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EFFECT OF BREATH HOLDING ON SPECTRAL DOPPLER DISPLAY AT INTERNAL CAROTID ARTERY BIFURCATION

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SUMMARY – Hemodynamic events in the area of terminal internal carotid artery bifurcation play an important role in the investigation of brain physiology and pathology. The aim of the study was to contribute to the present understanding of the relation between blood velocity in the bifurcation components, and pressure and structural changes at the local level, crucial for the development of apex aneurysm. Comparison of transcranial Doppler spectra of the components with the level of hypercapnia, i.e. with the length of conscious breath holding, produced results indicating a high significance of blood velocity in the development of the mentioned pathology. Doppler shift in the ACM component at three measured levels (following apnea of 0-10, 20-30 and 40 seconds) for the peak systolic velocity was 2.1, 2.7 and 2.9 kHz, respectively. The respective values for the ACA component were 1.9, 2.7 and 2.8 kHz. At the first two levels, the respective values for the ACM M1 segment were 2.5 and 3.4 kHz. Special significance was recorded for so-called swerve losses, which occur on sudden change of blood direction into the ACA component. These losses are closely related to blood velocity, and they are essential in the development of aneurysm. Because of ethical norms and potential risk of the experiment, the author performed the measurement on himself and by himself. A low-frequency pulsing probe of 2 MHz with a Multi-Dop P ultrasonic device (DWL – Elektronische Systeme GmbH) was used in the study.

Key words: *Carotid artery, internal, pathology; Cerebrovascular circulation, physiology; Respiration, physiology; Aneurysm, ultrasonography*

Introduction

A number of scientists have emphasized the importance of terminal internal carotid artery (TICA) bifurcation related to the referential point in transcranial Doppler (TCD) examinations of the brain base arteries as well as to the analysis of subtle blood flow changes in the course of some motor and cognitive activities. They have also emphasized the relevant pathologic changes of brain structures, especially vascular, and general physiologic events in the body[1,2]. This complex region has special importance because of the possible development of saccular aneurysm on the bifurcation apex[3,4].

The main characteristic of Doppler spectrum of TICA bifurcation is a bidirectional signal of blood flow with relatively stronger low-frequency components. The explanation of this bidirectional pattern lies in different directions of the blood flow in MCA (M1 segment, towards the probe) and ACA (A1 segment, away from the probe), and the explanation of stronger low-frequency components is found in the blunt insonation angle of the more or less curved course of TICA (curve concavity: inner wall – smaller radius – predominantly turned laterally – towards the probe; and curve convexity: outer wall – greater radius – turned medially – away from the probe). The stronger low-frequency components can also be explained by the centrifugal force effects of the shifted erythrocyte flow by MCA direction towards the outer convex side of the curve, and ACA direction, first shifted laterally (towards the stream by MCA) and at the bifurcation apex especially at high velocities abruptly shifted to ACA (Fig. 1)[5-11].

Breath holding accompanied by strong development of hypercapnia causes extensive dilatation of the brain cor-

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tical arterioles, and therefore, an increase in the blood flow velocity in the basal cerebral arteries. In this way, it is possible to find an appropriate link between blood velocity changes and changes in the spectral Doppler display of certain flow segments. This also relates to the investigated bifurcation[5,7,12-14].

The aim of the study was to determine the relation between blood flow velocity and length of breath holding. In this way, certain facts about hemodynamics in the bifurcation region can be obtained.

Table 1 shows basic physiologic and hemodynamic phenomena during conscious breath holding.

Methods

The detection and analysis of blood flow in TICA bifurcation were performed by a pulsating low-frequency 2 MHz probe of a Multi-Dop P ultrasound device (DWL – Elektronische Systeme GmbH). Through the anterior and middle right temporal window, the pulsating ultrasound beam with a power of 99-100 mV, sample volume size 13 mm, was directed to the precisely defined target depth of 65 mm. The examined area and depth were determined by specific conditions of the examination, and because of ethical norms and potential risk of the experiment, the author performed the measurement on himself and by himself. The study was performed in sitting position, in the conditions of complete relaxation. In order to avoid Valsalva's effect, the phase of breath holding was entered at the end of shallow expiration. Otherwise, respiratory excursions were minimal. The fast Fourier transformation analysis (FFTA) was adjusted to 128 frequency components (resolution). The scale ranged from 6000 Hz (234 cm/s) to 9000 Hz (351 cm/s). The measurement of the precisely defined standard parameters of Doppler spectrum of the bifurcation components of peak systolic velocity (PSV), end diastolic velocity (EDV), resistance index (RI), pulsatile index (PI), mean blood flow value (MEAN), and PSV to EDV ratio (S/D), and measurement of the relation of the border between stronger and weaker frequency components related to PSV and EDV was performed five to ten times after three strictly defined periods of breath holding, i.e. first period 0-10 s, second period 20-30 s, and third period of ≥40 s. The same measurement was also performed at MCA depth of 46-52 mm. Study results are graphically and tabularly presented.

Statistical data analysis was done by the Microsoft Excel 2000 program on a Pentium II 233 MHz computer.

Results

Increasing the breath holding time led to a significant increase in the blood flow velocity in MCA M1 segment. PSV, EDV and MEAN rose at an appropriate rate, while PI, RI and S/D decreased (Table 2). Almost identical changes occurred in the MCA bifurcation component. Here it is important to consider the real insonation angle of blood stream in the curve (Table 2). In the ACA component, velocity parameters did no show such an increase, which was especially noticeable at higher velocities in ICA, where PI, RI and S/D decreased with the rise of velocity (Table 2). The height of the border between stronger and weaker spectral components in the MCA component significantly rose in relation to PSV and EDV with the increase in blood velocity (Table 3). At normal breathing, Doppler signal in MCA M1 segment showed a diametrically opposed arrangement of stronger and weaker spectral components as compared with the signal in the bifurcation. Higher spectrum frequencies had a relatively higher intensity. Upon blood flow acceleration, there also was a significant broadening of strong components towards lower frequencies in M1 segment.

Figure 2 shows the relation between the length of breath holding and mean velocity in MCA M1 segment and TICA bifurcation components.

Discussion

Many researchers emphasize the importance of partial carbon dioxide (pCO_2) pressure as a significant factor of cortical arteriolar dilatation, and the significance of increase in the blood flow and blood flow velocity in cerebral arteries[5,7,12,13,15]. Therefore, the reaction of arteriole dilatation to the increased concentration of carbon dioxide (hypercapnia) in the blood is used in important diagnostic methods used to test vasomotor reactivity and cerebrovascular reserve[5,7,15-17].

There is common consensus that almost all methods, be they more complex (based on inhalation of an O_2 and CO_2 mixture; acetazolamide test) or less complicated but more risky, based on conscious breath holding, in normal conditions lead to an increase in the blood flow velocity in both cerebral circulation basins, without changing dimensions of the basal cerebral artery lumen[5,7,12-14,16,17]. The increase of blood flow velocity in basal cerebral arteries and in TICA bifurcation components can be explained by basic equations of fluid dynamics and hemo-

Table 1. Basic physiological and hemodynamic phenomena during experimental breath holding

Normal breathing during total relaxation		
Conscious breath holding during precisely defined time period		
The emergence of hypercapnia		
Vasodilatation of cerebral vasomotor arterioles with a decrease of pressure (P2) in their supplying region		
Pressure gradient dP (P_1-P_2) rises between ACI and arteriolar supplying regions of cerebral arteries		
The results are:		
Flow increase	$Q = \frac{dp \text{ x } Pi \text{ x } r^4}{8 \text{ x } n \text{ x } L}$ (Poiseuille's relation)	with arteriolar dilatation, total r and dP significantly rise
Blood flow velocity rises	$v = \frac{dP \text{ x } r^2}{8 \text{ x } n \text{ x } L}$	n = viscosity r = vessel radius L = length of vessel segment
Total resistance falls	$R = \frac{8 \text{ x } n \text{ x } L}{Pi \text{ x } r^4}$	Pi = Ludolf's number (3.14)
Kinetic energy of the blood stream rises	$Ek = \frac{m \text{ x } v^2}{3}$	v = blood velocity m = density, mass
Centrifugal force in the curve rises	$F = \frac{m \text{ x } v^2}{Ra}$	Ra = curve radius
The fastest flow direction before complete separation into MCA and ACA becomes more vertical in relation to the ultrasound beam and bifurcation apex		There is a significant rise in pressure the bifurcation apex at the site of stream swerve, especially in ACA.
Direction of blood swerve into ACA is on increasingly sharp and swerve losses are greater. blood Swerve radius of blood stream (Ra) becomes smaller.		

dynamics (Table 1). Poiseuille's equation explains this very clearly[18,19]. Therefore, as the time of breath holding is longer, hypercapnia is greater, arteriolar dilatation is stronger, total resistance to the flow is lower, and the blood flow and its velocity rise[7].

The study obviously confirmed the positive relation between breath holding time and blood flow velocity in basal cerebral arteries (PSV, EDV, MEAN). Breath holding also leads to the fall in RI, PI and S/D.

In order to understand the results obtained, it is necessary to emphasize that the force of spectral frequency component signals is proportional to the number of erythrocytes moving in the same direction and causing the same Doppler shift (the importance of gray scale)[5,8,19].

Let us direct our attention to the characteristics of Doppler spectrum in TICA bifurcation. The bidirectional or 'butterfly' waveform spectrum has already been mentioned. In the conditions of rest and normocapnia, the signal force (represented by the gray scale intensity) of the low-frequency spectrum components throughout the cycle is relatively stronger than that of the high-frequency components. This refers to the positive display part (towards the probe) as well as to the negative display part (away from the probe)[5]. During the systole, the relatively well

Table 2. Relation between the length of breath holding and basic Doppler spectrum parameters of the investigated MCA (M1) segments and TICA bifurcation components

Parameter	Breath holding			Breath holding			Breath holding		
	0-10 s	20-30 s						≥40 s	
	MCA M1	bifurcation components		MCA M1	bifurcation components		MCA M1	bifurcation components	
		MCA	ACA		MCA	ACA		MCA	ACA
		(65 mm)			(65 mm)			(65 mm)	
PSVcm/s	96.8	82.9	74.2	134.4	104.3	103.9		113.3	110.8
df in kHz	2.5	2.1	1.9	3.4	2.7	2.7		2.9	2.8
				Increase 38.8%					
EDVcm/s	43.0	37.2	32.8	60.8	49.5	44.2		61.3	50.3
df in kHz	1.1	0.9	0.8	1.5	1.3	1.1		1.6	1.3
				Increase 41.3%					
MEANcm/s	61.2	51.0	45.0	84.2	65.3	60.8		80.8	71.0
df in kHz	1.6	1.3	1.1	2.1	1.7	1.5		2.1	1.8
				Increase 37.6%					
PI	0.88	0.9	0.92	0.86	0.85	0.99		0.65	0.85
RI	0.55	0.55	0.55	0.54	0.56	0.57		0.46	0.53
S/D	2.22	2.23	2.26	2.20	2.33	2.38		1.85	2.20

Explanation: transformation formula on the scale: v in cm/s = df in kHz x 39; the device records concrete df in Hz and transforms it into appropriate scale velocity in cm/s using correction factor cos 10° (0.98481) – this is satisfactory in smaller insonation angles; according to this, the values obtained nearly correspond to the real velocities in MCA M1 segment. Besides the absolute increase, the relative increase of PSV, EDV and MEAN in M1 segment after breath holding of 20-30 seconds is also shown.

noticeable border between the stronger and weaker components rises towards higher frequencies, and during the diastole it falls down.

The study results indicate the following: the spectral form analysis shows that the increase in blood flow velocity causes greater homogenization of erythrocyte flow in the more vertical relation to the bifurcation apex and penetrating ultrasound beam. This is primarily related to the fastest blood layer of the MCA bifurcation component (effects of velocity, mass, inertia, centrifugal force). At the same time, the erythrocyte flow which will swerve into ACA bifurcation component also becomes more homogenized and inclines towards the MCA stream. In this way, this erythrocyte stream can even contribute to the strength of positive low-frequency signals. There is an increasing 'separation' by the inner curve wall at the beginning of ACA. At the bifurcation apex, proportionally to the blood flow velocity, the middle joint flow, sharply swerving, is abruptly (especially in ACA direction) separated into ACA and MCA direction. Doppler records two flows of opposite directions and of significantly strong spectral components, from basal to apical values.

The sharpest swerve with the blood flow velocity increase occurs in ACA direction. At the site of sharpest swerve at the bifurcation apex, there is a significant transformation of great amounts of kinetic energy into potential pressure energy. This is accompanied by adequate wall convexity, especially in the systole phase. As the central shock stream becomes more vertical, the stress is also stronger. There is a significant strain of local wall structures of the mentioned convexity, and the possibility of the development of aneurysm increases (Fig. 1).

Blood has its volume, mass, velocity, and inertia. When the blood enters the curve, centrifugal force effects occur proportionally to the flow velocity, and these effects cause a shift of fluid particles and erythrocytes towards the outer wall of the curve. This is mostly related to the fastest parts of velocity profiles. The explanation of this can be found

Table 3. Relation between the length of breath holding and relative border height between stronger and weaker frequency components in the spectrum of MCA bifurcation component

Parameter	Breath holding 0-10 s (65 mm)	Breath holding 20-30 s (65 mm)	Breath holding ≥40 s (65 mm)
PSV	82.9 cm/s (2.1 kHz)	104.3 cm/s (2.7 kHz)	113.3 cm/s (2.9 kHz)
EDV	37.2 cm/s (0.9 kHz)	49.5 cm/s (1.3 kHz)	61.3 cm/s (1.6 kHz)
Border height at PSV level	47.7 cm/s (1.2 kHz)	79.5 cm/s (2.0 kHz)	101.4 cm/s (2.6 kHz)
Border height at EDV level	23.4 cm/s (0.6 kHz)	43.5 cm/s (1.1 kHz)	56.3 cm/s (1.4 kHz)
Relation between border height and PSV	57.57%	76.22%	89.50%
Relation between border height and EDV	62.98%	87.88%	91.76%

Explanation: target insonation depth of MCA bifurcation component is 65 mm; scale transformation cm/s in kHz is obtained by the formula: v in cm/s = df in kHz x 39; in the Doppler formula, the device uses correction factor cos 10° (0.98481).

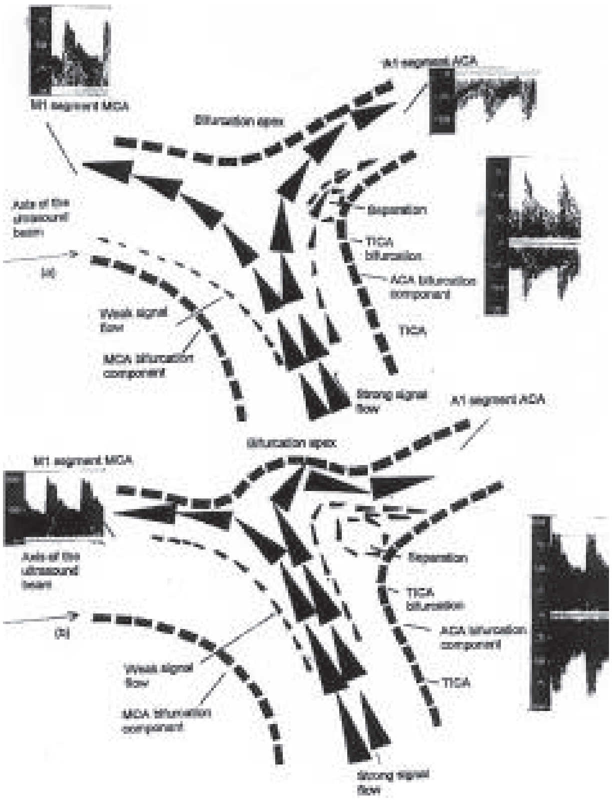

Fig. 1. Blood flow in TICA bifurcation at normal breathing (a) and after prolonged breath holding (b)

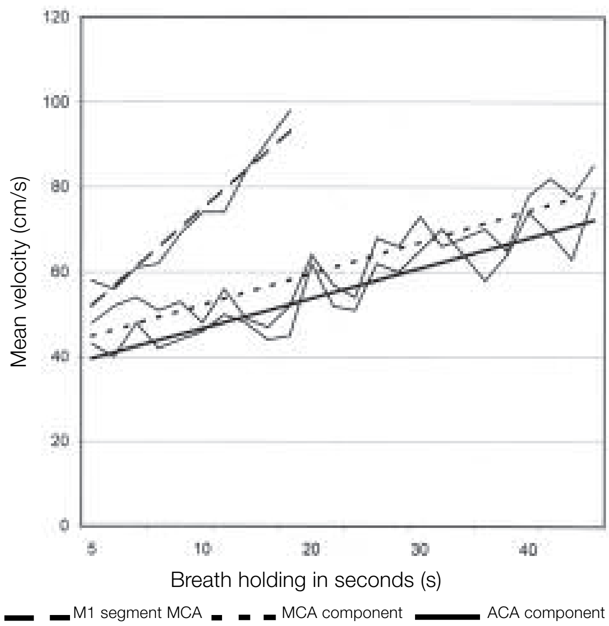

Fig. 2. Relation between the length of breath holding and mean velocity in MCA M1 segment and TICA bifurcation components

r MCA M1 segment = 0.956
r ACM component of bifurcation = 0.933
r ACA component of bifurcation = 0.927

in the formula of the centrifugal force strength, which is proportional to the mass and square of velocity, and inversely proportional to the size of the curve radius (sharper curve, smaller radius, greater force). At the outer curve wall, the streams are condensed, the pressure is increased, and the velocity is decreased. The velocity profile is significantly asymmetrical. The separation of the blood flow stream from the vessel wall is possible. The Bernoulli relation does not apply to this case[6,11]. While local pressure at the bifurcation apex rises, the blood pressure at the concave inner wall of both curves remains lower.

The increase in blood flow velocity leads to a sharper swerve in ACA direction (A1 segment), and to a certain degree but not so strongly, in MCA (M1 segment) direction. The so-called curve losses occur, consisting of two components: swerve losses and frictional stress losses. As the radius of the curvature is smaller, swerve losses are greater and frictional stress losses are smaller. Greater radius leads to smaller swerve losses and greater frictional stress losses[11]. The mentioned losses of movement energy are manifested as the local pressure rise, heat release, and mechanical changes of fine wall structures. Using the fluid mechanics expressions, we can say that the increase in blood velocity in TICA leads to increasing swerve losses in ACA direction. The released energy causes significant exertion of vessel wall structures, as well as the previously mentioned risks[3,4].

The analysis of blood velocity increase in the bifurcation components shows that velocities in the MCA component regularly follow the determined velocity increase in MCA (M1 segment). Considering the supposed blunt insonation angle of MCA component in relation to MCA (M1 segment), and an adequate blood flow velocity increase in the curve, we can also obtain the mentioned regular velocity increase. On the other hand, a much lower increase of velocity in the ACA component, despite the supposed significant decrease of the insonation angle, can be explained by the significant rise in swerve losses, incomparably greater than during swerving into MCA.

The analysis of hemodynamic events at the exit of blood flow from the bifurcation into a relatively flat, mildly curved MCA segment shows that the velocity increase leads to increasing erythrocyte flow homogenization at the outer part of the curve (the events continue in TICA), where velocities are also greater. There is an abrupt transfer from zero velocity by the very wall to maximum velocities, the density being high almost everywhere. Because of that, all spectrum frequencies show relatively strong signals. Considering the great blood flow velocities, it is certain that disorders of the blood flow do occur, and there are additional explanations in accordance with Reynold's relation. The pulsatile character of the blood flow has, at increasingly higher velocities, an additional potentially damaging effect on the wall in the region of bifurcation apex.

Harmonious activity of the elastic thread system in the area of bifurcation apex is indispensable for the swerve losses to remain within a tolerable range. This harmony of activities is determined by the wall metabolism and by physiological and biochemical processes related to elasticity: higher velocities require greater activity of the elastic system. Greater activity compensates for greater swerve losses, but leads to stronger wall metabolism, more heat release, and formation of detrimental products, especially free radicals that are extremely harmful for elastic structures. Some recent investigations show great resistance of the bifurcation apex to the effects of heat and free radicals[20].

When analyzing these issues, it has to be stressed that besides a number of factors which are favorable to the development of intracranial aneurysms, family and genetic components are also very important[4,21-23].

Conclusion

Conscious breath holding accompanied by hypercapnia represents a strong stimulus for dilatation of distal vasomotor resistive arterioles. The length of breath holding is proportional to the degree of induced hypercapnia. It is also proportional to the blood flow velocity acceleration in basal cerebral arteries. Spectral forms of TICA bifurcation components are closely connected to the degree of hypercapnia and the accompanying blood flow velocity. They all contribute to the explanation of hemodynamic events in the investigated region and development of aneurysm at the sites of highest pressure and strain of the vessel wall.

The observed swerve losses in the ACA bifurcation component presented by a disproportionally small rise in blood velocity in relation to the velocity increase in MCA M1 segment and MCA component, just point out the weakness of elastic structures of the bifurcation apex, greater deformation of the wall (convexity), and the risk of aneurysm development. This especially refers to people with family inclination to this pathology.

Therefore, individuals with a family history of subarachnoid hemorrhage (SAH) should have the possibly existing pathology examined as early as possible. However, due to the high cost of such examinations, swerve losses in the area of accessible bifurcations could be evaluated through tests, shorter periods of breath holding, and by the relatively less expensive TCD method. Individuals with greater losses should further be under special observation.

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Sažetak

UTJECAJ PREKIDA DISANJA NA IZGLED DOPLERSKOG SPEKTRA BIFURKACIJE TERMINALNOG DIJELA UNUTARNJE KAROTIDE

N. Barić

Hemodinamička zbivanja u području bifurkacije terminalnog dijela unutarnje karotide čine važno mjesto u ispitivanju fiziologije i patologije mozga. U tom smislu je cilj istraživanja bio dati doprinos shvaćanju veze brzine krvi u sastavnicama bifurkacije s tlačnim i strukturalnim promjenama na lokalnoj razini, presudnima za razvoj apikalne aneurizme. Usporedbom transkranijskih doplerskih spektara sastavnica sa stupnjem hiperkapnije, tj. s duljinom svjesnog prekida disanja, dobiveni su rezultati koji upućuju na veliko značenje brzine krvi u razvoju spomenute patologije. Dopplerov pomak u sastavnici ACM na tri razine mjerenja (nakon apneje od 0-10, 20-30 i 40 sekunda) iznosio je 2,1, 2,7 i 2,9 kHz za vršnu sistoličku brzinu. Vrijednosti za sastavnicu ACA bile su 1,9, 2,7 i 2,8 kHz. Te vrijednosti na prvim dvjema razinama iznosile su za M1 segment ACM 2,5 i 3,4 kHz. Posebno značenje dobivaju tzv. gubici skretanja nastali pri nagloj promjeni smjera krvi u sastavnicu ACA. Ovi su gubici u uskoj vezi s brzinom krvi. Oni se pretvaraju u tlačnu, toplinsku i mehaničku energiju. Bitni su u razvoju aneurizme. Zbog etičkih norma i potencijalne opasnosti eksperimenta autor je mjerenja provodio vlastoručno na samome sebi. Tijekom ispitivanja rabljena je niskofrekventna pulzirajuća sonda od 2 MHz u sklopu ultrazvučnog uređaja Multi-Dop P (DWL – Elektronische Systeme GmbH).

Ključne riječi: *Karotidna arterija, unutarnja, patologija; Cerebrovaskularna cirkulacija, fiziologija; Respiracija, fiziologija; Aneurizma, ultrasonografija*