Analysis of amniotic fluid impact on the fetus during traffic accidents

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Abstract

The subject of protection of pregnant women in modes of transportation has been around for a quarter of a century, however, the models that have been developed so far still require workload to accurately imitate the phenomena taking place during traffic accidents. According to the researcher's knowledge, none of the previous models focused on the possible consequences of an accident for the fetus, focusing only on the pregnant woman. The research objective was to investigate the impact of the amniotic fluid on the fetus during traffic accidents, in order to define risks related to them occurring in the uterus. The researcher investigated the influence of the position of the fetus as well as velocity of the amniotic fluid for the possible trauma of the fetus. The analysis was performed on a 2D simplified models of a 40-week-old fetus, which dimensions were acquired from the newborns data. During the study the properties of amniotic fluid corresponding to the gestation age were taken into consideration. The placement of the fetus inside the uterus has been simplified by the method commonly used with water-ship simulations, which allowed to set the amniotic fluid in motion in the direct of the fixed fetus. The calculations were performed with the use of the Ansys Fluent software. All cases of underpressure in the area of the fetal skull were considered potentially dangerous, as it may cause increased blood flow, which may result in increased pressure in the blood vessels of the brain and in extreme cases, even intercranical bleeding – however, the values of the dangerous underpressure are not yet known. The knowledge gained in the project shows the importance of the topic, which will be continued in the author's work focused on creating 3D CFD models based on ultrasound fetal data.

Keywords: traffic accident; pregnant road safety; fetus model; CFD; road safety; shear stress analysis; fetal damage; trauma; pregnancy; crash test model

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1. Introduction

Crash test models exist now for more than 70 years - starting with cadaver testing, through animal testing to creating dummies. Throughout these years men models were broadly developed, yet models of women were left behind. Even though the first official victim of the automobile accident was a woman (1869), the first dummy in the history Sierra Sam (95th percentile man) was made for military purposes in 1949. The standards defining the safety of women, including pregnant women differ from the real safety during collision. This phenomenon occurs because test dummy representing the female is a scaled-up male model. Dr Hideyuki Kimpara in his research [1] presents the difference in the occurrence of injuries by sex, highlighting the results of Roberts and Compton from 1993, which clearly shows that a 50 percent chance of chest injuries in a front collision may happen at a speed of 44 km/h for men and only 38 km/h for women. The 5th percentile male cannot substitute for the 50th percentile female, and disregarding the differences in the injury mechanism in women helps distinguish women (along with the elderly) as the more vulnerable group. It was not before 1996 when Pearlman and Viano created the first pregnant crash test dummy [2]. The model was a standard Hybrid III dummy with a pregnancy insert made from vinyl shell filled with silicon which simulated amniotic fluid. The paper claims that inside the insert representing a 28-week fetus model with accelerometers was placed, however none of the fetus data was presented. The researchers continued their work on the model and expanded the team by several scientists, among whom cooperation with Jonathan Rupp turned out to be crucial. Rupp decided to focus on the placenta abruption phenomena, which shaped later research tendencies of the finite element method models studies. Created MAMA-2B model [3] consisted of both, human tissue material data (for placenta and uterus) and data based on Hybrid III 5th percentile (all parts of the model excluding placenta and uterus). Years of work on modifying the physical model for static tests, in 2008 a modified version of the Perlman and Viano models was created, in which the uterus was represented as a silicone bladder filled with water [4]. During the work on changes in the MAMA-2B model, development of computer models of pregnant women occurred, both scientific and commercial. In 2003, Moorcroft presented its multi-body model [5] which allowed for the analysis of the effectiveness of security measures during accidents, The model allowed for the analysis of the case of a woman in 30th week of pregnancy during three cases of crashes: with fastened seatbelt and active airbag, with only fastened seatbelt and without protecting systems. Year later, Volvo Cars company announced their FEM model - Linda – of a 36-week pregnant woman with human-like tissue data for abdomen and base from Hybrid III model data. Over time, more models of pregnant women made with the use of various engineering tools appeared: a model of a pregnant driver was created with the use of male cadaver placed on the stand in driving position [6] or 26-week pregnant woman voxel model for electromagnetic dosimetry [7]. It is also worth mentioning the work on hybrid models based on MRI scans, which are used to estimate the expected birth weight [8], and the work on a female cervical spine model [9], that can significantly improve safety of women during road accidents. According to the researcher's knowledge, none of the previous phantoms representing woman took into consideration amniotic fluid – fetus movement. Moreover, most of scientific work focus on placenta abruption phenomena, while other possible traumas are somewhat forgotten. The paper presents the author's innovative approach of designing fetus related models, which involves the use of the Computer Fluid Dynamics (CFD) software to improve understanding of the phenomena occurring inside the uterus during traffic collision. To the best of author's knowledge, this is the first model using CFD software in fetus study.

2. Methodology

Computational Fluid Dynamics software use Finite Volume Method based on approximation of model's geometry by creating the control region around the fixed point [10]. The control region may be a cell of the mesh, or it may be created irrespectively to the mesh as long as it meets conditions of the differential equations used in the model. The process of creating CFD model has its own procedure in which it should be implemented. The order of the steps presents as listed: creating the geometrical model, discretization of the model, computational model, imputation of materials, setting the boundary conditions and the initial conditions, setting the calculation parameters, calculations and getting the results [11]. By using planes of symmetry, it is possible to reduce the computational time – this procedure was also used in this case. During the discretization of the model, attention was paid to the appropriate selection of the shape and size of the mesh since the results are subject to the accuracy of the mesh. The main attributes of the discrete models are: the shape of the elements, orthogonality, structurality, blockiness, regularity and possibility of movement [11].

Creating the two-dimensional models, the CFD software uses Finite Area Method instead of the Finite Volume Method. While creating the mesh, it is advised to think over what advantages and disadvantages using triangular and rectangular element has. While it is easier to correctly put on the triangular mesh, the rectangular mesh is more accurate and faster to calculate. Minimum number of elements in the flow area should not be smaller than five. It is possible to combine different kinds of the grid by putting a layer of rectangular grid in the principal for the flow area, and triangular on the rest of the model. While doing so, it is important to remember about keeping the grid size ratio as close to the one value as possible [11].

The computational model varies depending on the type of the flow and the selection of the equations that describe it. During this step, researcher's experience is the key to a properly selected calculation method [11].

After selection of the computational equations and choosing the materials for the model's elements, the boundary conditions and initial conditions are being defined. CFD software define parameters such as temperature, pressure, velocity of the flow etc. Boundary conditions selection in most cases require choosing inlet and outlet of the region, as well as the walls of elements that interfere with the flow. It is also advisable to name the sections for easier and faster implementation of the boundary conditions and to receive the results. Setting flow initial conditions allow to choose the parameters in terms of the tested flow (e.g. initial temperature for the thermal analysis). In order to speed up the calculations it is possible to change relaxation factors, bearing in mind that as the relaxation factor value increases, a discrete model with better quality parameters is required [11]. During calculations, the convergence of the results may vary depending on number of performed iterations. Final results should represent the actual behavior of the fluid as accurately as possible.

The anthropometric data of newborns [12] were used as the starting base to model a simplified model of the fetus at 40 weeks. Data such as the head radius (0.0539 m) and the total length (not exceeding 0.54 m) were used. Based on Varbruggen's [13] model, the radius of the uterus (in this case modeled as a tunnel with a width equal to doubled radius of the uterus) was 0.124 m. This value was changed due to the need for correct mesh overlay, and finally amounted to 0.136 m. The model located inside the tunnel of the fetus was modeled in the fetal position and rotated three times by 90 degrees, which finally allowed to obtain the following models: the initial one, rotated by 90, 180 and 270 degrees in relation to the initial one.

The discrete model consisted of two types of mesh elements: triangular and rectangular elements. Most of the model was filled with triangular elements with graded size from 3 to 0.9 mm. There were five layers of rectangular elements called inflation elements around the fetus (Figure 1). Such distribution of the elements allows for quicker correct positioning of the mesh (triangular elements) and obtaining results with greater accuracy (rectangular elements). The number of elements in individual models was close to 280,000, ranging from 279,662 in the initial position to 281,294 in the position rotated by 270 degrees.

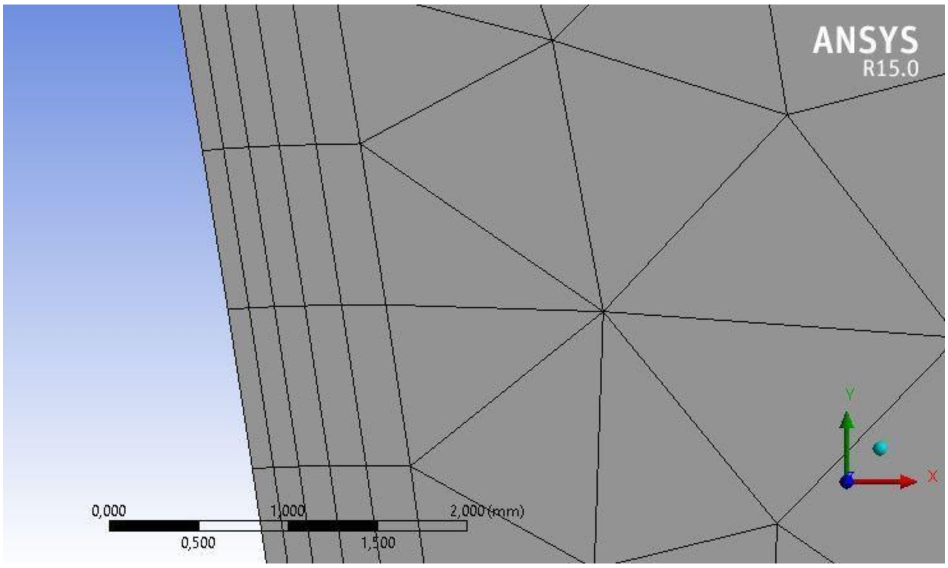

Figure 1: Inflation elements in the surroundings of the fetal model and visible transition to triangular elements.

A method was also used to reverse the relationships between the interacting elements of the model - instead of setting the fetal model in motion, velocity was given to the amniotic fluid, which allowed to shorten the computational time.

The computational model requires to define the calculation type and calculation model. In this case, the calculation type based on the pressure distribution and constant iteration time estimation. Calculation type based on the pressure means solving the pressure equations one after another which is relatively slow, however memory - efficient. The entire calculation process is described in detail in the software manual [14]. During the calculations, model was given the Earth's gravity of 9.81 m/s^2. It was assumed that the flow of amniotic fluid is turbulent, for

this reason, it was decided to use the k-epsilon computational model, which reflects well the turbulence in the layers next to the walls, and has low sensitivity to the set conditions.
The material properties of the fluid were also defined by assigning a density value and a dynamic viscosity coefficient. The fluid density value was established on the basis of the known water density at 36-40ºC (human body temperature) which is 993 kg/m^3 [15]. This value is taken as a baseline value, as the amniotic fluid is composed of nearly 99% water. In addition to water, glucose, proteins, lipids and exfoliated fetal epithelial cells are present, which indicates a higher density value. As a result, the final value was set as 997 kg/m^3. Based on research data the value of the dynamic viscosity coefficient was set as 0.0008 Pa·s [16]. Numerical calculations were carried out for all four models, each of them was subjected to a fluid with a flow speed of 15 km/h (4.16 m/s) and 45 km/h (12.5 m/s) based on literature [17] while the number of iterations was selected as 1500.

3. Analysis and Results

Figure 2 shows the assigned values of the length of the curve constituting the plane of symmetry of the fetus. The given values were presented on the model representing the initial position of the fetus, but their equivalents in the other three positions remained unchanged, which means that in all models:
-the connection of the occipital bone with the spine (base of fetal head) is set as 0 m,
-flexion of the thoracic spine is set as 0.2 m,
-flexion at the height of the sacrum is set as 0.35 m,
-knee-joint is set as 0.5 m,
-frontal bone is set as 0.75 m,
-the connection of frontal and parietal bone is set as 0.8 m,
-the occipital bone is set as 0.9 m,
-and the connection to the starting point value is close to 1 m.
The above values will be used in the analysis of the occurrence of shear stresses described in the diagrams below.

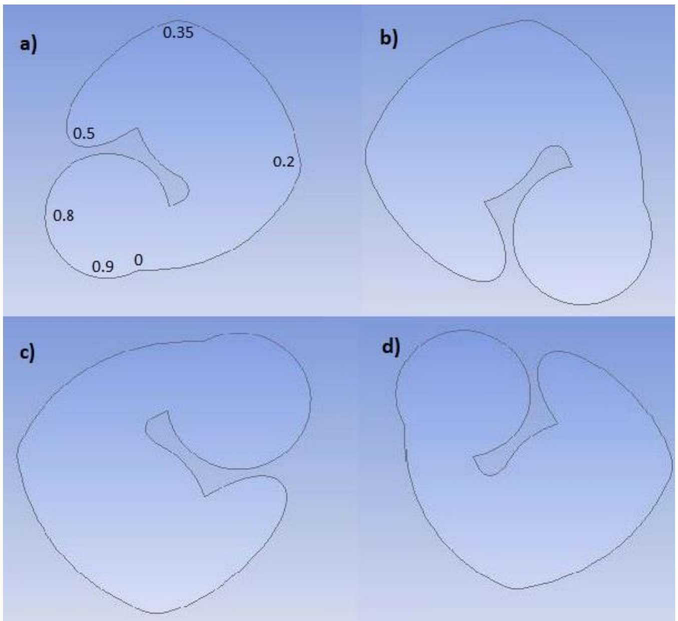

Figure 2: Numerical identification of the characteristic elements of the fetus along with the presentation of its four tested positions: a) initial position, b) rotated by 90 degrees, c) rotated by 180 degrees, d) rotated by 270 degrees.

In the initial position, three distinct increases in shear stresses were noticed: in the cervical spine, in the sacral flexion area and in the parietal and occipital bone junction. At a given initial speed of 4,16 m/s (15 km / h), their values are respectively: 600 Pa, 1200 Pa and 1400 Pa (Figure 3).

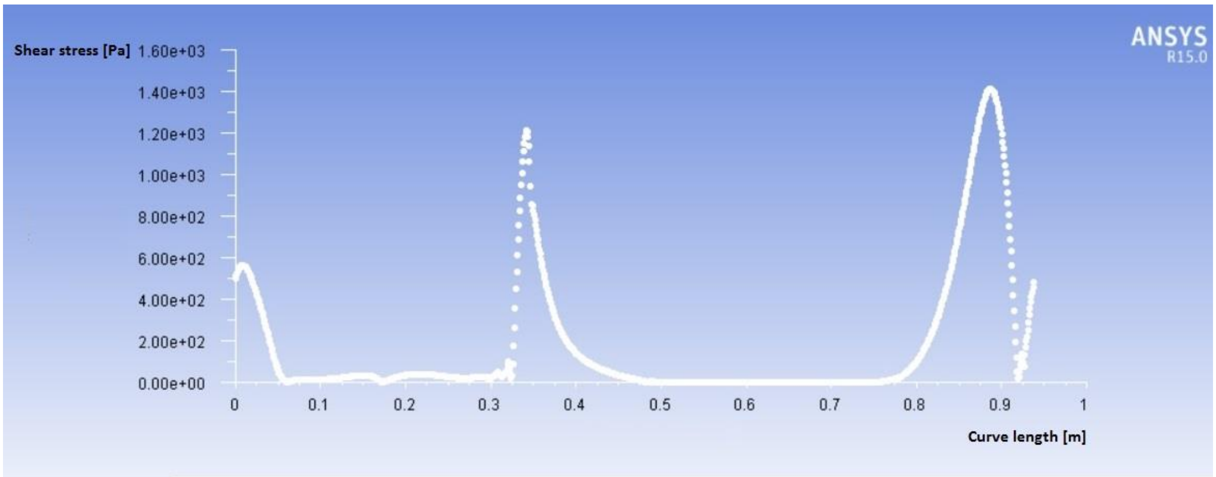

Figure 3: Distribution of shear stress on the fetus (initial position, amniotic fluid velocity set at 4,16 m/s).

After rotating the model by 90 degrees (Figure 4), at the same given velocity of the amniotic fluid, the formation of a local maximum in the areas of thoracic spine flexion (1200 Pa), knee-joint (400 Pa) and junction of parietal bone with the occipital bone (maximum global value of 1400 Pa) were recorded.

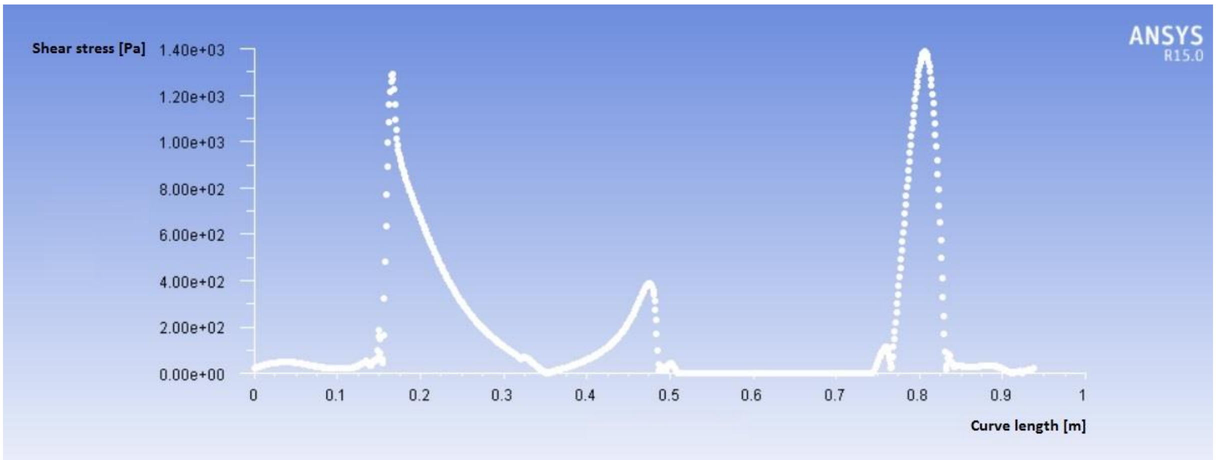

Figure 4: Distribution of shear stress on the fetus (position rotated by 90 degrees, amniotic fluid velocity set at 4,16 m/s).

In the case of fetal model rotated by 180 degrees (Figure 5) in relation to the initial position, three zones with a clearly increased value of shear stress were also noticed. Those are: area of cervical spine (600 Pa), sacrum area (maximum global value of 1800 Pa), and the junction of parietal and occipital bones (1100 Pa).

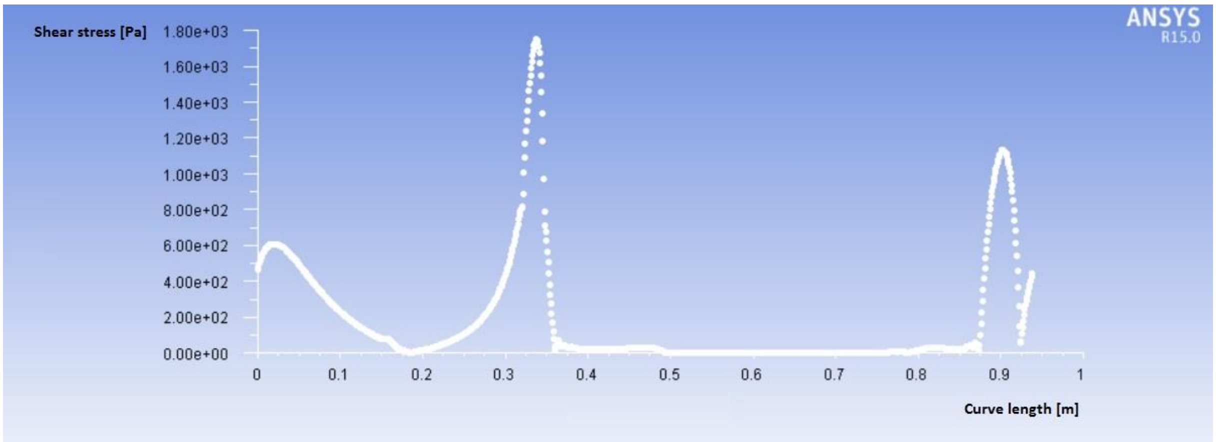

Figure 5: Distribution of shear stress on the fetus (position rotated by 180 degrees, amniotic fluid velocity set at 4,16 m/s).

The last of the analyzed models, rotated by 270 degrees from initial position (Figure 6) was characterized by the presence of two maximums occurring in the area of thoracic spine bend (maximum global value of 1700 Pa) and at the junction of parietal and occipital bone area (1200 Pa).

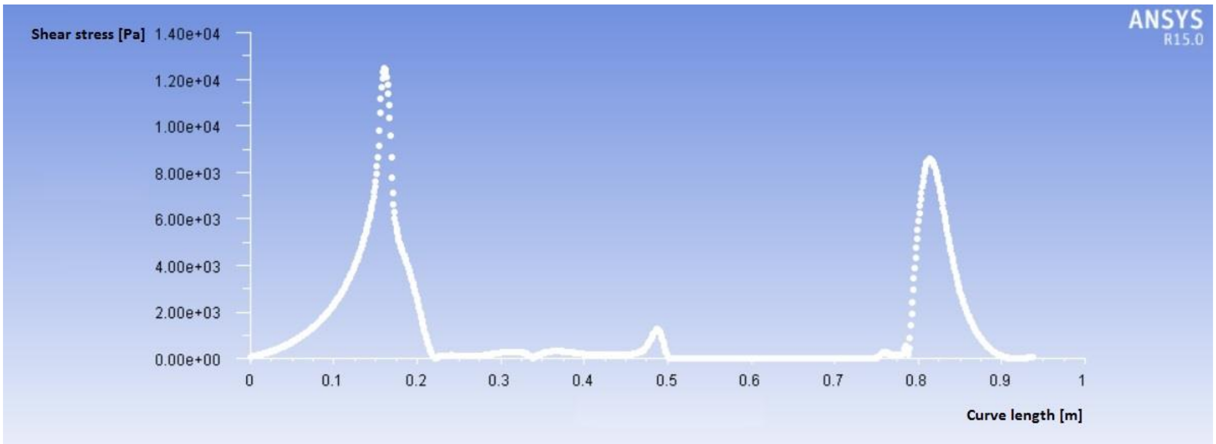

Figure 6: Distribution of shear stress on the fetus (position rotated by 270 degrees, amniotic fluid velocity set at 4,16 m/s).

In all four cases, the relationship between the areas of occurrence of shear stresses at a given higher initial velocity of the amniotic fluid (45 km / h equal to 12.5 m / s) remains the same. The areas of local and global maximum occurrence remain unchanged, they only differ in value. Interestingly, the values of the global maximum are not three, but eight or even eleven times greater.

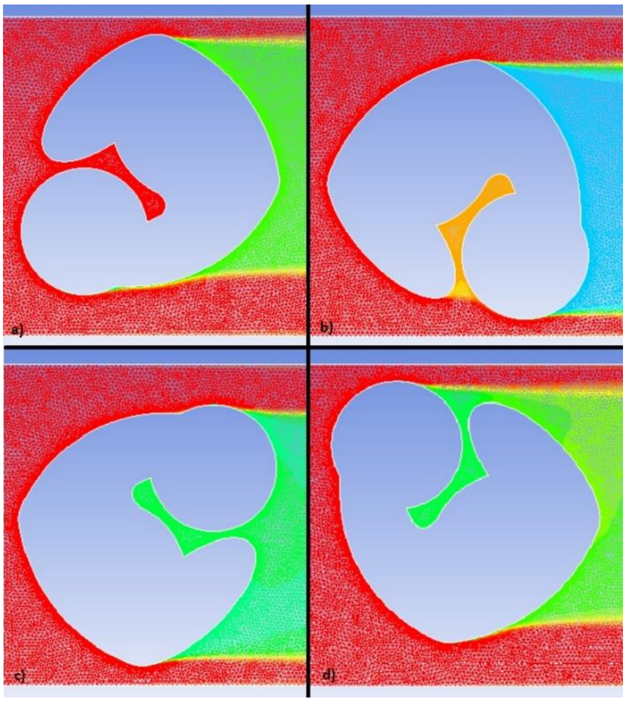

Figure 7: The visual representation of the pressure distribution areas during simulation of the model (constant pressure - red and underpressure - green): a) initial position, b) rotated by 90 degrees, c) rotated by 180 degrees, d) rotated by 270 degrees.

The comparison of the pressure distributions at the two given velocities of the amniotic fluid showed the preservation of the same tendency, therefore the cases will be discussed according to the position of the fetus, but without the separation for the cases with different fluid velocities.
The first case of the fetus in the initial position (Figure 7a) shows a pressure drop along the distance from the parietal bone, along the occipital bone and up to the sacrum. The remaining areas of the fetal area maintained a constant pressure value, equal to the set one (however, its value is not crucial for the obtained results).

In the case of the model rotated by 90 degrees (Figure 7b), there was an increase in the pressure value on the surface with which the fluid stream is in direct contact (from the bend of the spine in the thoracic section to the knee joint). The pressure remained constant in the area between knee joint and the skull bones, with the exception of the area near the frontal-parietal junction where the value increases again. After an increase in this value, a decrease in pressure can be seen along the cross-section of the parietal and occipital bones and along the cervical and thoracic spine.
The model rotated by 180 degrees (Figure 7c) from the initial one also showed a pressure increase in the areas where the rushing stream first meets the fetus. In this case, fluid flow affects the entire length of the spine together with occipital bone, except for the presence of a local minimum at the junction of the spine with the occipital bone. The remaining area of amniotic fluid around the fetus maintains a constant pressure.
The last of the analyzed cases, fetus model rotated by 270 degrees (Figure 7d) in relation to the initial one, showed the presence of a global maximum at the junction of the occipital bone and the spine. There was also a drop in pressure in the area where the parietal bone joins the frontal bone, and further along the frontal bone.

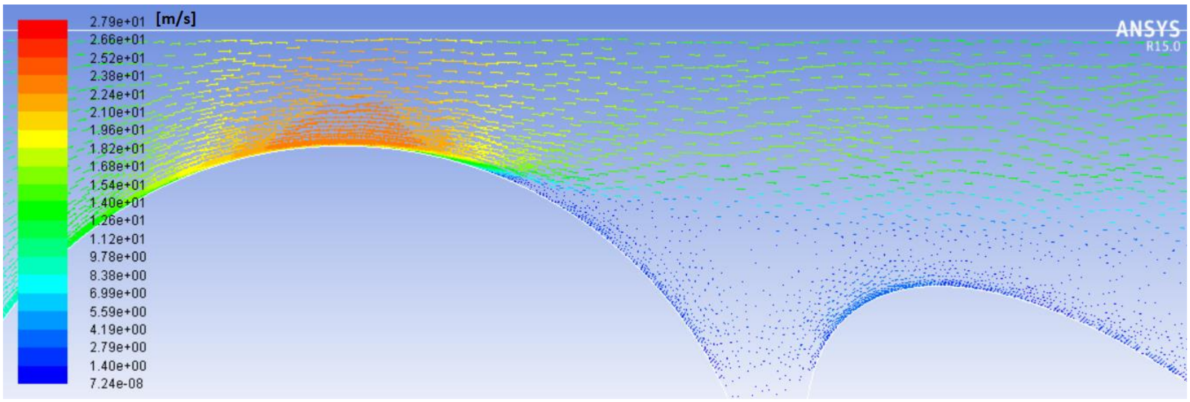

Figure 8: Distribution of the velocity of the amniotic fluid around the fetal head -fetus rotated by 270 degrees from the initial position (dark blue – fluid vortices).

The speed of the fluid stream at the joint of the skull bones is 22.4 m/s (81 km/h) at the set speed of 4.16 m/s (15 km/h). After passing this zone, the stream of fluid breaks comes off from the cross-sectional surface of the fetus, and fluid turbulences form in the area between the fetal head and knee joint (Figure 8), the velocities of which do not exceed the initial set during the flow simulation. The center of the vortex is shifted closer to the knee joint, which causes the underpressure and may have an influence on inducing shear stresses in this area.

4. Discussion

The analysis of four cases allowed to define areas of potential risk of injuries. In three cases (model rotated by 90, 180 and 270 degrees from initial position) the areas of overpressure occurred. In most cases, the impact of overpressure was limited to the spine area. Taking into consideration fetal position of the fetus as a result of such pressure, one should expect a possible greater inclination towards the inside. The increase in pressure can also be observed in the area of the frontal-parietal conjunction (model rotated by 90 degrees), parietal bone (model rotated by 180 degrees) and the connection of the occipital bone with the spine (model rotated by 270 degrees). Due to evolutionary condition of the skull, which lacks rigid cranial sutures, the head does not receive any injuries during childbirth, despite the presence of high pressure. Therefore, it was concluded that the areas of overpressure do not pose a threat to the fetus.
During the analysis areas of underpressure were observed in all models. Particular attention was paid to cases in which underpressure occurs in the area of the skull bones, i.e. the parietal and occipital bones (initial and rotated by 90 degrees positions), the connection of the parietal bone with the spine (model rotated by 180 degrees) and the connection of the parietal and frontal bone (model rotated by 270 degrees). These areas have been marked as potentially at risk of trauma, in terms of sufficiently high underpressure occurrence may cause an increased inflow of blood to the brain, which may damage its structures. However, the study was not intended to determine these values, but only to indicate a potential hazard. Attention was drawn to the overlapping of the areas of underpressure with the areas of amniotic fluid turbulence (Figure 8).
The analysis and comparison of graphs showing the distribution of shear stresses together with maps showing the distribution of the amniotic fluid velocity revealed a direct correlation between them. The very phenomenon of increased amniotic fluid velocity in some of the studied areas has been associated with the Venturi's effect (with the reduce of flow cross-section, the speed of the amniotic fluid increases which results in higher values of the shear stress).

Although the results based on this phenomenon may seem controversial, there are known cases of fetal brain damage as a result of a traffic accident where the pregnant woman did not suffer any visible injuries [18]. The performed autopsy showed injuries in the convexity and base areas of the brain, which led to the conclusion that the fetal brain was affected by cutting and tensile forces causing it to collide with the bones of the skull.

5. Conclusions

The conducted research is a good start of work on the model based on Computational Fluid Dynamics. The areas of increased shear stresses, in particular those around the skull bones, are the main interest for future research. The next step in the evolution of the model will be the creation of a three-dimensional model in which the fetus will be set in motion. Due to the possible undesirable influence of the negative pressure (especially in the brain regions) the existing pressure values will also be taken into consideration. The conducted study and its continuation in subsequent editions are aimed at focusing on cases in which the fetus was injured or died as a result of traffic accidents without placental abruption. The subject of placental abruption has already been widely researched by numerous teams around the world, but the fetal-amniotic fluid relationship at the time of the accident is still unknown. 3D Computational Fluid Dynamics model of fetus behavior during collisions will allow to fill the existing research gap.

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