. 9 under the Ministry of Health of the Republic of Udmurtia. All patients underwent radiological, ultrasound, cytological and morphological examinations in a clinical setting.

Research materials and methods

The research into changes in arterial flow spectrum involved 2 236 patients in health aged 20 to 73, with 41 % men and 59 % women. Several types of experimental measurements were done. In order to prove occurrence of junction in contralateral arterial flows, the studies were performed on brachial artery (n = 1236).

Prior to applying tourniquet onto shoulder, the measurements were done employing Pulsed-wave Doppler on brachial artery in patients in health. After, with tourniquet applied onto shoulder, arterial flow spectrum was evaluated employing Power Doppler placed proximal and distal to the tourniquet. Visual differentiation of contralateral arterial flows was done during Spectral Doppler ultrasonography representing images of multidirectional blood flow spectra on both sides of the baseline. In addition, by means of Doppler ultrasonography, contralateral arterial flows were studied in major vessels, i.e. aorta, brachial artery, and at mouths of renal arteries. Another clinical study consisted in studying arterial blood flow in mesenteric arteries of small intestine proximal and distal to the barrier and employing visual angio-tensometry technique (n = 1000). That study preceded surgical intervention.

In order to determine organ viability, the authors suggested using the device to diagnose organ pathology and carry out optometry to record hemodynamic parameters (Russian patent of invention No. 2687775 (Sigal, 2019a)). ELKAR-6 electrocardiograph with magnification of electric signals ×10 or 20 mm/mV (Axion, Russia) was used as a graphic recorder. In order to record hemodynamic and motor skills parameters simultaneously, the paper tape rate was set at 5 mm/s. Ultrasound tests were carried out by Biosound MyLab 70 scanner (ESAOTE, Italy) and Acuson Antares (Siemens, Germany) with a linear scanning sensor ranging from 5.0 to 13.0 MHz.

Statistical analysis

STATISTICA 6 software (TIBCO Software Inc., California, USA) was used to carry out statistical analyses. For the purposes of determination sensitivity, specificity and accuracy of the proposed method, the obtained data were processed by parametric methods (the Student's t-test, the Pearson's chi-squared test, ROC-curve, as well as by rank-based nonparametric test (the

Kruskal – Wallis one-way analysis of variance). Correlation and regression analyses were performed followed by comparison of values. Distribution of quantitative traits was assessed using the Kolmogorov – Smirnov test for arithmetic calculation of average values difference, standard deviation of difference, and standard deviation of average difference error with a critical value of significance at 5 %. The Wilson's test was used to evaluate confidence intervals for relative parameters.

For the purposes of prognostic ability evaluation of the proposed method, the ROC-curve analysis was performed to determine the area under the curve (AUC) with correlation between true and false indicators (with confidence interval at 95 %). The results were further discriminated by the Wilkes method. The Student's t-test was used to calculate difference at significance level $p < 0.05$.

Results

Studies of major vessels

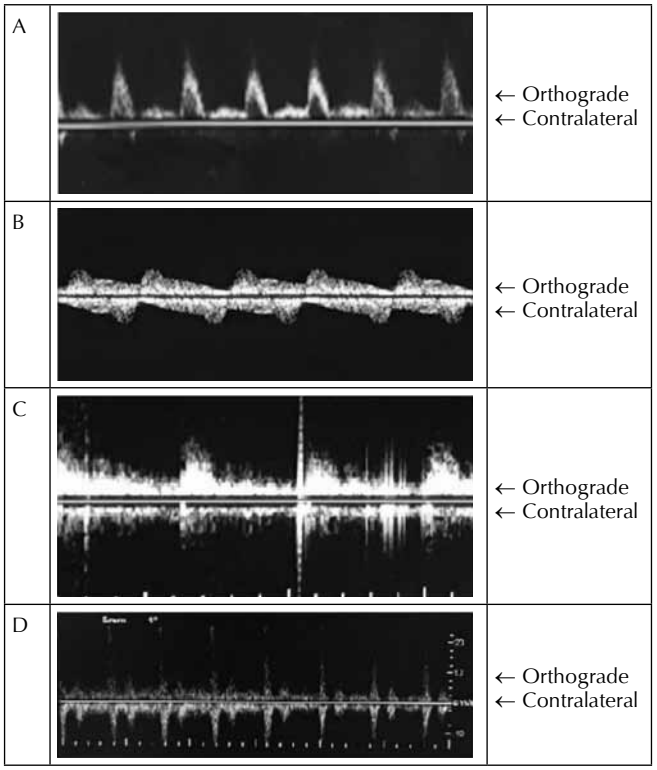
Orthograde and contralateral arterial flows differ insignificantly from each other for intramural arterial vessels, if compared to major flows, which is indicative of increasing intravascular resistance in them. The lowest resistance of orthograde blood flow to contralateral blood flow was revealed in aorta, brachial artery, and at mouths of renal arteries (table 1).

Table 1. Comparison of maximum rate indicators for orthogonal and contralateral blood flows in arteries, where *X* is an indicator mean value, d_x is a standard deviation error margin, S_x is a standard deviation. Differences among groups at $p < 0.05$ were statistically significant.

Artery	Blood flow	Maximum flow rate indicators	
		$X \pm d_x$ (cm/s) S_x	*t p*
Aorta	Orthograde	121.6±45.8 26.98	13.97 <0.05
	Contralateral	3.5±0.2 1.24	
Brachial artery	Orthograde	24.4±0.08 0.05	15.43 <0.05
	Contralateral	2.57±0.23 0.14	
Mouth of renal artery	Orthograde	124.4±39.7 13.55	14.18 <0.05
	Contralateral	5.6±0.05 0.03	
Segmental branches of renal artery	Orthograde	90.9±28.5 14.95	14.55 <0.05
	Contralateral	12.57±0.5 1.93	
Parenchymal branches of renal arteries	Orthograde	45.6±20.9 12.30	1.24 >0.05
	Contralateral	42.2±18.3 10.00	
Intramural colon vessels	Orthograde	5.2±3.3 1.75	1.68 >0.05
	Contralateral	4.2±2.3 1.80	
Ramus profundus a. cystica	Orthograde	2.31±0.6 0.27	1.34 >0.05
	Contralateral	1.8±0.9 0.66	
Knee joint artery	Orthograde	2.62±0.16 0.77	04.03 >0.05
	Contralateral	2.0±0.04 0.2	
Deep palmar arch artery	Orthograde	32.65±0.02 0.08	1.43 >0.05
	Contralateral	8.28±0.02 0.09	

In half of cases, it was impossible to differentiate contralateral multidirectional blood flow in aorta (Fig. 1*A*).

Figure 1. *A* – Doppler curve in aorta (orthograde and contralateral blood flows in patient in health)**; *B* – Doppler curve in parenchymal branches of renal arteries** (in patient in health)**; *C* – Doppler curve of arterial blood flow in *ramus profundus a. cystica (in patient in health)*; *D* – Doppler curve in deep palmar arch artery *(in patient in health)*.**



In the course of studies, criteria for gallbladder spectral curve (*ramus profundus a. cystica*), renal artery and deep palmar arch arteries were determined. Systolic spectral curve peaks proved bidirectional blood flow in projection of aortic arches, which corresponds to collision of flows in artery (fig. 1B, C, D). Blood flow spectrum changed its direction below and distal from arterial arches taking unidirectional motion while maintaining

or increasing the blood flow rate. There was no statistically significant difference revealed between orthogonal and contralateral blood flows in deep palmar arch and gallbladder arteries ($p > 0.05$) (Fig. 1D).

At various points of renal artery (at its mouth, in segmental and parenchymal branches), the phenomenon of junction of contralateral arterial flows revealed different rates above and below the baseline on the spectral curve (tab. 1, fig. 1B). Above the baseline, the rate of orthograde blood flow was 124.4 ± 39.7 cm/s at mouth, 90.9 ± 28.5 cm/s in segmental branches, and 45.6 ± 20.9 cm/s in parenchymal branches (decreasing). The rate of contralateral blood flow in an increasing order had its minimum value at mouth (5.6 ± 0.05 cm/s) and its maximum value in parenchymal branches (45.6 ± 20.9 cm/s) respectively. There was statistically significant difference revealed between orthogonal and contralateral blood flows at mouth ($p < 0.05$) and in segmental branch ($p < 0.05$). However, in overall, contralateral component was not always present. In vessels with collateral flow, the maximum rate of orthograde blood flow in parenchymal branches of renal arteries was 45.6 ± 20.9 cm/s. The maximum rate of contralateral blood flow was 42.2 ± 18.3 cm/s. There was no statistically significant difference revealed between orthograde and contralateral blood flows ($p > 0.05$).

Studies of brachial artery under tourniquet application

The maximum blood flow rate in brachial artery was evaluated by ultrasound examination of orthograde arterial flow before it was constrained by tourniquet application, and after. The lowest values were revealed in contralateral flow (2.57 ± 0.23 cm/s before tourniquet application, and 0.7 ± 0.01 cm/s after). The maximum rate values of orthograde and contralateral blood flows in brachial artery before tourniquet application and after were significantly different from each other ($p < 0.05$) (table 2). Orthograde arterial blood flow was recorded above the baseline, and contralateral blood flow below the baseline.

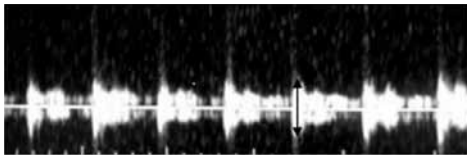
Table 2. Comparison of maximum rate indicators for orthogonal and contralateral blood flows in brachial artery, where *X* is an indicator mean value, d_x is a standard deviation error margin, S_x is a standard deviation. Differences among groups at $p < 0.05$ were statistically significant.

Brachial artery	Blood flow	Maximum flow rate indicators	
		$X \pm d_x$ (cm/s) S_x	*t p*
Prior to tourniquet application	Orthograde	24.4±0.08 0.05	15.43 < 0.05
	Contralateral	2.57±0.23 0.14	
After tourniquet application	Orthograde	2.5±0.02 6.16	6.06 < 0.05
	Contralateral	0.7±0.01 0.29	

Studies of intramural intestine vessels

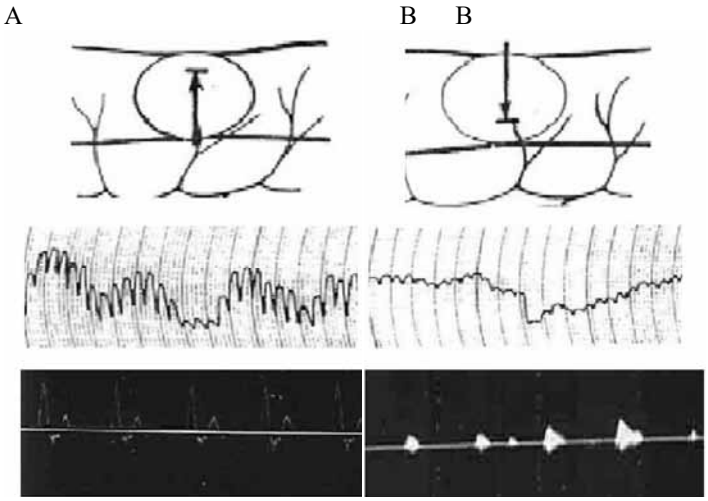
Using Doppler ultrasonography to study intramural vessels in projection of arterial arches of viable small intestine, multidirectional blood flow was recorded indicative of junction and interaction of contralateral arterial flows. Intramural vessels echogram of small intestine in healthy patient proved the occurrence of bidirectional blood flow symmetrical on both sides of the baseline (Fig. 2).

Figure 2. Doppler ultrasonography of arterial blood flow in small intestine (in patient in health)**.**



The outcome of qualitative and quantitative analyses performed by the angiotensometry device with a transparent plate barrier for intramural flows in arteries of small intestine is given in Table 1 and Figure 3 (17).

Figure 3. Arterial blood flows in intact small intestine. A – mesenteric (arterial blood pressure 110/85), B – antimesenteric (arterial blood pressure 80 mm Hg). Cumulative arterial blood pressure equals to 128/80 with the paper tape rate set at 5 mm/s and magnification of electric signal ×10 mm/mV.

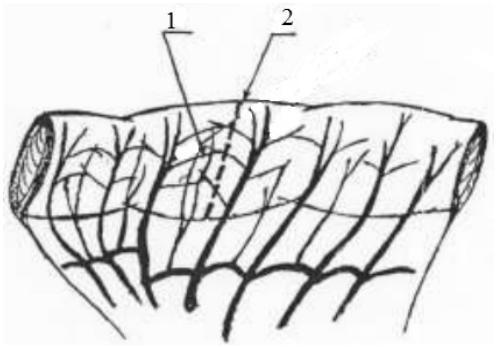


The outcome of this study was referred to for the purposes of improving various techniques of operative intervention in intestinal obstruction, and preventing anastomotic leaks after intestinal anastomosis, as well as preventing failure of intestinal stump suturing (fig. 4).

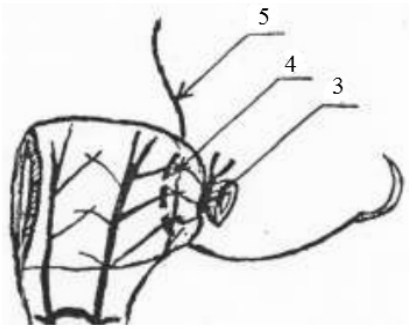
The proposed technique to prevent intestinal stump failure by purse suturing requires applying ligature in intestine at the distance of 0.5 to 1.0 cm from the junction point of contralateral intramural vessels. Purse suturing is done at the junction point of these vessels. At that, the suturing string runs above visible intramural vessels, which helps to reduce complications upon completion of this type of intervention (18).

Figure 4. Intestinal obstruction preventive technique. A – prior to operative intervention (1 – junction of arterial vessels, 2 – resection line in small intestine); B – after operative intervention (3 – intestine stump, 4 – purse suturing at the junction of contralateral intramural vessels, 5 – purse suturing above visible intramural vessels).

A



B



Discussion

This research paper proves the occurrence of junction of contralateral arterial flows by means of studies thereof in brachial artery under tourniquet application. Visual differentiation of contralateral arterial flows was done using Spectral Doppler to produce images of multidirectional blood flow spectra on both sides of the baseline. Doppler ultrasonography provided for studies of contralateral arterial flows in major vessels in humans, i.e. aorta, brachial artery, and at mouths of renal arteries. Contralateral flow rate was significantly lower and significantly different if compared to orthograde flow. Nonetheless, in vessels with collateral flow at the level of renal parenchyma, *ramus profundus a. cystica*, intramural intestinal vessels and arterial arches of knee joints, these flows were multidirectional and almost equal to each other as regards their rate.

In the course of studies, the maximum rate of orthograde blood flow proved to be higher than that of contralateral flow. This pattern concerns such vessels as aorta and brachial artery. Statistically significant difference in linear rate between orthograde and contralateral blood flows was found for vessels in kidneys, intestines, gallbladder and knee joints. These patterns of contralateral flow attributed to the fact that interaction of contralateral flows occurs in the center of hemodynamic arterial arches, as well as at their periphery. One condition remains constant, i.e. collision of contralateral arterial flows, which was proved by this research. Ultrasound data evaluation provided for the statement that, under inflammatory responses, bidirectional blood flow changed but did not subside. Bidirectional blood flow was not present in organs or tissues under threat of ischemia.

Consequently, both in a clinic setting and under experimental research study, novel hemodynamic phenomena of interaction and mutual transformation of arterial flows were discovered employing original angiotensometry, pulsomotorography and ultrasound monitoring techniques of great practical bearing, and diagnostic and therapeutic significance in medicine.

Nowadays, during ultrasound examination, quite common are errors arising from inaccurate estimation of vascular diameter, inaccurate diagnosis of stenosis or vascular thrombosis, determination of erroneous hemodynamically significant and insignificant indicators under various disorders and abnormalities of vascular development (19, 20, 21, 22). False positive and false negative results often take place when evaluating peripheral resistance in arterial vessels by ultrasound. This may lead to equivocal diagnosis of inflammatory pathology, diffused diagnostic lesions, thromboses, stenoses, etc. (23, 24, 25).

The rationale behind this research is justified by recent emphasis on the problem and field under study.

Efremushkin et al., in their research papers published in 2009 (26) highlighted the importance of researching into role and significance of systematic blood pressure, distribution of cardiac output and kinetic energy, as well as blood flow carried by major vessels. The authors stated that equally important is the relation between pulse wave rate values and linear blood flow velocity, between mechanism of its formation and occurrence patterns. The authors also studied the issue of reflected waves and occurrence thereof. By reference to Doppler ultrasonography, rate, oscillator modes and energy components of hemodynamics in arterial trunks were studied in healthy young people. The authors shared the conclusion that formation of auxiliary accelerated blood flow on Doppler-generated image was more likely associated with damping behavior of aorta, and was not the indication of reflected wave because it did not meet the physical properties of wave formation in healthy persons (26).

Based on the novel approach and involving 4D phase contrast magnetic resonance imaging technique, Zarrinkoob et al. were able to proceed with simultaneous numerical evaluation and ranking of principal bypaths in patients with carotid stenosis (27). This study demonstrated the novel approach to mapping and understanding of hemodynamic abnormalities in stenosis, and compensatory mechanism of bypaths, which would be impossible to achieve at any earlier stage (27).

In 2020, Abdelnaby published a research study on changes in hemodynamics in ovarian and uterine arteries to assess all hemodynamic changes in growing placenta and fetus in 15 healthy buffalo heifers. Indices of resistance, pulsatility, peak systolic velocity, final diastolic velocity, and blood flow rate were evaluated on ipsilateral and contralateral sides of fetus. Abnormal pa-

rameters in Doppler form for uterine artery, i.e. Doppler indices and peak indices at final rates, revealed constraints in intrauterine growth and abnormal pregnancy likely leading to prenatal death or birth of fetus with abnormalities. With the reference to this research study data, transrectal Doppler ultrasonography proved to be indispensable in terms of non-invasive technique to evaluate utero-ovarian blood flow during pregnancy (28).

The research study proved that the interaction of contralateral arterial flows was of academic and practical value for medical purposes, i.e. formation of different blood flow patterns; modeling lesion affects caused by insufficient blood perfusion (such as necrosis and ischemic pathology); bridging misbalance between actual blood supply and required needs of organs or tissues; viability evaluation of organs under different surgical interventions; prevention of necrosis, failure of anastomosis sutures, cuts, ischemic enteritis and colitis (24, 29).

Interaction of contralateral arterial flows is important in surgery during planned and emergency operative interventions on hollow organs, for prevention of failures of suturing, anastomoses, ischemic necrosis and intestine and stomach stumps leakage. The described technique was used when setting intestinal stumps at the point of junction of contralateral arterial flows when performing resection (18). Upon detecting normal intramural location of arteries, the appropriate measures were taken to have suture band available and resection level determined. After the intestinal stump was implanted, using intestinal anastomoses, patients experienced no complications (30).

The studied technique used for determination of contralateral arterial flows provides for evaluation of resistance to arterial blood flow in vessels (31).

The practical bearing of the phenomenon under study lies in the fact that baseline indicators described in this research paper can act as useful diagnostic tool to detect possible abnormalities, and can become the basis for diagnosis of diseases of local and diffuse pathology in various organs, as well as for preventing diagnostic errors. This technique is noninvasive by its nature, and has high resolution and good accuracy represented by quantitative indicators obtained during blood flow examination. Low trauma risk and absence of contraindications to introduction of this diagnostic technique enables its use when examining a wide range of patients.

Conclusion

Employment of this novel technique focusing on optometry to record hemodynamics parameters, and the existing methods to diagnose organ pathology gave the possibility to perform quantitative analysis of contralateral arterial flows significance. This research paper, by reference to Doppler ultrasonography, discussed interaction of contralateral arterial flows in major and intramural vessels. Orthograde arterial flow proved the maximum blood flow rate at systolic peaks above the baseline. Contralateral arterial flow was revealed in an instant at systolic peaks below the baseline.

The phenomenon of interaction of contralateral arterial flows being subject of this research is of high practical bearing for immediate determination of intravascular arterial resistance, prevention of false positive and false negative results, as well as for detection and differentiation of various vascular pathologies.*

***Statement on Compliance with Ethical Standards:** Disclosure of potential conflicts of interest

The authors declare that there is neither financial, nor personal relationships with other people or organizations that could inappropriately influence (bias) their work.

Ethical approval: All procedures performed in the studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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