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An analysis of the effect of impact loading on the destruction of vascular structures in the brain

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Abstract

Subdural hematomas are one of the frequent complications of head injuries. Such hematomas result from exceeding the border strength values of bridging veins. Subdural haemorrhages are life-threatening and are a frequent cause of considerable pathologies. Traffic participants and also soldiers who participate in armed conflicts are the most vulnerable to head injuries. Although hematomas have been studied for many years the mechanism of hematoma formation has not been fully clarified as yet. In the paper, the effort of brain tissue structures due to the propagation of shock wave was analyzed. Particular attention was paid to the deformation ability and changes in the energy of bridging veins. This research was concerned with changes in mechanical properties of these veins in the frontal, parietal and occipital regions of the brain. For the present research the authors have constructed finite element models of brain tissue fragments and conducted numerical studies taking into account the boundary conditions arising from violent overloads that result from combat operations. As the result of the conducted numerical analysis, critical values of strain and stress have been obtained. The analysis showed high diversity in the properties of the different regions of the brain tissue. The studies carried out by the authors rendered it possible to assess the effort of the tissue structures of veins in connection with mechanical parameters, including geometrical parameters, in particular in relation to the likelihood of hematoma formation.

Keywords: bridging vein rupture, subdural haematoma, biomechanical properties of cerebrovascular system, FEM, impact loading, dynamic model

1. Introduction

Destructive changes of brain tissues are the cause of serious neurological and neurobehavioral disorders. The significance of these changes is often described in epidemiological studies made in Europe. A high rate of traumatic brain injuries (TBI), including fatal consequences, was reported (235 hospitalized cases per 100 thousand persons) [18]. It should be noted that the frequency of TBI occurrence is estimated only on the basis of the number of hospitalized cases, and the injured persons who do not request medical assistance or do not have access to medical care are not taken into consideration. Thus, the real incidence rate is probably 3 to 4 times greater than reported. According to the World Health Organization (WHO) traumatic brain injury (TBI) constitutes a major public health issue all over the world. The World Health Organization predicts that by 2020 TBI will have outnumbered many other diseases and will have become the main reason of death and disability [25]. Rapid loading to which people are exposed in traffic accidents or in combat conditions frequently results in exceeding the strength of brain tissues. Bridging veins are most susceptible to damage on account of their anatomical location and structure [6]. The vascular system of the brain nourishes the brain's nerve cells. Degradation of vessels due to fast changing loading results in the disruption of transportation channels and disturbance of metabolic pathways. Disorders in blood supply to the brain are the main cause of central nervous system dysfunctions, including lifestyle diseases.

Overload, resulting from head impact and also from acceleration - deceleration changes due to rapid head movements, is the reason of vessel dysfunction. The injury most often occurs as a result of knocking the head against a hard surface or a rapid displacement of the brain with respect to the skull, as a result of, for example, traffic accidents, sports injuries as well as acts of violence[17]. Especially soldiers who take part in armed conflicts constitute a group particularly vulnerable to destruction of the vascular system [2]. Craniocerebral injuries result in permanent disability and a total exclusion from social life which is connected with a long-term treatment. They also generate high costs borne by the state.

One of the most common complications of head injury is, among others, acute subdural hematoma (ASDH). It is a frequent cause of death in patients after severe head injuries [20], and may also lead to neurobehavioral sequelae, such as disturbances of consciousness [18]. The etiopathology of subdural hematoma is connected directly with exceeding the range of deformability of bridging veins and such an excess over the values in the range may occur at rapid acceleration. J.B. Coombs et. al. describe the frequent occurrence of subdural hematoma in soldiers [3].

Mechanical properties of bridging veins are of fundamental importance in the etiology of subdural hematoma formation. Even though bridging veins have a very important function in brain tissues, their detailed morphology, histology and mechanical properties have not been described in detail [8]. It is worth emphasizing that numerical methods have a significant role in studies which describe destructive changes in the brain [19]. A certain knowledge to explain the physical phenomena related to the destruction of bridging veins can be gained by using effective algorithms, including boundary conditions, numerical models and computer software. Nevertheless, results of experimental studies play a crucial role in the analyses. Currently, animal samples are used in most of the experimental studies. There are only few references in the literature describing mechanical characteristics of bridging veins in post-mortem human samples [9], [20], [21]. Due to the differences in research methods, including mixed results obtained by various research teams, their interpretation is often rather ambiguous and vague. Horanin-Dusza in her studies on bridging veins in individual regions of the head demonstrated that sex had no effect on the mechanical properties of the veins, whereas Monea et al. (2014) reported that samples of female bridging veins had higher values of mechanical coefficients than those of males. Moreover, in many studies the Young modulus and characteristics of vein destruction differ considerably [9], [20], [21]. The differences may result, among others, from the fact that Delye’s and Monea’s studies considered the complex: the superior sagittal sinus – the outflow cuff segment – the bridging vein. Moreover, except for Lee and Horanin-Dusza, other authors did not mention exclusion of samples taken from bodies of patients who suffered from a head injury before death. At the same time it must be mentioned that in the study conducted by Lee and Monsson most of the samples were ruptured at the clamps, and this could result in measurement errors. The differences in mechanical properties can also follow from the location from which the vein was taken. Only few authors took into consideration the region of the head from which the samples were taken [9]. It should be noted that veins in various parts of the head are considerably differentiated in their length, diameter, angle with the superior sagittal sinus (SSS) [14], [26] and in their mechanical characteristics [9].

Moreover, [14] showed that the venous system is characterized by individual variability. It should also be remembered that rapid changes in biochemical processes and mechanical characteristics occur in tissues after death. Therefore, any reference made between experimental results and human tissues is burdened with considerable uncertainty. However, on the other hand, Monson et al. showed that veins taken during autopsy are characterized by very similar biomechanical properties to their equivalents taken during surgery [21]. It should be stressed, however, that this conclusion still requires further verification.

It is worth noting that the best solution is offered by human in vivo studies, but for obvious reasons they are prohibited. Another solution is to use physical models, however the selection of mechanical properties of materials poses a considerable problem, since biological tissues are involved. Analytical models also offer a useful solution, however the difficulty lies in the fact that not all self-adjoint problems can be described by local and global formulas. Therefore, at present one of the most effective ways of identifying the response of brain structures to loading is numerical modelling [4], [5]. In particular, the Finite Element Method designed for models of irregular geometry, composite materials and complex loading as well as complex boundary conditions is now the preferred method for studying head injuries [19]. Interest in using the FEM in modelling head structures in adults [22], [27], in children [23], and also in animals [17] has increased in the last decade. Numerical models of the head have been developed mainly for the needs of transportation and aerospace industries [15]. Recently, a few head injury models have been developed for studying blast-induced brain injuries [1]. The evaluation of the mechanical properties of the skull-brain interface is of crucial importance in numerical studies of the head. At the same time, a higher level of model validation can be achieved by constitutive equations of individual head structures [11], [15]. A great number of head numerical models have been already developed and they are still being expanded. However, there are few publications which describe the modelling of the vascular system [14], [27]. Due to a small number of experimental studies on bridging veins, including biomechanical and histological tests, and their scarce availability, [9], [20], [21] the majority of authors base their findings on similar mechanical characteristics and similar geometry of vessels. Up till now bridging veins have been modelled without distinction as to the various mechanical characteristics of individual brain regions. It should be underlined, however, that Horanin-Dusza in her experimental study proved that bridging veins show a certain differentiation of mechanical characteristics in individual brain regions, i.e., frontal, parietal and occipital regions. It is of importance, since bridging veins, depending on the brain region, react differently to forces acting during impact. According to the author, bridging veins in the frontal region show the largest deformability [9].

On the basis of a literature review it should be emphasized that the complexity of human head numerical models has grown considerably in the last two decades and each newer and newer model has additionally offered a solution to a clinical phenomenon. An interesting look at modelling was proposed by Zhang et al. [27], who demonstrated that incorporation of vessels to a 2D model of the brain results in increasing the strength of the very brain tissue through a contribution to the load bearing capacity, as is the case with reinforcing bars used in reinforced concrete structures. Unfortunately, at present it is not possible to incorporate the whole set of blood vessels into the 3D FE model due to the lack of computing capacity . It is reported in numerous papers that acute subdural hematoma is caused by a rupture of bridging veins as a result of a big and rapid movement of the brain relative to the skull. However, the phenomenon of subdural and subarachnoid hematoma formation, as well as the mechanics of damage of bridging vein walls has not been explained as yet. In numerical analyses , bridging veins were modelled as an element of simple geometry and the direction of flow from the bridging veins into the superior sagittal sinus (SSS), location, length and differences in mechanical characteristics in individual regions were not taken into consideration. Elongation of veins was analyzed as a change in the distance between defined points and this does not reflect the real deformability of the vessels. The criteria based on calculations of bridging vein tension do not allow a prediction of subdural hematoma occurrence. Moreover, experimental studies prove that the angle between vein and superior sagittal sinus, the direction of vein ramification, location, length as well as variable mechanical properties contribute to vessel strain. Some implementations attributed linear stiffness to elements of bridging veins, but at the same time they did not consider the differences in the length and the cross sectional area and this resulted in an underestimation of the real stiffness value which depends on the length and the location of bridging veins. Moreover, the assumption made in modelling that the vessels are linearly stiff is not fully in conformity with the real behaviour of blood vessels through which blood circulates under pressure. The work of Holzapfel should be mentioned here, who documented that the behaviour of vascular tissues is strongly nonlinear and viscoelastic. This follows results from their composition and the architecture of the microstructure. The walls of veins are composed mainly of collagen fibres and a soft matrix consisting of proteoglycans, elastine and smooth muscle cells. At the same time it should be emphasized that a precise analysis of the phenomenon is not possible with the use of global models, therefore some authors refine multiscale analyses or study subgroups, i.e., model in micro or nano scale using with some boundary conditions and transition characteristics. It is still a problem how to assume the characteristics of tissue structures. In global models it is usually assumed that the characteristics are in some ranges linear, whereas when we move to a molecular structure, the answer is not unambiguous and clear-cut. However, reports in the literature show that collagen is a component which stiffens the tissue, whereas other elements of vessel structure are more deformable [8]. Proteoglycans and smooth muscle cells which make up the walls of the bridging veins may be considered isotropic since they are not fibrous. On the other hand, elastin fibres which also constitute elements of veins have anisotropic properties, but their random spacing in the matrix leads to an isotropic behaviour [7].

Since numerical models which would take into consideration the division into various mechanical characteristics in individual regions of the brain do not exist, a need arises to conduct numerical analyses in which strain characteristics of the frontal, parietal and occipital regions of the brain would be taken into account. At the same time, border values which cause bridging veins destruction have not been determined yet, and the susceptibility of bridging veins to mechanical loading has still remained unexplained. Still, little is known about energy changes. They are partly studied in the paper. Energy changes may be of crucial importance for the evaluation of consequences which may arise in the mechanical response of blood vessels.

The objective of this study is to develop a global model that would consider vascular structures of the brain divided into the frontal, parietal and occipital regions. Depending on the region and the degree of disorders of the vascular system intersynaptic communication is impaired in individual regions of the brain. Naturally, this phenomenon is not unambiguous. At the same time, a problem still exists in assuming the right mechanical characteristics of brain structures and this is due to a small number of studies made on real models. Therefore, the authors decided to model bridging veins on the basis of experimental studies. Since there are no reports in the literature on the effect of blast induced loading on the bridging veins, it is attempted in the paper to analyze the response of bridging veins' structures to mechanical loading induced by a blast under an armoured vehicle. A numerical model of brain tissues with the bridging veins was developed, in which a division into the frontal, parietal and occipital regions is taken into consideration. The model was partly validated on the basis of experimental studies performed at the Wrocław University of Technology [9].

In this study, an exemplary event, in which a soldier knocks his head against an armoured vehicle roof as a result of an explosion under the body of the vehicle, is reproduced.

An analysis of the state of the art indicates that to date still, no study has been made on the mechanical response of bridging veins located in different regions of the intracranial space, taking into account different mechanical properties in individual regions. The aim of the research described herein was to analyze possible vascular structure destruction in the regions of anatomical location of bridging veins. Analyses of stress and strain as well as energy changes were of fundamental importance for the evaluation of degradation in blood vessel endothelium.

2. Materials and methods

2.1. Finite element head model

Modelling of brain tissue, which is a structure of irregular geometry and diverse properties, requires the use of advanced algorithms and computer methods [19]. A wide range of possibilities for analyzing structures of non-linear characteristics is provided by the Finite Element Method (FEM). In the paper, brain structures were identified on the basis of DICOM images obtained from computed tomography (CT). DICOM files were imported to the Mimics software in which a 3D model was obtained. The mesh was generated in ANSYS and imported to LS-DYNA software. The model consisted of a skull, dura mater, brain and 11 pairs of bridging veins divided into regions: frontal, parietal and occipital (Fig. 1). Special attention was paid to strain characteristics of vascular structures. The properties and geometry of individual veins were obtained in experimental studies made on post-mortem human samples Horanin-Dusza [9], Kędzia [14], and Monson et al. [21]. At head impact, the mechanical parameters of skull bones have a significant effect on the response of brain tissues, including bridging veins. In the study, the results obtained by Fahlstedt and his rationale for the modelling of skull bones were used. The Young modulus was assumed to be 15000 MPa, the Poisson ratio - 0,22 and density of 2000 kg/m3. The dura mater protects the brain tissues against mechanical damage and destruction of bridging veins in the subdural space. The dura secures the position of the brain and is a construction which the bridging veins enter. The mechanical values for the dura mater were taken as in [15], where the Young modulus is 31,5 MPa, the Poisson ratio: 0,45 and density: 1130 kg/m3. The brain tissue was modelled as a simplified solid disregarding its viscoelastic properties. Biomechanical properties of the brain structure employed in this study were based on the research of [24], where the Young modulus was 5,04 MPa, the Poisson ratio: 0,45 and density: 1040 kg/m3. Mechanical parameters of bridging veins in the fontal, parietal and occipital regions were estimated on the basis of mechanical characteristics obtained in experimental studies on human samples made post-mortem and taken from patients in whose cases a mechanical head injury was excluded [9]. An exemplary characteristic for a bridging vein in the parietal region is presented in Fig. 2.

2.2.Impact simulation

The forces of an explosion under an armoured vehicle thrusts the passenger up and he knocks his head against the roof (Figs. 3-4). Rapid loading forces and differences in the mechanical properties of bone and soft structures in the head generate accelerations, and then decelerations, as well as tissue displacement. One of the effects of this process is the impact of soft tissues against the interior rough surface of the skull.

In this study, the effect of an impact of the head against the roof of a vehicle on the system of bridging veins in individual regions of the head is investigated. LS-DYNA software was used for discretization of the system under investigation. To make the calculations possible it was necessary to determine boundary conditions which reflected with an appropriate accuracy the phenomena occurring in the real system. The head model was placed 30 cm away from the vehicle roof. The roof was modelled as a non-deformable steel plate fixed at the edges. The impact of the head against the plate was simulated at a velocity of 3m/s at the moment of impact. A series of tests were performed to analyze the effect of the impact force on the structure of bridging veins in individual regions of the head. Changes in strain, stress and energy of vessels were analyzed.

3. Results

Numerical analyses provided the response of brain structures to the applied mechanical (impulse) loading. When the head knocked against a hard obstacle the external kinetic energy was transferred to brain tissues and strained the vascular and nervous systems. According to the formula E=1/2*m*v2, the external kinetic energy acting on the head during the impact against the armoured vehicle roof, at a velocity of 3m/s, is 450 J. The calculations were made for a soldier weighing 100 kg together with the equipment. This energy is stored in brain structures in the form of elastic strain energy [7]. Changes in the values of the kinetic energy and internal energy for bridging veins as a function of time were evaluated taking into consideration their location in individual regions of the head (Fig. 5 and Fig.6). The analysis demonstrated that the characteristics for the frontal and parietal-occipital region differed considerably. The highest value of internal energy was observed in the bridging veins of the frontal region, after 4 ms it reached the value of 0,32 J (Fig.5). At the same time, between 3 and 4 ms the highest concentration of kinetic energy in bridging veins was observed in the frontal region, about 0,6 J (Fig. 6). The loss of kinetic energy is related to the collision of non-elastic bodies, i.e., the skull and the steel plate, and that is why the initial kinetic energy in bridging veins was higher.

An analysis of the results indicates that different strain and stress in individual regions of the head, including bridging veins, are the consequence of kinetic energy transfer from the bony structures of the skull to the vascular system of the brain. Figs. 7 – 12 illustrate the results of analyses of the distribution of forces, strain and stress in the elements of the system: skull – dura mater- vessels –brain. On the basis of the analysis it was found that the greatest concentration of stresses occurs in the frontal region (Fig. 9), where the maximum value was 0,58 MPa. At the same time, the bridging veins in the frontal region showed the greatest deformability (Fig. 9). The maximum force acting in the frontal region was 1,37N (Fig. 7), whereas the smallest stresses and strain were observed in the occipital region. The highest stress concentration in response to rapid acceleration and deceleration of the brain tissue in a horizontal plane was developed in the brainstem region (0,62 MPa) (Fig. 10). The highest value of stress exerted on the dura mater was observed in the parietal region, where it amounted to 0,15 MPa, whereas it was 59, 87 MPa in the skull (Fig.11).

The displacement of bridging veins in individual brain regions in three axes, namely: x, y and z, was also studied. On the X axis (in the negative direction) and Y axis (in the positive direction) the greatest displacements of bridging veins were observed in the frontal and occipital regions (Fig. 13 and Fig. 14). On the Z axis, i.e., in the direction of head impact, bridging veins in all the regions of the head were displaced by approximately 11 mm (Fig. 15). The greatest displacements were observed in the Z axis in the parietal region, though the difference in the Z axis displacements in the parietal region and the frontal as well as the occipital region was relatively small, approximately 2 mm. Moreover, results for displacements of the brain and with respect to the skull in the Z axis (Fig. 16) were also obtained. The difference between displacements of the two structures in the time range of 3 and 4 ms was 2 mm.

4. Discussion

It was shown in the numerical study that as a result of an impact to the head the energy was transferred deep into brain structures and caused rapid changes in the kinetic energy of bridging veins in the frontal, parietal and occipital regions. A high index of internal and kinetic energy of frontal veins caused the greatest strain and the greatest stress concentration in the frontal region. A destructive effect of internal energy transfer to brain tissues is described in the literature. Such a transfer results in unfolding of protein structures. Such unfolded protein structures having a larger number of hydrophilic amino acids residues since they are exposed to the aqueous fluid environment tend to involve more water molecules and thus initiate a cytotoxic cerebral oedema [7]. In the structure of bridging veins collagen fibres predominate over elastic elastin fibres [9]. The proteins which build up these two types of fibres make bridging veins resistant to tensile strength. Moreover, the arrangement of fibres in the subdural and subarachnoid regions differs significantly [26]. Oscillations of kinetic energy in bridging veins may result in the damage of polypeptide chains. Such damage causes microinjuries to the veins, thus their mechanical properties are weakened. This can be explained by the phenomenon that some hematomas develop several months after the trauma. An interesting study was carried out by Yamashima et al. They demonstrated a relationship between a rapid increase in venous pressure and tears in bridging veins which in consequence lead to the formation of clots in the subdural space. A more precise description of the problems referred to above may be perhaps obtained by using multi-scale models.

The displacement of the brain with respect to the skull was analyzed for a better assessment of vein degradation. The results of tests we carried out show that at impact in the horizontal direction the brain was displaced with respect to the skull by 2 mm. Qiliang Zhu et al. on the basis of experimental studies concluded that during natural bending of the head forward and backward (a quasi-static state) the brain is displaced in relation to the skull by 1 – 2 mm [12]. However, no report has been found in the literature on the influence of velocity on the brain displacement with respect to the skull along a horizontal axis. We are of the opinion that the main contributor to bridging veins destruction is the exceeding of the threshold values of strain under the influence of changes in velocity and acceleration. The brain displacement with respect to the skull should be treated as a secondary factor, thus the UDS FE head model [23] and the studies made by Huang [10], where bridging veins were modelled as a space between a node on the inner surface of the skull and a node on the outer layer of the brain, are not fully appropriate for the evaluation of threshold parameters of bridging veins.

In this study, we analyzed the effect of mechanical forces on the bridging veins in different regions of the brain. The bridging veins are located between the skull and the brain. In some sense, these veins form a suspension between the brain and skull. Investigation of the influence of mechanical energy on the brain without taking into account the characteristics of cerebrovascular structures between the brain and the skull may be incorrectly interpreted. Incorporation of bridging veins into numerical models can affect the stiffness of the brain-skull interface. Due to this incorporation, our results of numerical tests agree with the research by Mazumder et al. [17] who suggest that the brain–skull interface should be represented using linear springs of this stiffness. Kleiven [15] also described the mechanical response to bridging vein damage but did not take into account the different mechanical properties and geometric configuration of veins in different regions of the brain. Therefore, our test results differ from those achieved by Kleiven, because they were based on different experimental studies. Moreover, Kleiven made calculations for a different load case. The geometric configuration of the cerebral bridging veins is likely to be of substantial importance to the cerebral venous blood outflow regulation during physiological and pathophysiological conditions as presented by Famaey et al. [6]. In addition, Zhang et al. [27] demonstrated that incorporation of vessels to a 2D model of the brain results in increasing the strength of the very brain tissue through a contribution to the load bearing capacity, as is the case with reinforcing bars used in reinforced concrete structures. Therefore, there is a strict dependence between the structure and function of the numerical model of the brain.

5. Conclusions

Results on the prediction of the damage and biomechanical response of veins were obtained. The tests showed different characteristics of the kinetic and internal energy, strain and stress values in various regions of the head. On the basis of an analysis of these characteristics a high index of kinetic energy was identified in the frontal region. An increase in the kinetic energy resulted in the highest deformability of veins in the frontal region. The highest stress concentration was also observed in the frontal region. The results of numerical investigations showed a good correlation with experimental tests. The results obtained in the investigations related to energy, strain and stresses may prove that with such a head movement trajectory the bridging veins in the frontal region are most susceptible to destruction. This is confirmed by medical reports which say that subdural hematomas are most frequently localized in the frontal and parietal regions [13]. It should be remembered, however, that the susceptibility of bridging veins to mechanical loading and the formation of subdural hemorrhages is still a controversial issue.

In this study, we have obtained a reliable global model for predicting deformation, strain and stress on the bridging veins in different regions of the brain. The model has been properly validated and supplemented by a realistic geometry and appropriate loading and boundary conditions. The numerical model can be used in future for the validation/extension of the current head injury criteria and anthropometric models (HYBRID III). The numerical analysis described herein combined with advanced experimental studies can be highly relevant for the assessment of the effects of impact loading, to which, among others, soldiers in combat conditions or road users are exposed.

In summary, based on the developed numerical model we presented the impact of dynamic loads on the deformation of the blood vessels in different brain regions. To our knowledge this is the first numerical model which takes into account the different mechanical characteristics in different regions of the brain. In a slightly different study, similar experimental conclusions have been drawn and described by Holzapfel [8] and Famaey [6]. We have also found that a mild brain injury can cause damage to the bridging veins, while the damage of cerebral vessels can cause serious consequences in the future.

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Figures:

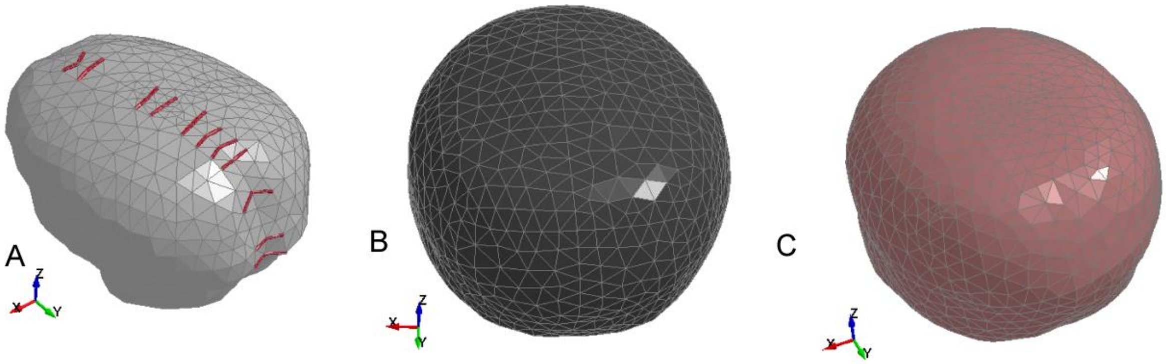

Fig. 1. Models of the head A – The brain with bridging veins, B – skull, C – dura mater

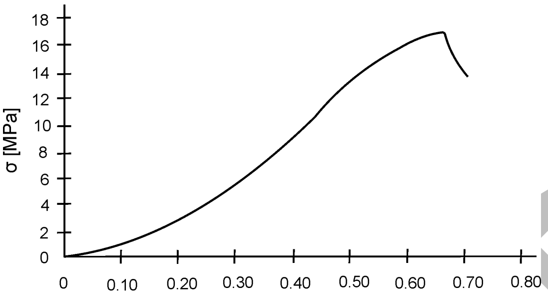

Fig. 2. Mechanical characteristics of a bridging vein from the parietal region [9]

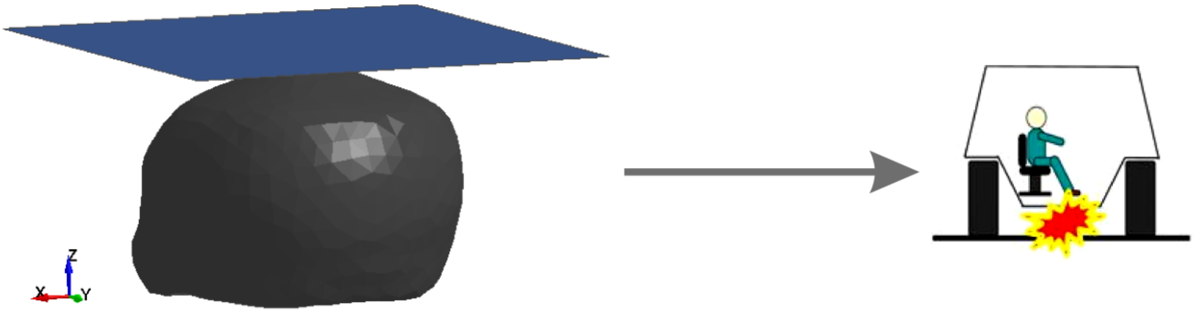

Fig. 3. Step 1. An initial state model. Explosion under the vehicle [16] – modified

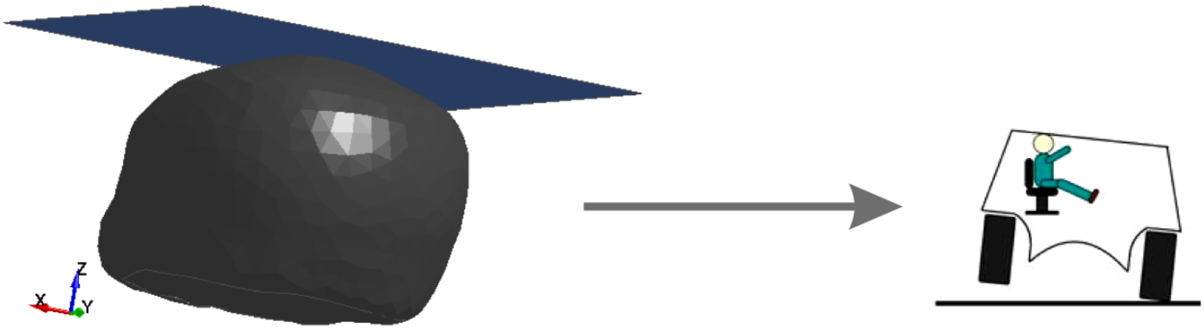

Fig. 4. Step 2. Impact of the head against the roof of a vehicle [16]- modified

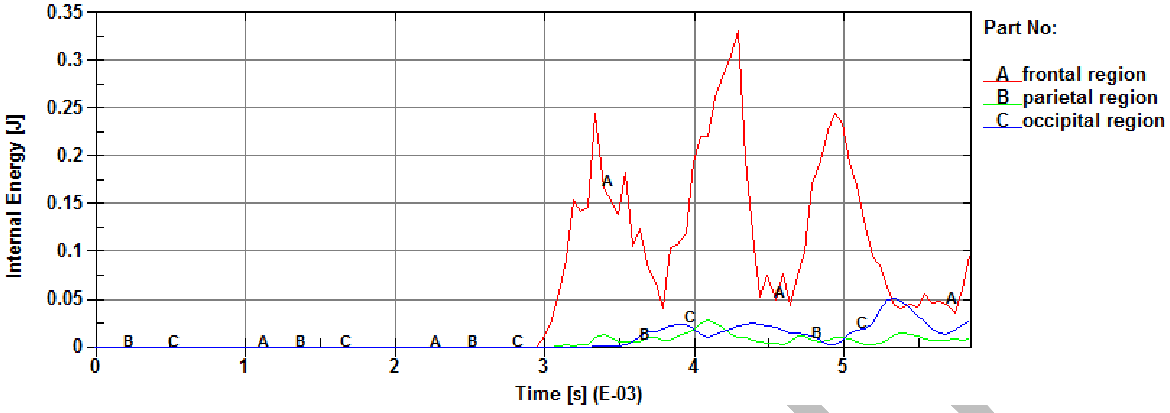

Fig. 5. Internal energy in bridging veins as a function of time A – frontal region; B –parietal region; C – occipital region after 4 ms

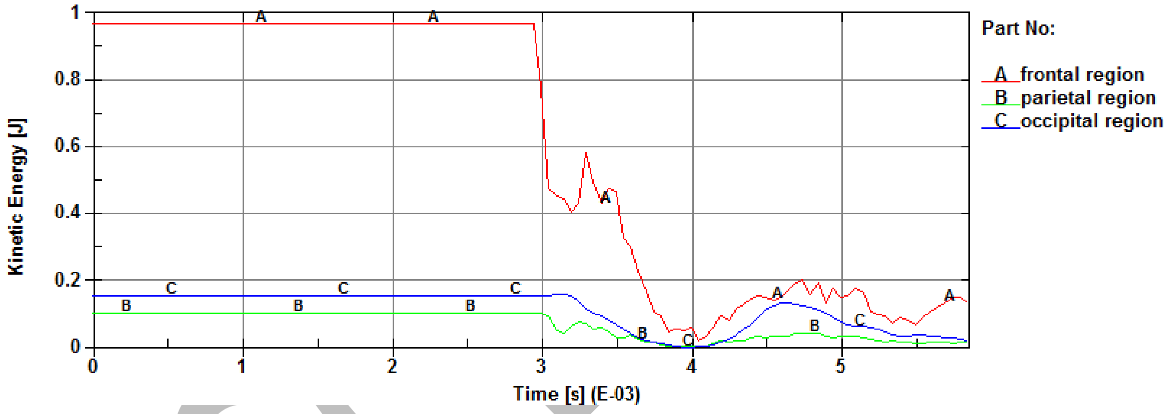

Fig. 6. Kinetic energy in bridging veins as a function of time A – frontal region; B – parietal region; C – occipital region at impact loading in the range of 3-4 ms

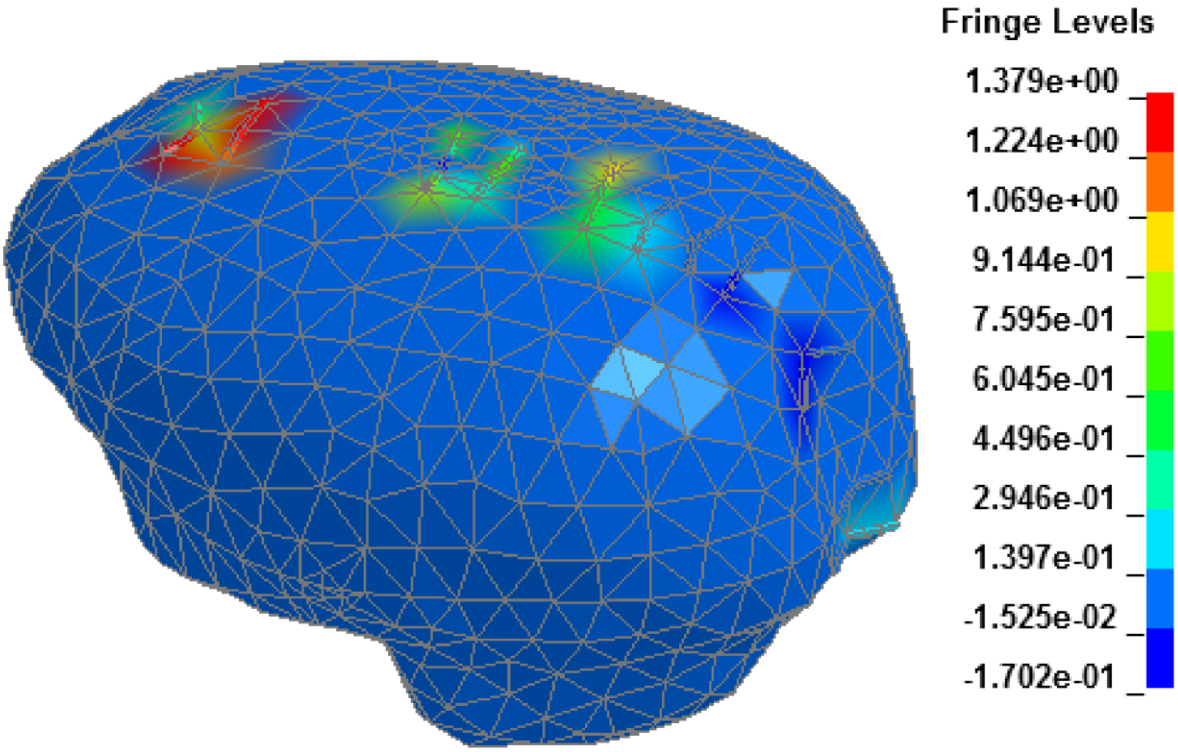

Fig. 7. Axial force in bridging veins: frontal, parietal, occipital regions. Max force 1,38N in frontal region

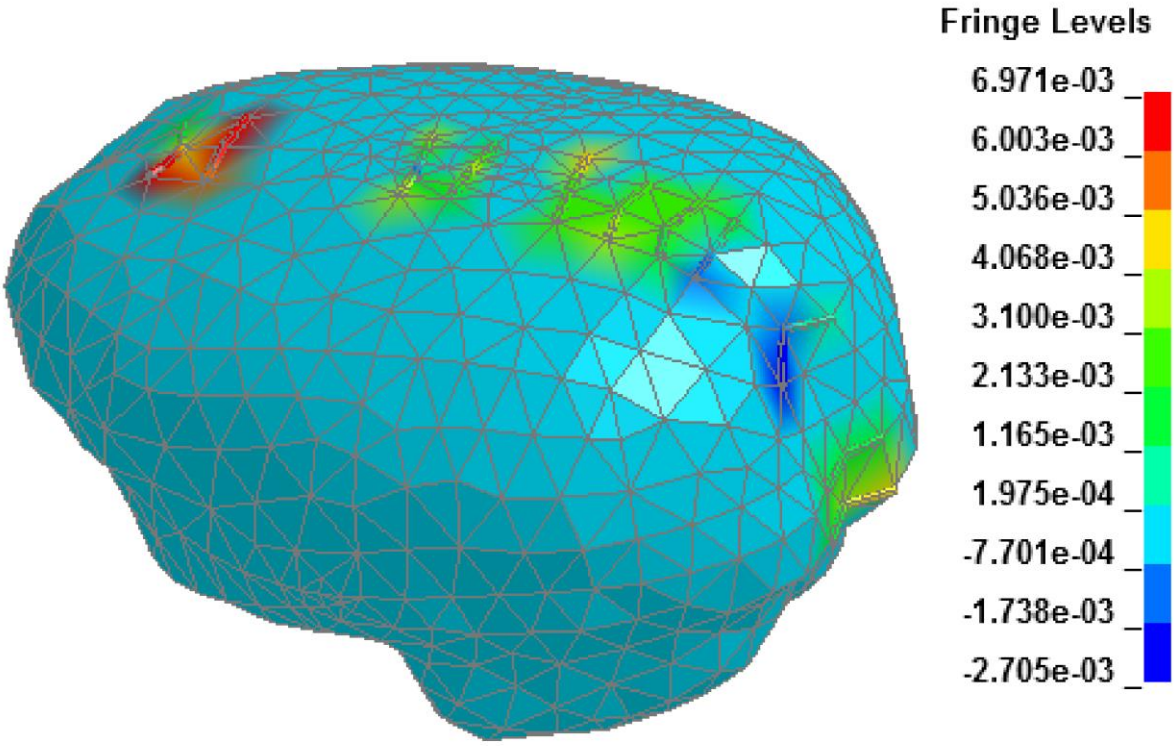

Fig. 8. Axial strain in bridging veins: frontal, parietal, occipital regions. Max strain 0,007

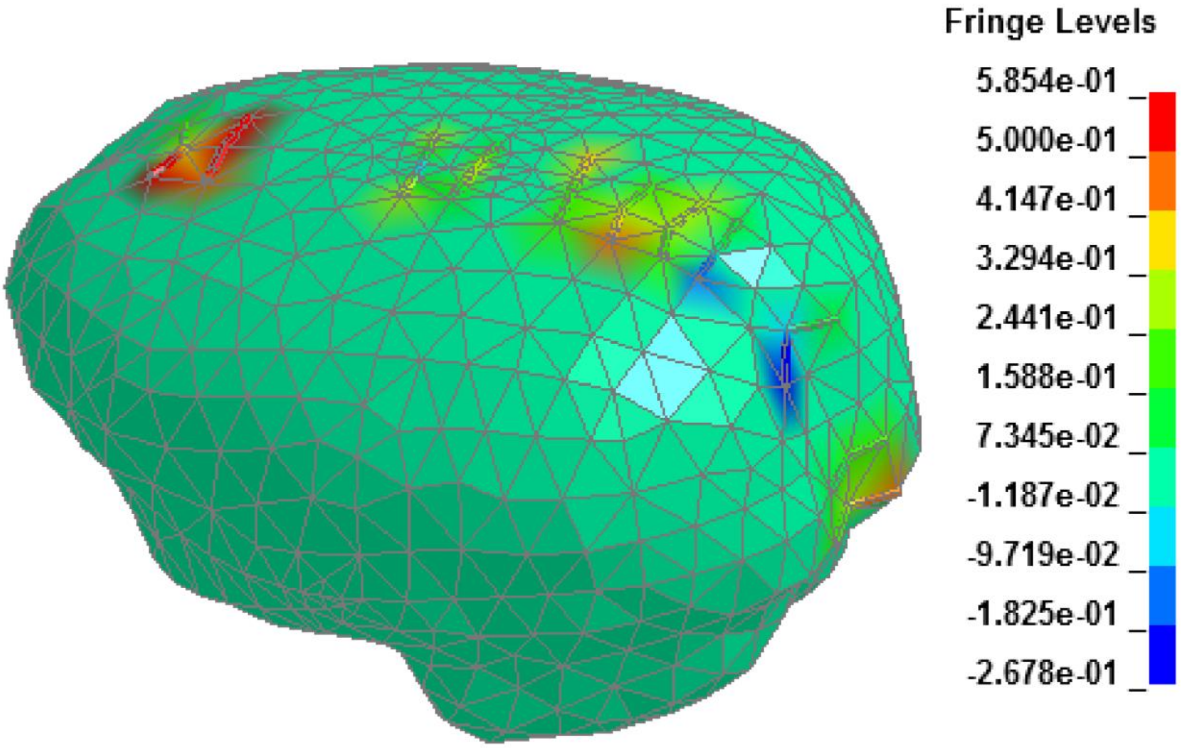

Fig. 9. Axial stress in bridging veins: frontal, parietal, occipital regions. Max stress 0,59 MPa

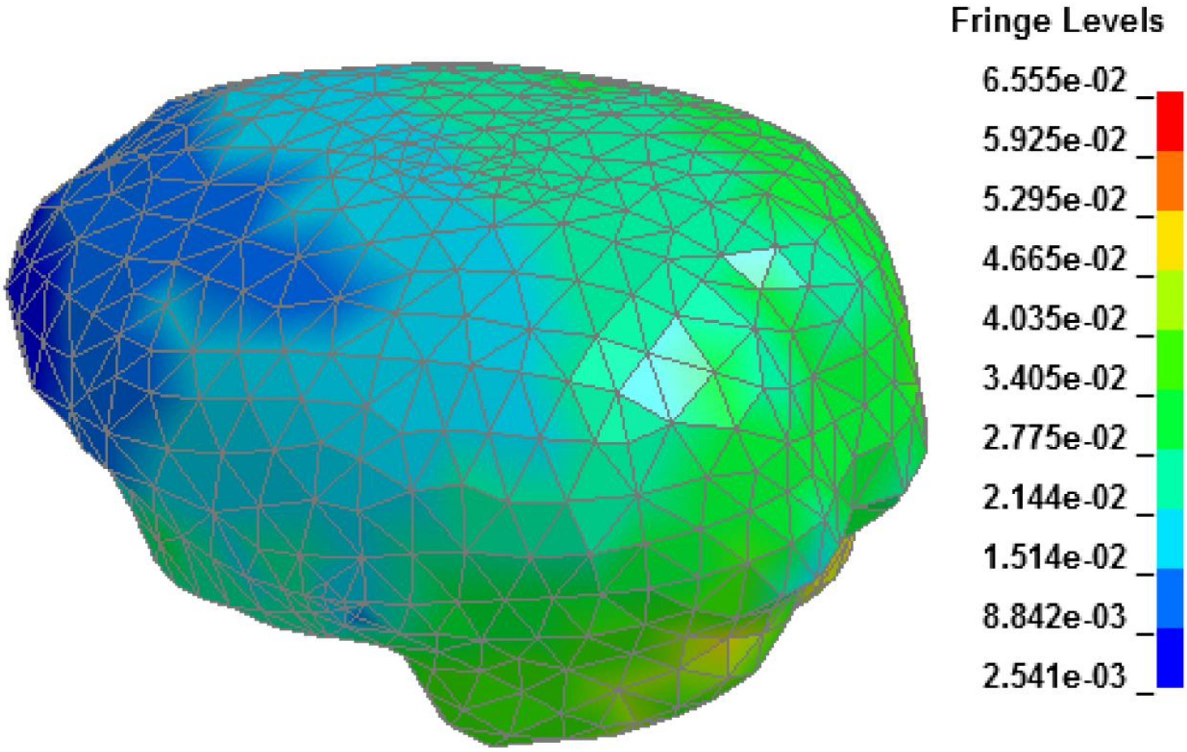

Fig. 10. Von Mises stress in brain. Max stress 0,066 MPa

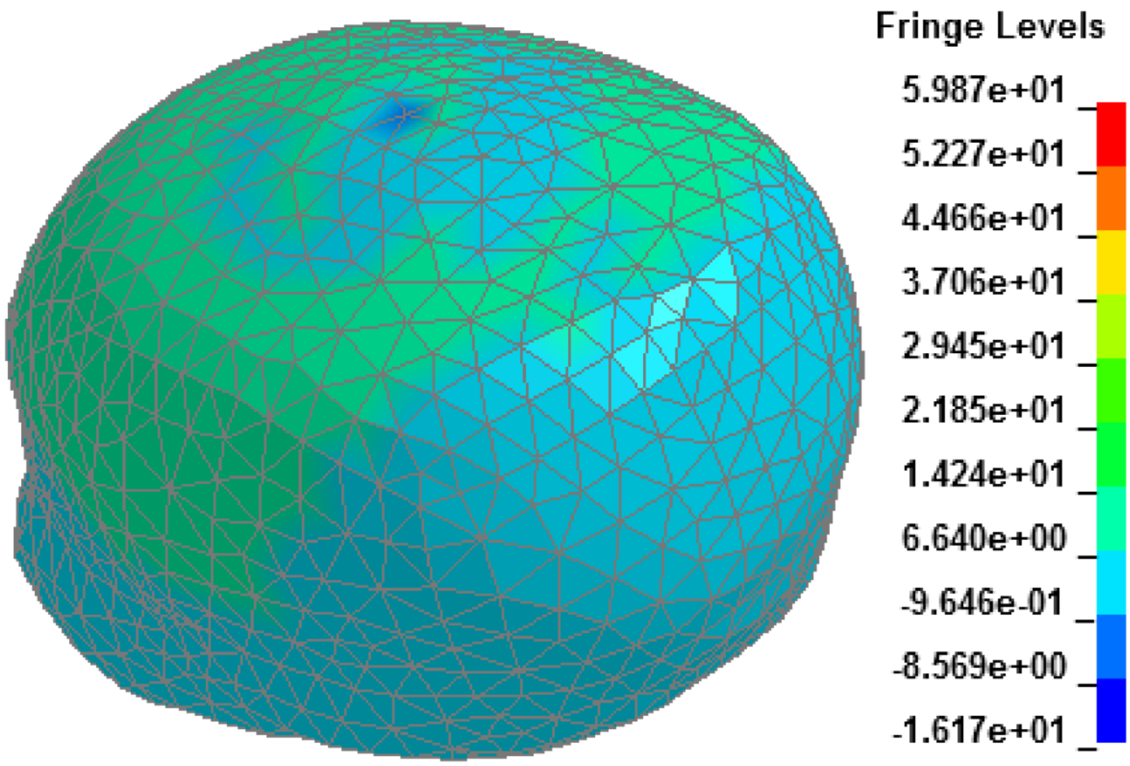

Fig. 11. Principal stress 1st in skull. Max stress 59, 87 MPa

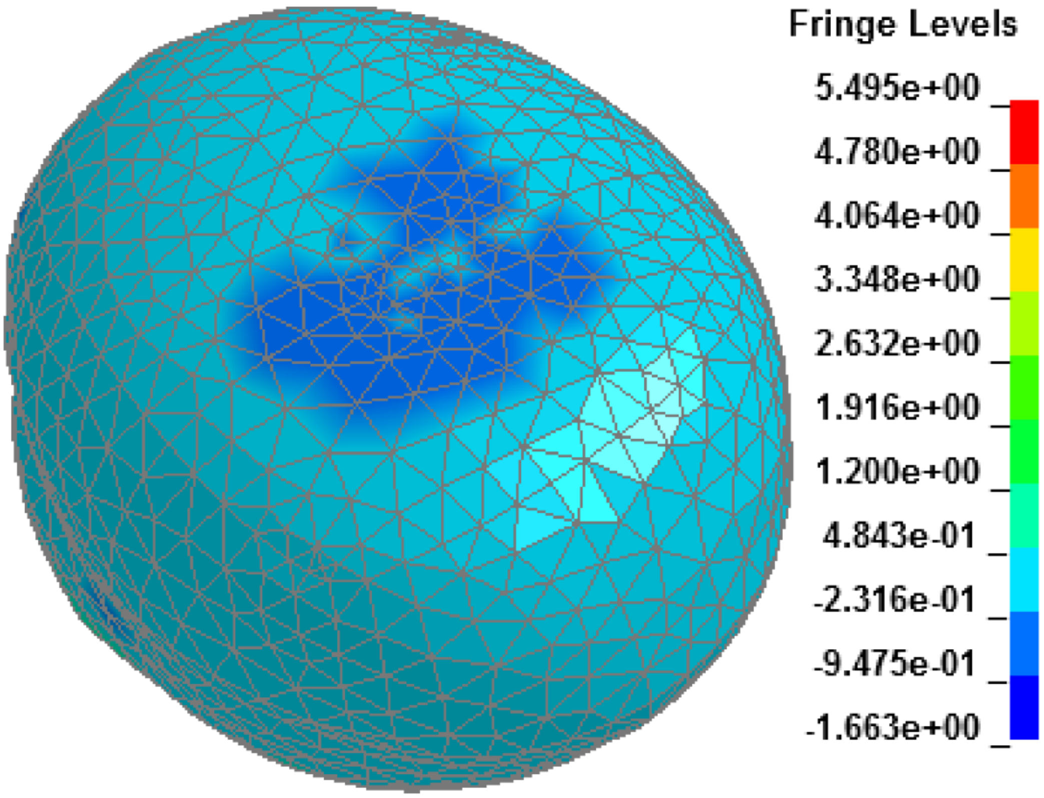

Fig. 12. Principal stress 1st in dura mater. Max stress 5,50 MPa

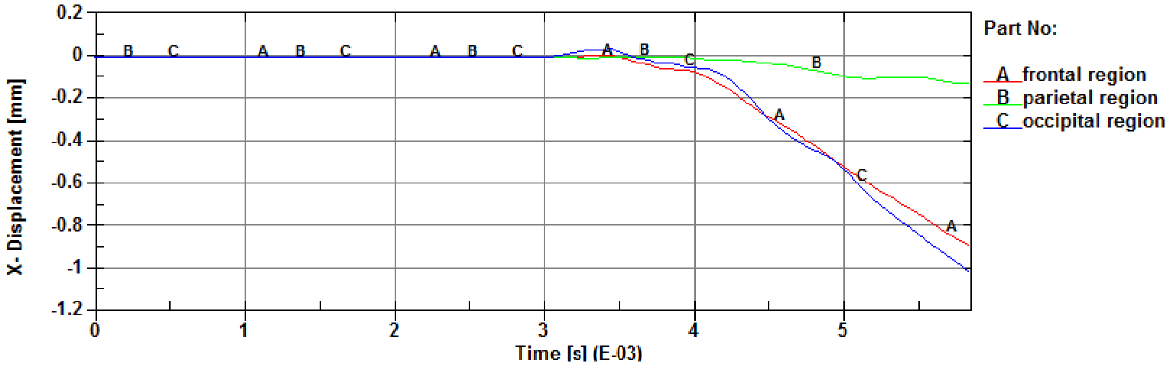

Fig. 13. Displacements [mm] of bridging veins in time [ms] in the X axis. A – bridging veins in the frontal region, B – bridging veins in the parietal region, C – bridging veins in the occipital region

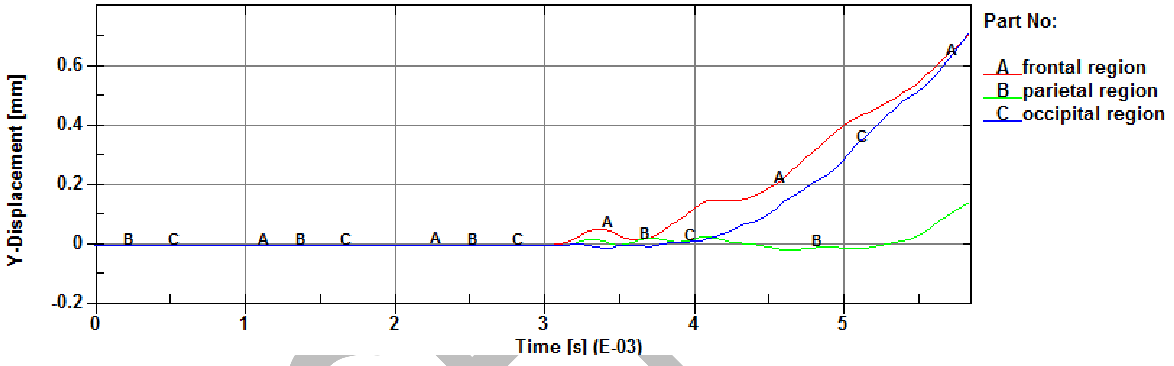

Fig. 14. Displacements [mm] of bridging veins in time [ms] in the Y axis. A – bridging veins in the frontal region, B – bridging veins in the parietal region, C – bridging veins in the occipital region

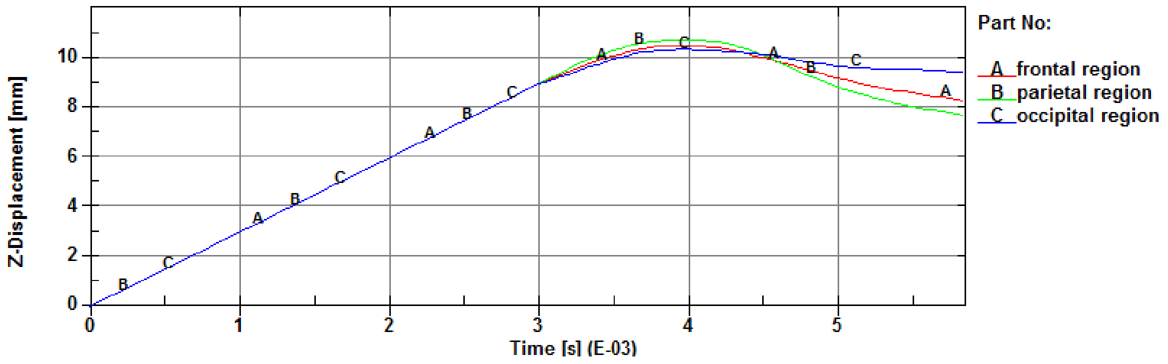

Fig. 15. Displacements [mm] of bridging veins in time [ms] in the Z axis. A – bridging veins in the frontal region, B – bridging veins in the parietal region, C – bridging veins in the occipital region

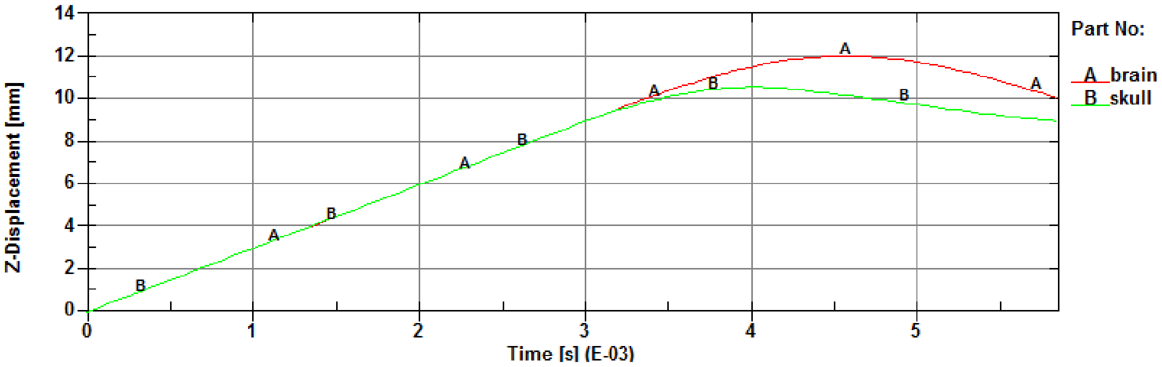

Fig. 16. Displacement of the brain [mm] with respect to the skull in time [ms] in the Z axis