ISSN 0022-0930, Journal of Evolutionary Biochemistry and Physiology, 2008, Vol. 44, No. 5, pp. 605—614. © Pleiades Publishing, Ltd., 2008.
Original Russian Text © Yu. E. Moskalenko, G. B. Weinstein, P. Halvorson, T. I. Kravchenko, N. A. Ryabchikova, A. Feilding, V. N. Semernya, A. A. Panov, 2008, published in Zhurnal Evolyutsionnoi Biokhimii i Fiziologii, 2008, Vol. 44, No. 5, pp. 513—520.

COMPARATIVE AND ONTOGENIC PHYSIOLOGY

Biomechanical Properties of Human Cranium: Age-Relayed Aspects

Yu. E. Moskalenko, G. B. Weinstein, P. Halvorson, T. I. Kravchenko, N. A. Ryabchikova, A. Feilding, V. N. Semernya, and A. A. Panov

Sechenov Institute of Evolutionary Physiology and Biochemistry, Russian Academy of Sciences, St. Petersburg, Russia

Received August 27, 2007

Abstract—Biomechanical properties of the human skull affect its dynamic tensility (pliability or compliance) at changes of intracranial volume and pressure ($\Delta V/\Delta P$). The work substantiates a possibility of noninvasive and dynamic evaluation of cranial compliance by synchronous recording of transcranial dopplerogram of middle cerebral artery and cranial bioimpedance that provides information about pulsative changes of intracranial pressure and volume, respectively, with subsequent computer pattern and phasic analysis of these processes. The characteristic peculiarities of the cranial compliance at rest and during action of functional hemo- and liquorodynamic tests were traced in people of the middle (40—50 years) and elderly (70—85 years) age groups as compared with the young group (20—30 years). A relative decrease of this parameter has been revealed in the middle age group due to an increase of rigidity of skull bones and ligaments, which indicates a decrease of tolerance of the intracranial circulatory system. However, in the group of 70—85 years the compliance parameters rose due to an increase of intracranial liquor volume and activation of liquor circulation inside the craniospinal space, which is a compensatory mechanism for maintenance of the adequate brain circulatory-metabolic activity.

DOI: 10.1134/S0022093008050101

Key words: intracranial hemo-liquorodynamics, cranial compliance, age-related aspect.

INTRODUCTION

Study of mechanical skull properties, based on determination of interrelations between the volume of the cranial content and intracranial pressure (P—V) is of multiplan interest and long has attracted attention of researchers [1, 2]. However, no marked progress in this aspect has been achieved so far due to methodical difficulties. Indeed, to determine the cranial P—V, it is necessary not only to measure invasively the intracranial pressure, but also to administer into the skull the fixed volumes of a liquor-substituting fluid, which is admissible only during neurosurgical interventions.

For several years, to study the cranial P—V, methods of mathematical modeling were applied; based on results of individual measurements, they allowed revealing some regularities of the skull biomechanics and introducing the notion of cranial pliability as of an important property of this complex structural system [3, 4], which is known in publications under the title of cranial compliance (CC).

Only recently a possibility has been shown of a noninvasive determination of the skull P—V by using MRI-tomography [5, 6], the most efficient turning out to be the approach, in which the contrast MRI was combined with modeling [7]. Be-

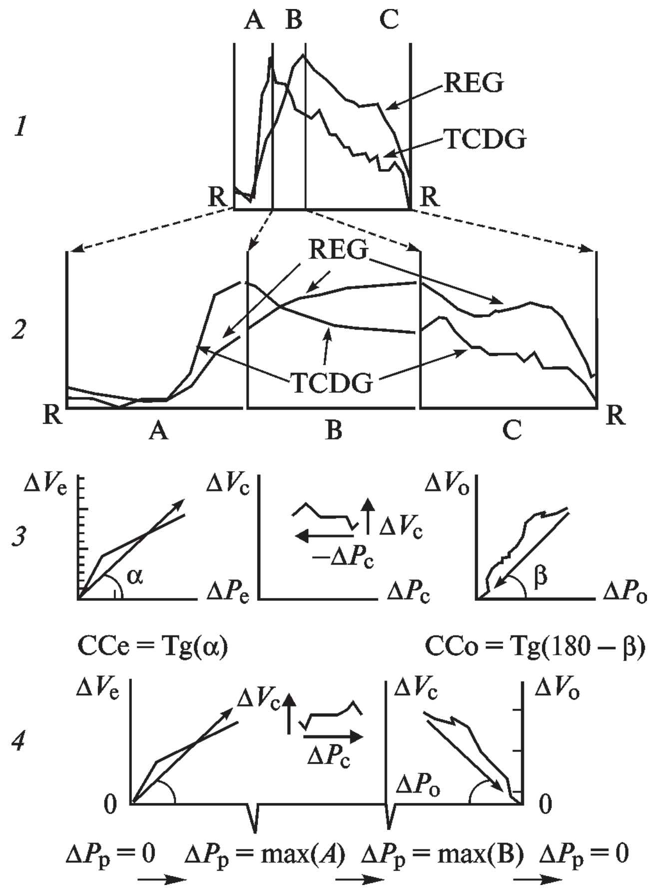

Fig. 1. Division of cardiac cycle according to data of standardized pulse curves of TCDG and REG (*1*) into phases: phase of elastic expansion (A), phase of compensation of CSF and blood volume in the cranial cavity (B), and phase of blood ouflow from the skull (C), their computer processing (*2*), and transformation into the dependence $\Delta V/\Delta P$ (*3*, *4*). Explanations are in the text.

yond any doubts, such approach gives good results, but its use is quite limited, as each such most expensive MRI-study is unique.

At the same time, there is a possibility of developing the method of estimation of the skull $P-V$ and of determination of its CC, which is available for a wide use both in physiology and in clinical practice. This method is based on simultaneous use of two noninvasive methods—rheoencephalography (REG) and transcranial dopplerography (TCDG), with subsequent analysis of their combined dynamics in the course of the pulse cycle by combination of the pattern and phasic methods. Such combined pattern-phasic analysis of trigger waves of these parameters, in turn, allows the noninvasive determination of interconnection of $P-V$ and calculation of the skull compliance in different phases of the pulse cycle. Taking into account the above-said, the present paper describes results of using combination of the TCDG and REG methods to evaluate the skull biomechanical properties and their peculiarities in the age-related aspect. Since the methodical approach used in the present study is novel, its description below will be paid a particular attention.

MATERIALS AND METHODS

$P-V$ and the cambial compliance were determined from results of simultaneous recording and combined analysis of TCDG recorded in the base of the middle carotid artery (MCA) and of REG at the ipsilateral frontomastoid position of electrodes, which provides information about the volume changes in the basin of the same artery. In the studies, we used the methodical complex that we described earlier [7–10]. The CC study was performed at the cardiac cycle period, as pulse oscillations of arterial pressure produce multiplan changes of the relation of volumes and pressures of liquid media in the skull. This approach was already used successfully at studying intracranial hemoliquorodynamics [11, 12].

Based on our accumulated experience [8, 11] for analysis of detection of the CC peculiarities, the cardiac cycle was subdivided into three phases, each differing by peculiarities of the ratio of the intracranial hemoliquorodynamics (Fig. 1).

The first phase, CCe, is the phase of elastic skull stretching, which represents a time period from the beginning of the pulse elevation of TCDG and REG to achievement of maximal TCDG values (Fig. 1, *1*A), the rise of TCDG in adult people always being ahead of the REG rise [11]. At this time period, the volume of blood inflowing into skull is determined exclusively by its biomechanical properties including the articular mobility of cranial bones in their junction places [13, 14], elasticity of brain meninges, and biomechanical peculiarities of other structural skull components, which is reflected in relations of dynamics of REG and TCDG dependences. The REG changes at the anacrota period correspond to a pulse increment of the intracranial blood volume, whereas the

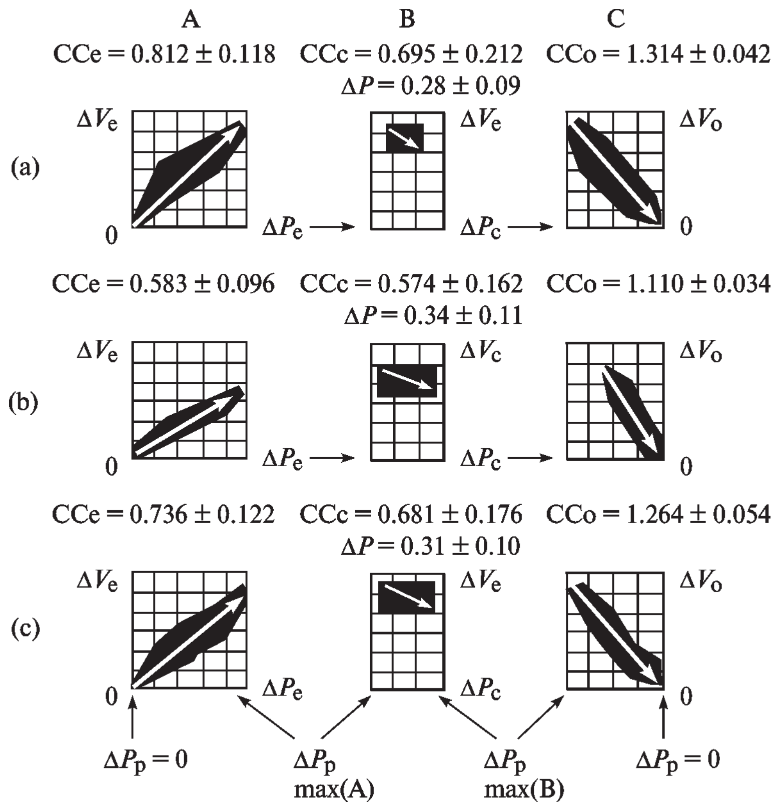

Fig. 2. Principle of calculation of values of CC (m ± St. Dev., $n = 15$) for various cardiac phase cycles (A, B, C) in three age groups of examinees. Age groups (years): (a) 20–30, (b) 40–50, (c) 75–85. Other explanations are in the text.

TCDG changes reflect an elevation of the intracranial pressure initiated by a rise of the blood volume in the skull.

The second phase, CCc, is the phase of compensations. It represents a time period between the maximal TCDG and REG values (Fig. 1, *1*B), which is determined by a change of ratio of volumes and pressures of liquid media (blood and cerebrospinal fluid, CSF) in the skull at the given time period. It is important that at this time period, the recorded parameters often change to opposite directions and non-proportionally.

This fact indicates that at this time period of the cardiac cycle, compensatory CSF overflows occur in the very skull cavity and between cavities of the skull and the spinal column. If maximal values of the TCDG and REG pulse waves coincide, this means that the compensatory CSF overflows either are absent or are not revealed by the used procedure.

The third phase of the cardiac cycle, CCo,—from the beginning of a decrease of REG to completion of the cardiac cycle characterizes the blood outflow from the skull (Fig. 1, *1*C). Participated in this phase, apart from the cardiac output energy, are respiratory pressure changes in the system of the superior vena cava; therefore, depending on the respiration phase, the REG levels in the beginning and end of the cardiac cycle often do not coincide. This means that depending on respiration phase, some blood volume can be left in the cranial cavity, which agrees with results of MRI-studies [6].

Thus, from positions of the concept of CC, the cardiac cycle can be presented as three components shown in graphs (Fig. 1), each formed by different factors.

An important step determining eventually the possibility of using in practice the data about peculiarities of TCDG and REG dynamics at the cardiac cycle period is standardization of the process of treatment of the obtained data. This is the only possible way to provide the compatibility of results of studies not only in different people examined under similar conditions, but also in the same person in different organism states.

The process of analysis of results obtained using the simultaneous TCDG and REG recording was standardized with aid of possibilities of the software Chart 5..2,6, Chart 3.52 ACP PowerLab-4 and consisted in three stages.

(1) First standardized were the chosen for analysis of initial pulse waves of TCDG and REG. The criterion for choice of the pulse waves characterizing state of the studied system (rest, action of functional tests, etc.) is the absence of any artifacts on the chosen curves, which is reflected in their similarity with neighbor pulse cycles with the same initial background and respiration phase. The process of standardization of the TCDG and REG pulse waves by amplitude and duration of the TCDG and REG pulse curves, of which result is presented in Fig. 1, *1*, was described in our previous publications [8, 11].

(2) Further, the above-identified three phases of the pulse cycle were presented as individual graphs with *P—V* coordinates, with identical scale on the ordinate axis, while the abscissa axis scale was made the same, i.e., standardized regardless of the real duration of some particular cardiac cycle phase (Fig. 1, *2*).

(3) Then each of the graphs (Fig. 1, *2*) was transformed into the TCDG—REG dependence, which corresponds to the *P—V* dependence; for unification of the presented data, the ratio of the coordinate became equal to 1.0. Thereby each of the obtained graphs represented the *P—V* dependence for each cardiac cycle phase in comparable coordinates (Fig. 1, *3*). With such way of presentation of the obtained data, it is possible to determine CC for each of the above phases of the cardiac cycle.

In the phase of the elastic skull stretching, CCe can be determined from results of measurement of the slope angle of the straight line approximating the TCDG—REG dependence in this cardiac cycle phase. This is admissible, as deviations from the real dependence of these parameters from the straight line are insignificant and seem to be determined by random factors. In Fig. 1, *3*, and Fig. 2, these straight lines are presented as the lines with arrows indicating direction of the ΔP change in this particular graph.

In the second cardiac cycle phase, the ratio $\Delta P/\Delta V$ already depends not on the biomechanical skull properties, but on compensational overflow of CSF, its volume, and conductivity of liquor circulation pathways as well as on regional changes of the cranial blood filling. The phase of compensatory CSF overflows can represent a fragment of a curve of quite different configuration that is determined by peculiarities of the ratio of volumes and pressures of liquid media—blood and CSF in the cranial cavity and is expressed in the CCc parameter. The CCc parameter can change within wide limits.

Here the extreme cases are, first, the presence of changes of V_c with unchanged ΔP_c and, second, the presence of ΔP_c with unchanged ΔV_c. The former indicates redistribution between the blood and CSF volumes in the cranial cavity without changes in the intracranial pressure, while the latter—an active replacement of CSF from the cranial cavity into the cerebrospinal space due to an elevation of the intracranial pressure, with the ratio of the blood and CSF volumes in the skull remaining unchanged. Corresponding to the first case is the value of $\Delta V/\Delta P > 1.0$, while to the second case—$\Delta V/\Delta P < 1.0$. The intermediate position is occupied by the situation when ΔP and ΔV are equal and the $\Delta V/\Delta P$ ratio amounts to 1.0. This indicates the absence of any compensational liquorodynamic processes.

The third phase is characterized by return to the initial value of blood and CSF volumes in the skull. Therefore, this dependence in the $V_o—P_o$ coordinates represents a monotonously descending curve that also can be approximated by the straight line, the informational parameter for CCo serving the slope angle of the approximating straight line.

The data presented as three individual graphs on the ratio of parameters of the simultaneous TCDG and REG recording in the chosen cardiac cycle phase (Fig. 1, *3*) can be grouped and present as the summarized graph. This needs, in turn, corresponding transformations of abscissa axes of these graphs, as each of the graphs in Fig. 1, *3*, is calculated independently.

Indeed, in the beginning of each coordinate system (Fig. 1, *2*) there are values presented on axes of the graphs. However, if this is acceptable for the ordinate axis, it is not for the abscissa axis, as whereas on the graph of the Fig. 1, *3*A, the pressure (P_e) rises from the initial level to its maximum value, on the graphs of Fig. 1, *3*B, and Fig. 1, *3*C, it decreases from the maximum value to its initial value. If on the graph of the Fig. 1, *3*B, the pressure (P_e) decreases insignificantly, within the limits between the maximal REG and TCDG values, on the graph in the Fig. 1, *3*B there occurs the main fall of the pulse pressure (P_o) to the initial value.

Therefore, for the possibility of comparing the above-presented cardiac cycle phases, direction of abscissa axes of the graphs in Fig. 1, *3*B, and Fig. 1, *3*C is to be changed to the reverse in order to them corresponding to direction of abscissa axes of the graphs in Fig. 1, *2*.

This is not difficult to perform using the software Macintosh-G4 (OS-10.4) Canvas 6–10. Results of such transformation are shown in Fig. 1, *4*. As a result, the scale of ΔP on the abscissa axis in the graphs is non-uniform by its value and direction: initially the ΔP_e value gradually rises to reach maximum at the maximal value of the TCDG pulse wave (Fig. 1, *4*A). Then P_c in the phase of compensations somewhat decreases (Fig. 4, *1*B) and returns to the initial level in the phase of blood outflow from the skull (Fig. 1, *4*C). In other words, P_e in the graph of the Fig. 1, *4*A, increases from the initial to the maximal level, while in the graphs of Fig. 1, *4*B, and Fig. 1, *4*C, the pressures P_c and P_o decrease. As a result, the initial or zero P_e value (Fig. 1, *4*A) is located on the left, while at the end of the cardiac cycle, P_o (Fig. 1, *4*C) it is on the right.

The above-presented transformation allows combining the graphs representing peculiarities of the *P*—*V* dependence for the system of skull at various cardiac cycle phases that characterize changes in its internal volume both due to the biomechanical cranial properties and due to systemic processes—changes of the volume ratio of blood and CSF in the skull and the CSF overflow into the spinal cavity. Such transformation also allows introduction of the measurement unit common to all CC constituents. Indeed, since in graphs A and B of the Fig. 1 the obtained dependence can be approximated by the sloped straight line, while the total appearance of the *P*—*V* dependence is close to that of the tangential straight line [2], the most acceptable for expression of CC can be the value of tangency of the slope angle of the approximating straight line. CCe can be expressed numerically as tangency of the slope angle of the approximating straight line Tgα (Fig. 1, *4*A), while for CCo, due to a change in the abscissa axis orientation in this graph, the numerical value of CCo will correspond to Tg $(180° - \beta)$. The numerical CCo value will correspond to the ratio $\Delta V_c/\Delta P_c$ in the graph of the Fig. 1, *4*B.

To better characterize the parameter important for understanding of ways of compensation of the systolic blood volume in the skull, it is also worth indicating, together with the $\Delta V/\Delta P$ ratio, the ΔP_c value in this cardiac cycle phase as the ratio of the ΔP_c value in the graph of the Fig. 1, *4*B, to the abscissa axis value of this graph, restricted by the maximal ΔP value at the moment of maximum of the TCDG pulse wave (ΔP_p max A) and the ΔP value at the moment of the maximal REG value (ΔP_p max B).

It is to be emphasized that the above-considered dependences relate only to the fragment of the total *P*—*V* curve determined by the value of the arterial pressure pulse change. Meanwhile, there is a possibility of enlarging the boundaries of this curve fragment, which can be realized by using functional tests affecting various parameters of the intracranial hemoliquorodynamics. Thus, the ratio of volumes and pressures of intracranial liquid media can be changed by a respiration delay for 20–30 s, which increases the intracranial arterial blood volume and suppression of liquorodynamic processes. An increase of the CSF volume and pressure in the skull can be caused by pressing on the abdominal area, which increases the blood filling of vertebral venous plexuses and initiates the CSF outflow into the skull (the Stuckey's test) [14]. The brief respiration delay during a deep inspiration decreases, while during the deep expiration—increases the skull venous blood filling [15]. It is also possible to use other functional tests, for instance, those of Valsalva and Kwekkenstedt, and orthostatic tests.

To find out the actual significance of the above-expressed considerations about the noninvasive and dynamic monitoring of the ΔP—ΔV ratio for skull and its peculiarities at various phases of cardiac cycle, 60 healthy people aged from 18 to

55 years were examined. At the examination, the patients were in the horizontal position with closed eyes. The REG electrodes, 3 cm^2 in area, were applied frontomastoidally, while TCDG was recorded in the basis of the middle cerebral artery as a rule via the temporal “window” in the skull. In some cases in elderly people the TCDG recording was performed via the orbital “window.” After recording of the background for 1 min there were recorded 5–7 cardiac cycles on the background of the deep inspiration and expiration and after 2–3 min—at the 30-s delay of respiration and 2 min later the Stuckey’s test was performed for 20 s. To analyze changes of the TCDG and REG ratio on the background of functional tests, pulse cycles were chosen in the beginning of the Stuckey’s test (2–4 s) to reveal effect of primary changes of liquorodynamics. At the delay of respiration, the pulse cycles were taken for analysis before the end of the test. Recordings were performed mainly from the right hemisphere, but in several cases, when the hemispheric asymmetry could be expected, the recording with use of all enumerated tests was done both to the right and to the left.

The results were expressed as the mean ± the standard deviation ($x \pm S_x$).

RESULTS AND DISCUSSION

Data of determination of CC components in various phases of the cardiac cycle indicate that values of these parameters vary within significant limits if to summarize the results obtained in all examined people in the quiet state. Thus, the CC value is within the limits from 0.52 to 1.23 to amount, on average, 0.71 ± 0.14 ($n = 60$), while the CCc value fluctuates from 0.23 to 1.90, on average, 0.66 ± 0.2 ($n = 60$). The ΔP values amount to from 0.10 to 0.70 rel. units, on average, 0.32 ± 0.14 ($n = 60$). The CCo parameter changes relatively less—from 1.15 to 1.38, on average, 1.23 ± 0.06 ($n = 45$). Values of the linear blood flow rate for the examined persons at rest are within the limits from 26 to 98 cm/s to amount, on average, 56.6 ± 17.1 cm/s ($n = 45$).

These figures show that values of the CC components as well as the blood flow rate in the middle cerebral artery vary significantly in different people. Therefore, to get an idea of the boundaries of their physiological norm, it is reasonable to group the examined persons by some sign; the most acceptable among those seems the age-related one, as with age there are changed biomechanical skull properties, liquorodynamic processes, and cerebral blood flow.

Taking into account our earlier obtained data [8, 11], it follows that due to peculiarities of intracranial hemoliquorodynamics the most interesting is comparison of the CC component values in the younger (20–30 years), intermediate (40–50 years), and older (70–85 years) age groups. Indeed, differences in the CC component values at rest in these age groups differ essentially from each other (Fig. 2), but vary less within the limits of one age group. This follows from the CCe and CCo values shown in the graphs (Figs. 2A, 2C), in which the P—V ratio is expressed as the approximating straight line with an arrow that also is of informative significance, like in Fig. 1, and dispersion of data of individual determinations of CC components is shown as drafted zones around the arrows.

The CCc differences in the chosen age groups change within the wider limits, as compensatory liquorodynamic processes can be realized by different ways. This is reflected in that the V_c—P_c dependences can have quite different appearance; for their approximation the most suitable is a rectangle with the sides reflecting the mean ΔV_c and ΔP_c values (Fig. 2B). The rectangle sides correspond to dispersion of data of different studies within one age group, while the $\Delta V_c/\Delta P_c$ ratio corresponds to CCc. The ΔP_c value also varies essentially in different measurements regardless if CCc, which confirms its independent informational significance.

A high variability of CCc and P_c indicates a complex character of CSF overflows in the considered phase of the cardiac cycle, and all peculiarities of these overflows cannot be revealed by the used combination of methods of TCDG and REG due to the comparatively low resolution capability of each of these methods, as the studied area of the cranial cavity is sufficiently expanded.

This is confirmed by the studies carried out with aid of the phase-contrast MRI-tomography, which allow identifying three kinds of CSF circulation at the cardiac cycle period: circulation in the area of cerebral ventricles, in the skull subarachnoid space, and between skull and the spinal space [16].

Meanwhile in our performed studies, all three phases of the liquor circulation are summated. Therefore, the presented here CCc and *P*c values are to be considered complex parameters of compensatory CSF overflows.

The data presented in Fig. 2 show that in the middle age group the CCe values have the lowest values as compared with other age groups. This means that with age, the cranial cavity pliability that consists in the ability to provide an additional systolic blood volume decreases until a certain age, but further this parameter rises again. Most likely, CCe decreases as a result of an increase of rigidity of junctions between skull bones, which decreases their articular mobility and, hence, reduces a possibility of pulse change of the skull pattern in spite of a rise of compensatory liquor overflows (which is indicated by an increase of CCc and P_c). As a result, tolerance of the system of intracranial hemoliquorodynamics in the middle age group on the whole decreases [8, 11]. This is manifested in that in the older age group, an increment of the CCc and P_c values is observed, which indicates a rise of activity of compensational liquorodynamic mechanisms.

The values of CC components in all age groups were found to depend on the state of the intracranial hemoliquorodynamics. Thus, at action of functional tests aimed at increasing blood filling of the cranial cavity both due to a rise of the venous blood filling of the skull in the expiration phase) and at a decrease of the brain arterial tone (the delay of respiration), CCe somewhat increases, while at the CSF inflow into the cranial cavity (the Stuckey's test) it decreases (Fig. 3).

However, these changes are relatively not prominent and are close to those proportional in all age groups. This indicates that the vascular and liquor systems do not play the key role in formation of CCe.

Much greater changes at action of functional tests involve the parameters recorded at the period of the middle phase of cardiac cycle (Fig. 4). The most marked CCc changes are observed at the delay of respiration and in the Stuckey's test in the younger and intermediate age groups, the P_c changes being in the opposite direction with respect to the CCc changes. This indicates that the liquor volumes and pressures in the compensation phase are intercorrelated, i.e., ratios of blood and CSF volumes in the cranial cavity change. In the middle and young age groups the CCc response to the Stuckey's test exceeds 1.0. This indicates the prominent CSF inflow into the skull and accordingly a decrease of cerebral blood filling. The lowest changes of the studied parameters at functional tests are observed in the oldest age group. This seems to be a consequence of a decrease of brain vessel elasticity and of conductivity of craniospinal liquor spaces.

The CCo values at rest, which are the highest in

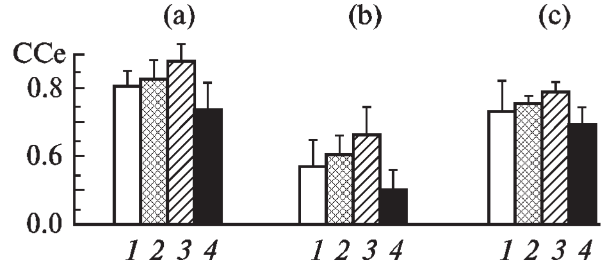

Fig. 3. Values of CC (m ± St. Dev., $n = 15$) in various age groups at rest (*1*), at the deep inspiration (*2*), at delay of respiration (*3*), and in the Stuckey's test (*4*). (a)–(c) As in Fig. 2.

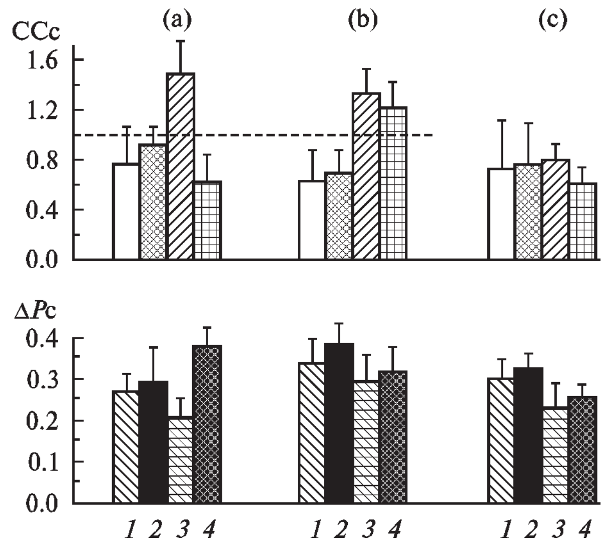

Fig. 4. Components of CCc and ΔPc (m ± St. Dev., n = 15) of the phase of compensation of liquid media in the skull. Designations are as those in Figs. 2 and 3.

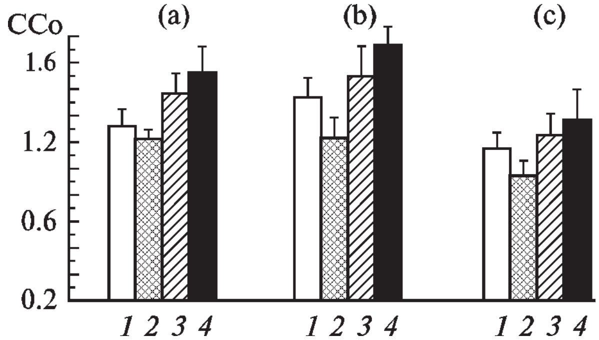

Fig. 5. Phase of blood outflow from skull in various age groups (CCo). Designations are as those in Figs. 2 and 3.

the middle age group, somewhat decrease at facilitation of the blood outflow from the skull (a deep inspiration) and rise with increase of the cranial arterial blood filling and at an increase of the CSF volume. Relatively lower changes are observed in the older age group (Fig. 5). These data indicate the CCo formation to be based on interaction of pressures and volumes of intracranial liquid media—blood in intracranial veins and CSF in liquor spaces. A rise of arterial blood filling at delay of respiration promotes interaction of these volumes. Comparatively similar CCo values at rest in all age group indicate relative stability of mechanisms of blood outflow from skull regardless of age.

The above-presented data indicate that during the cardiac cycle a complex of changes occurs in ratio of volumes and pressures of liquid media (arterial, venous blood and CSF) in the cranial cavity. This process depends essentially on biomechanical properties of the skull as a complex structural system. In various cardiac cycle phases the effect of the cranial biomechanics is different. Thus, the cranial pliability is the most prominent in the first cardiac cycle phase, therefore changes of the P—V interconnection in this phase represent an important parameter of the state of this system—its pliability that provides a possibility of accommodating the pulsed blood inflow to the skull and, hence, is responsible for the circular-metabolic provision of the brain activity. The latter is much associated with age-related changes of the skull properties, which is manifested in CCe changes, and this needs the corresponding compensatory CCc and CCo changes.

It is important to emphasize that that the age-related changes of the CCe parameter are the lowest in people of the middle age group.

This fact is of interest both in the fundamental and in the applied aspects. A CCe decrease can be understood as a consequence of a decrease of the skull reserve volume possibilities due to a decrease of the articular mobility of skull bones with age. This is accompanied by an age-related decrease of the cerebral blood circulation due to development of atherosclerotic processes. As a result, conditions for the brain tissue circulation-metabolic provision turn out to be the least favorable. So far it is hard to evaluate the age frames for this unfavorable situation, the number of examined people is comparatively small. It is also unclear what the significance of additional factors is, for instance the effect of gender. Therefore, the above-presented data are to be considered as the preliminary ones, and this problem merits further special serious study.

Non less interesting is the elucidation of what causes a CCe rise at the older age. One of several explanations can be based on the fact of marked reduction of the brain mass with age. Indeed, MRI-studies have shown reliably that after 50–55 years the cerebral substance mass decreases gradually, approximately by 0.7% per year [17–19]. This means that the volume of spaces filled with CSF participating actively in compensation of changes of liquid media volumes in the cranial cavity in the older age group can increase by 50–60 ml, which is comparable with the total CSF volume in the skull in norm. It is to be noted that formation of age–related CCe changes can also be affected by biomechanical properties of the brain vascular system; however, contribution of this factor seems to be insignificant, as no effect of age difference on functional vascular tests has been revealed.

The data presented in this paper also are a proof for a possibility of noninvasive and repeated determination of the cranial compliance and of its components, each of them has its own independent informative significance. Thereby there is a possibility of tracing changes of this parameter in dynamics, specifically, on the background of action of functional tests and at other different actions. At the same time, it is to be noted that the proposed method has the considerably lower precision than the methods based on the phase-contrast MRI-tomography. Thus, the resolution capability of the above-described procedure is lower and it does not allow tracing in dynamics some peculiarities of liquorodynamics, as this can be done with aid of the phase-contrast MRI-tomography. However, the simplicity of the considered procedure and a possibility of the many-time repetition of studies are its doubtless advantages, which makes the above-described method of determination of the cranial compliance quite competitive in comparison with MRIT-methods.

The above-presented data clearly show some specific age-related peculiarities of CC and of its components, specifically a decrease of CCe and CCc in the middle age group. In practical aspect, this is to be taken into account when developing ways of prevention and treatment of manifestations of dysfunctional disturbances of intracranial hemo-liquorodynamics, which begin to develop in this age group on the background of age-related changes of biomechanical cranial properties.

REFERENCES

1. Gray, W. and Rosner, M., Pressure–Volume Index as Function of Cerebral Perfusion Pressure, *J. Neurosurg.*, 1987, vol. 67, pp. 377–380.
2. Marmarou, A., Shulman, K., and Rosende, R., A Nonlinear Analysis of CSF System and Intracranial Pressure Dynamics, *J. Neurosurg.*, 1978, vol. 48, pp. 332–344.
3. Urino, M., A Mathematical Study of Human Intracranial Hydrodynamics. Part I. The Cerebrospinal Pulse Pressure, *Ann. Biomed. Engineer.*, 1988, vol. 16, pp. 379–401.
4. Fin, L. and Grebe, R., Three Dimensional Modeling of the Cerebrospinal Fluid Dynamics and Brain Interaction in the Aqueduct of Sylvis, *Comput. Mech. Biomech. Biomed. Engineer.*, 2003, vol. 6, no. 3, pp. 163–170.
5. Alperin, N., Mazda, M., Lichtor, T., and Lee, S., From Cerebral Fluid Pulsation to Noninvasive Intracranial Compliance and Pressure Measured by MRI Flow Studies, *Curr. Med. Imag. Rev.*, 2006, vol. 2, pp. 117–129.
6. Raskin, P., Alperin, N., Sivaramakrishan, A., Surapaneni, S., and Lichtor, T., Noninvasive Intracranial Compliance and Pressure Based on Dynamic Resonance Imaging of Blood Flow and Cerebrospinal Fluid Flow: Review of Principles, Implementation, and Other Noninvasive Approaches, *Neurosurg. Focus.*, 2003, vol. 14, no. 4, pp. 1–8.
7. Moskalenko, Yu.E. and Weinstein, G.B., Formation of Current Concepts of Physiology of Cerebral Circulation: Comparative Analysis, *Zh. Evol. Biokhim. Fiziol.*, 2001, vol. 37, pp. 374–384.
8. Moskalenko, Yu.E., Weinstein, G.B., Halvorson, P., Kravchenko, T.I., Feilding, A., Ryabchikova, N.A., Semernya, V.N., and Panov, A.A., Age-Related Peculiarities of Interconnections between Brain Circulation, Liquorodynamics, and Human Cranial Biomechanical Properties, *Fiziol. Zh. im. I.M. Sechenova*, 2007, vol. 93, pp. 788–798.
9. Moskalenko, Yu.E., Principes de Representation Objective des Resultats du Traitement Ostopatique Cranien, *ApoStill* (*Le Journ. de l'Ostipat. France*), no. 7, pp. 22–30.
10. Moskalenko, Yu.E. and Kravchenko, T.I., Intracranial Liquorodynamics: Fundamental Grounds and Application to Practice, *Innovats.*, 2005, no. 4, pp. 112–114.
11. Moskalenko, Yu.E., Weinstein, G.B., Halvorson, P., Ryabchikova, N.A., Kravchenko, T.I., Feilding, A., Panov, A.A., Semernya, V.N., and Markovets, S.P., Age-Related Peculiarities of Ratio of Indexes of Functioning of Intracranial Hemo- and Liquorodynamics Systems, *Zh. Evol. Biokhim. Fiziol.*, 2006, vol. 42, pp. 602–610.
12. Moskalenko, Yu.E., Kravchenko, T.I., Freiman, W., and Weinstein, G.B., *Fundamental'nye osnovy kranial'noi osteopatii* (Fundamental Grounds of Cranial Osteopathy), St. Petersburg, 2002.
13. Moskalenko, Yu.E., Kravchenko, T.I., Gaidar, B.V., Weinstein, G.B., Semernya, V.N., Mayorova, N.F., and Mitrofanov, V.F., About Periodical Mobility of Human Cranial Bones, *Fiziol. Chelov.*, 1999, vol. 25, no. 1, pp. 62–70.
14. Moskalenko, Yu. and Kravchenko, T., Wave Phenomena in Movements of Intracranial Liquid Media and the Primary Respiratory Mechanisms, *The AAO Journ.*, 2004, vol. 14, no. 2, pp. 29–40.
15. Moskalenko, Yu.E. and Khilko, V.A., *Printsipy issledovaniya sosudistoi sistemy golovnogo mozga cheloveka* (Principles of Study of Human Brain Vascular System), Leningrad, 1984.
16. Ambarki, K., Baledent, O., Kongolo, G., Bouzerar, R., Fall, S., and Meyer, M.-E., A New Lumped-Parameter of Model of Cerebrospinal Hydrodynamics during the Cardiac Cycle in Healthy Volunteers, *IEEE Transact. Biomed. Engineer.*, 2007, vol. 54, no. 3.
17. Coffey, C.E., Saxton, J.A., Ratcliff, G., Bryan, R.N., and Lucce, J.F., Relation of Education to Brain Size in Normal Aging. Implications for the Reserve Hypothesis, *Neurology*, 1993, vol. 53, pp. 189–196.

18. Coffey, C.E., Wilkinson, W.E., Parashos, I.A., Soady, S.A., Sullivan, R.J., Patterson, L.J., Figiel, G.S., Webb, M.C., Spitzer, C.E., and Djang, W.T., Quantitative Cerebral Anatomy of the Aging Human Brain: A Cross-Sectional Study Using Magnetic Resonance, *Neurology*, 1992, vol. 42, pp. 527–536.

19. Courchesne, E., Chisum, H.J., Townsend, J., Cowless, A., Covington, J., Egaas, B., Harwood, M., Hinds, S., and Press, G.A., Normal Brain Development and Aging. Quantitative Analysis at *in vivo* MR Imaging in Healthy Volunteers, *Radiology*, 2000, vol. 216, pp. 672–682.