

# Qualitative Evaluation of Faults (Mathematical Incorrectness) in Anatomical Model for Regional Anaesthesia Simulator

Elena Zaitseva, Miroslav Kvassay, Vitaly Levashenko  
 Department of Informatics  
 University of Zilina  
 Zilina, Slovakia  
 {elena.zaitseva, miroslav.kvassay,  
 vitaly.levashenko}@fri.uniza.sk

Thomas M. Deserno  
 Department of Medical Informatics  
 Uniklinik RWTH Aachen  
 Aachen, Germany  
 deserno@ieee.org

Victor Voski  
 Department of Anaesthesiology  
 University Hospital RWTH  
 Aachen, Germany  
 vvoski@ukaachen.de

Andreas Herrler  
 Faculty of Health, Medicine and Life Sciences  
 Maastricht University  
 Maastricht, The Netherlands  
 a.herrler@maastrichtuniversity.nl

**Abstract**—Regional Anaesthesia (RA) is a rapidly growing field, which appears to be a great challenge for novices in terms of learning a new technique. Although many training methods are available, they do not provide a sufficient training that gives novices an opportunity to gain all skills required to perform RA safely. New prototypes of RA simulator have been developed under project RASimAs (Regional Anaesthesia Simulator and Assistant). The RASimAs prototypes are based on a Virtual Physiological Human model that includes anatomy, physics and biological functions. One of the possible ways to develop this model is based on the use of existing 3D anatomical models (e.g., ZygoteBody, Anatomium3D Anatomy Model). The model for RA simulator is inducted based on some physiological layers that are indicated in these 3D models separately. This indicates existence of intersections between different layers, what is not good for development of RA simulator. Therefore, intersections between different layers of Zygote Male Human Anatomy Collection v.4.0 (a part of ZygoteBody) are considered and investigated in this paper.

**Keywords**—regional anaesthesia simulator, anatomical model, error, incorrectness, RASimAs

## I. INTRODUCTION

The principal goal of use of information technologies in medicine is improvement of health care. This application provides a new concept of *Health Information Technology* (HIT) that supposes use of computer hardware and software that deals with the storage, retrieval, sharing, and use of health care data, information, and knowledge for communication and decision-making [1]. The HIT is composed of computers and communications attributes that are combined together to build systems for health monitoring and diagnosis, medical treatment, and patient care. Application of such system allows decreasing medical error and increasing level of patient care. An important part or component of this system is medical personnel. Because of that, the development of a high-reliable healthcare system has

to be implemented in conjunction with creation of background for rise of qualification level of medical staff. Inadequate technical skills resulted from limited training methods are one of the most difficult challenges faced by trainees today. Current teaching methods have failed to provide the sufficient training for young medical specialists. They include simple phantoms, cadavers, video teaching and, if it is possible, training on human volunteers or colleagues. These methods have limited capabilities and, therefore, development of new training methods is a current issue. A possible way to solve these limitations is application of computer-based simulator.

The important part of any medical simulator is a virtual 3D anatomical model [2–4]. *Virtual Environment* (VE) is used for different purposes in medicine and healthcare [5], and it intends to provide a balance between engagement and aspects of learning using the simulator. VE can allow a wider range of content and the enhanced learning through the different subjects and learning methodologies [3, 4]. Typically, medical simulators are developed based on a *Virtual Physiological Human* (VPH) 3D model. This implies that reliability of a simulator depends on the quality of the used VPH model. As a rule, model's quality and simulator's reliability are evaluated in step of testing after designing the simulator. Reliability analysis of a system in design is a complex and unformalized problem. This problem is caused by a lot of specifics of the elaborated system (in particular, the medical simulator). In this paper, we consider the preliminary reliability evaluation of the simulator for *Regional Anaesthesia* (RA) in the step of design. This simulator has been developed under the project RASimAs (*Regional Anaesthesia Simulator and Assistant*) [5, 6]. The evaluation is implemented by qualitative analysis of the designed VPH model. This analysis allows us to obtain basic statistics about possible inconsistencies. These inconsistencies are interpreted as initial faults of the model, which can cause failure and unacceptable functioning of the simulator.

This work has been supported by the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 610425.

## II. ANATOMICAL MODEL FOR REGIONAL ANAESTHESIA SIMULATOR

A medical simulator is designed with application of a 3D anatomical model typically. The anatomical model is generally used to improve visualization of specific patient data. The reviews of possible methods for the design of anatomical models for the simulator are presented in [7, 8]. Creation and design of correct and exact anatomical model is an important step in the elaboration of any simulator for medical application. The model can be created as an original product or developed based on the existing products, such as ZygoteBody or Anatomium3D Anatomy Model [5–7].

In this paper, we consider simulator for *Ultrasound Guided Regional Anaesthesia* (UGRA) [5, 6]. The UGRA-simulator [5, 7] has been developed under the project RASimAs to be used by anaesthesiologists in training. The safe performance of RA requires good theoretical, practical and non-cognitive skills. Gaining these skills allows trainees to achieve confidence in its performance and to minimize possible complications. UGRA permits injecting a local anaesthetic directly near the target nerve, but it requires developing multitasking skills such as holding an ultrasound probe in one hand and a needle in another while analysing ultrasound images. Therefore, the anatomical model for the *Regional Anaesthesia Simulator* (RASim) had to allow trainees to learn the ultrasound anatomy and improve their scanning and needling techniques required for safe performance of UGRA avoiding on-patient training. At the same time, human (patho-)physiology had to be contained in this model. This supposes individualization of patient-specific data. These requests cannot be implemented based on application of existing anatomical models [7].

The previous paragraph implies that the important aspects of the anatomical model for the RASim can be declared as:

- the individualization of patient-specific data;
- the application of different layers (skin, skeletal, muscles, connective including fat, lymphatic, circulatory, nervous, etc.) at once.

Developing a VE based on the simulator for training RA requires VPH-based model elaboration. Existing products such as ZygoteBody and Anatomium3D Anatomy Model have been considered for the model elaboration in the first step of the implementation of the RASimAs project. Unfortunately, such model was insufficient due to inconsistencies and a lack of anatomical correctness. The existing anatomical models have well-elaborated layers of human body separately. However, the anatomical model for UGRA simulator needs to use some of these layers at once [7, 9]. This causes intersections in the model – some biologically separated structures (e.g., muscles and skeleton) overlap. For example, in case of Zygote Male Human Anatomy Collection v.4.0 (a part of ZygoteBody), which is primarily considered in this paper, existence of intersections between the layers representing circulatory system, muscles, nerves, skeleton, and skin have been shown in [9]. As it can be viewed in Fig. 1, the skeleton overlaps muscles, and the blood vessels intersect with a bone, partly lying within the bony structures. These intersections have influence on the quality of the developed model for the simulator. Therefore, they can be

interpreted as faults of VPH model used for UGRA-simulator [5, 6]. These data can be used for the next estimations of reliability of the simulator.

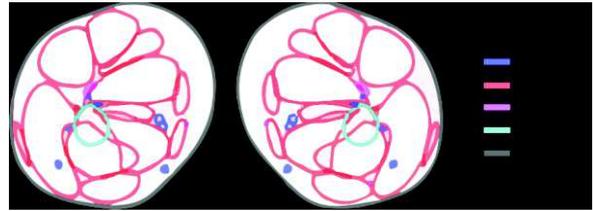


Figure 1. Zygote male model's intersections shown for layers representing blood, muscles, nerves, skeleton, and skin (cross-section of the thighs).

ZygoteBody and Anatomium3D Anatomy Model have several shortcomings that penalize their use in development of the anatomical model for RASim. The following three groups of important shortcomings have been indicated in [9]: inconsistencies, incorrectness and incompleteness.

Inconsistencies or intersections appear in enhanced model by combination of some layers that are separate in the initial anatomical model (Fig. 1). Incorrectness results from incorrect positions of structures in the model with respect to their anatomical location in a human body. For example, in case of the femoral region, animated 3D observations and millimetre axial slices showed a wrong positioning of the femoral nerve in relation to the iliopsoas muscle. Incompleteness is caused by missing some structures. For example, fascia iliaca and fascia lata in the femoral area are missing.

Initial shortcomings in the final models can cause errors and failures in exploitation of the RASim, missing structure will make it even useless. The investigation of initial faults as statistics of shortcomings and their qualitative analysis can be useful for the evaluation of reliability of the simulator.

## III. SHORTCOMINGS IN 3D ANATOMICAL MODEL FOR DESIGN OF ULTRASOUND GUIDED REGIONAL ANAESTHESIA SIMULATOR

Two anatomical models (ZygoteBody and Anatomium3D Anatomy Model) have been considered for the design of VPH-based model for UGRA-simulator RASim. In this section, basic statistics about and the shortcomings of Zygote Male Human Anatomy Collection v.4.0, which is a part of ZygoteBody, are investigated. This was done using open source software Blender version 2.76 [10].

### A. Zygote Male Model

Zygote Male Human Anatomy Collection v.4.0 consists of 8 different layers that represent individual systems of human body. From these layers, correctness of the following was considered – skeletal, muscular, connective (this layer is mainly composed of cartilages around joints) (Fig. 2), lymphatic, circulatory, and nervous (Fig. 3). The remaining 2 layers (skin and other organs) are not deeply investigated in this paper (the reason for this will be explained at the end of this section after providing some results of our analysis).



Figure 2. Zygote male – skeletal, muscular, and connective layers.

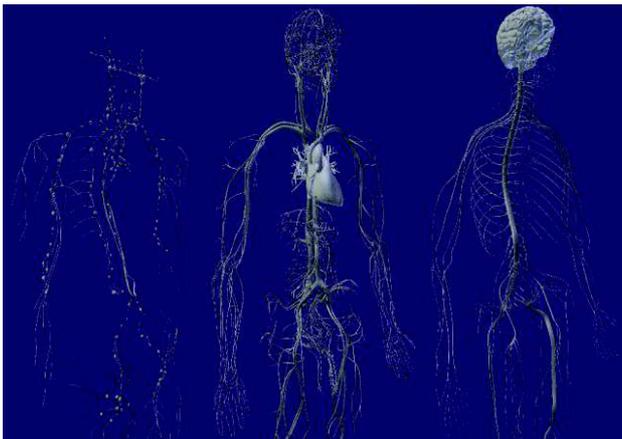


Figure 3. Zygote male – lymphatic, circulatory, and nervous layers.

Every layer is composed of many objects that represent individual elements of the system modelled by the layer. For example, the skeletal layer is composed of 246 objects that correspond to the bones, the intervertebral discs, and the cartilages connected ribs with the breastbone (Fig. 4). The surface of every object is modelled as a triangle mesh (Fig. 5).

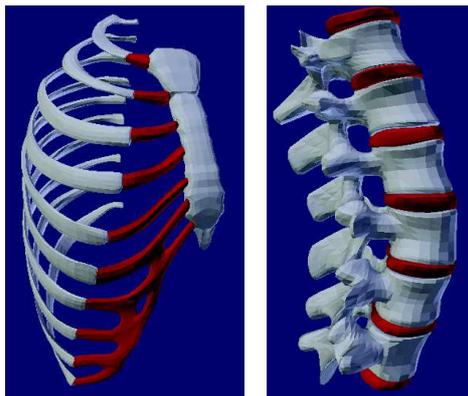


Figure 4. Zygote male – individual objects (the red objects correspond to cartilages).

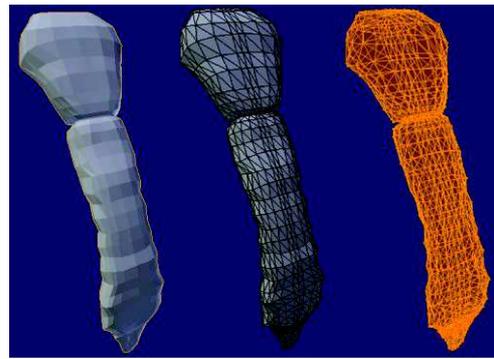


Figure 5. Zygote male – model of the breastbone.

### B. Physical Correctness of Zygote Male Model

A triangle mesh is composed of 3 types of elements – vertices, edges between vertices, and faces (triangles) bounded by edges and vertices (Fig. 6). A triangle mesh is manifold if the following two conditions are satisfied [11]:

- each edge is incident to only one or two triangles,
- the triangles incident to a vertex form a closed or an open fan (Fig. 7).

If at least one of these two conditions is not satisfied, then it means that the mesh cannot be a surface.

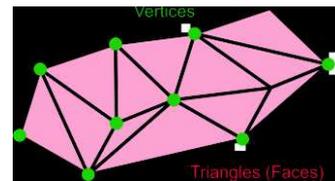


Figure 6. Triangle mesh.

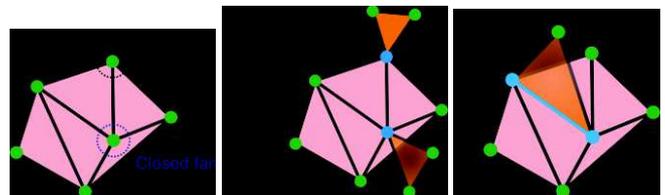


Figure 7. Manifold and non-manifolds caused by vertices and edge.

On the other hand, if a mesh is a manifold, then it does not mean that it creates a surface of a 3D object. This requires that a manifold does not contain any boundary. So, a manifold without boundary is defined as a manifold that contains only such vertices that create a closed fan. (Please note that in case of a manifold with boundary, the boundary is defined by the edges that are incident to only one face).

The previous paragraphs imply that a realistic virtual model of a human body has to be composed of objects whose surfaces are manifolds without boundaries. Because of that, we focused on checking such correctness of the Zygote male model in the first stage of the analysis. The results of this analysis are presented in Tables I and II.

TABLE I. BASIC STATISTICS ABOUT ZYGOTE MALE LAYERS

Layer	Objects	Non-manifolds	Manifolds with boundaries
Skeletal	246	1 (0.41%)	0 (0.00 %)
Muscular	563	12 (2.13 %)	505 (89.70 %)
Connective	415	2 (0.48 %)	202 (48.67 %)
Lymphatic	381	0 (0.00 %)	82 (21.52 %)
Circulatory	688	21 (3.05 %)	182 (26.45 %)
Nervous	275	12 (4.36 %)	27 (9.82 %)

Table I deals with individual objects detected in the layers of the Zygote male model. As we can see, there are very few objects whose surfaces do not create manifolds. On the other, a lot of objects are defined by meshes that represent manifolds with boundaries. Typical examples of such objects are muscles, cartilages around joints, and blood vessels. In case of muscles, this is caused mainly by the fact that the parts that are connected to bones are not closed (Fig. 8). In case of cartilages and blood vessels, these numbers result from the fact that these objects have no thickness (Fig. 9). This table also implies that the most correct layer from physical point of view is skeletal layer.

Tables II-IV provide more detailed statistics. As we can see in Table II, most of the edges and vertices that create non-manifold structures are in muscular and circulatory layer. In case of edges that are incident to just one face, i.e. edges that create boundary of a manifold, most of them are in muscular and connective layers.

### C. Overlapping Layers in Zygote Male Model

The previous analysis, whose results are summarized in Tables I and II, gives us a detailed view on the physical correctness of Zygote male model. However, it tells us nothing about overlaps between the objects, which are the main subject of this paper. Clearly, their investigation requires computation of intersections between the objects in the layers, as shown in Tables III and IV.

Tables I and II show that a lot of objects in Zygote are modelled as manifolds without boundaries, i.e. objects whose triangle meshes contain holes (Fig. 8 and Fig. 9). However, if we want to identify and quantify which objects intersect each other, we have to fill these holes. For this task, we used a method for automatic holes filling implemented in Blender. After filling the holes, we were able to compute intersections between each two objects. The results of this analysis are presented in Tables III and IV.



Figure 8. Zygote male – vertebral muscles and muscles on the head.

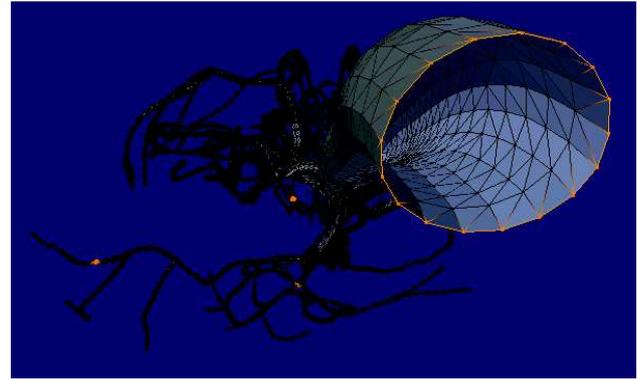


Figure 9. Zygote male – the aorta modelled as an object without thickness of the wall (seen from cranial).

Table III focuses on numbers of vertices that are inside other objects. More precisely, the cell in the  $i$ -th row and the  $j$ -th column shows how many vertices of the  $i$ -th layer are inside objects from the  $j$ -th layer. For example, in case of the 1<sup>st</sup> row, value 3.01 % means that about 3 % from 196,787 vertices (i.e. about 5,920 vertices) that creates skeletal layer (Table II) are inside objects that skeletal layer is composed of. Similarly, number 23.19 % means that about 23 % from 196,787 vertices (i.e. about 45,635 vertices) that creates skeletal layer are inside muscles. In case of the 2<sup>nd</sup> row, the 1<sup>st</sup> number indicates that about 12.70 % from 296,735 vertices (i.e. about 3,768 vertices) that muscular layer is composed of (Table II) are placed within objects of skeletal layer. All these calculations were performed using common functions provided by Blender.

TABLE II. BASIC STATISTICS – PHYSICAL CORRECTNESS OF THE ZYGOTE MALE MODEL

Layer	Vertices	Non-manifold vertices	Edges	Non-manifold edges	Boundary edges
Skeletal	196,787	6 (0.00 %)	589,231	2 (0.00 %)	0 (0.00 %)
Muscular	296,735	119 (0.04 %)	886,997	114 (0.02 %)	17,024 (1.92 %)
Connective	158,672	2 (0.00 %)	473,301	0 (0.00 %)	8,606 (1.82 %)
Lymphatic	53,245	0 (0.00 %)	157,441	0 (0.00 %)	996 (0.63 %)
Circulatory	401,468	126 (0.03 %)	1,201,191	89 (0.01 %)	2,733 (0.22 %)
Nervous	367,849	36 (0.01 %)	1,101,881	26 (0.00 %)	1,196 (0.11 %)

TABLE III. INTERSECTIONS BETWEEN OBJECTS OF TWO LAYERS (AFTER AUTOMATIC HOLES FILLING) FOR INNER VERTICES

Layer	Skeletal	Muscular	Connective	Lymphatic	Circulatory	Nervous
Skeletal	3.01 %	23.19 %	24.83 %	0.06 %	0.71 %	0.65 %
Muscular	12.70 %	18.30 %	4.57 %	0.03 %	1.05 %	0.52 %
Connective	20.97%	17.23 %	24.59 %	0.01 %	0.80 %	0.09 %
Lymphatic	1.94 %	16.75 %	0.47 %	12.18 %	3.56 %	0.57 %
Circulatory	17.18 %	11.00 %	1.24 %	0.14 %	9.22 %	2.26 %
Nervous	22.73 %	11.81 %	0.31 %	0.03 %	2.97 %	3.64 %

TABLE IV. INTERSECTIONS BETWEEN OBJECTS OF TWO LAYERS (AFTER AUTOMATIC HOLES FILLING) FOR JOINT VOLUME

Layer	Skeletal	Muscular	Connective	Lymphatic	Circulatory	Nervous
Skeletal	0.07 %	9.17 %	9.31 %	0.02 %	0.23 %	16.67 %
Muscular	2.84 %	3.75 %	5.02 %	0.03 %	0.37 %	0.23 %
Connective	52.41 %	9.11 %	3.81 %	0.01 %	0.26 %	0.11 %
Lymphatic	2.69 %	13.79 %	0.38 %	3.22 %	6.02 %	0.68 %
Circulatory	1.17 %	5.95 %	0.23 %	0.20 %	7.23 %	0.37 %
Nervous	79.35 %	3.60 %	0.09 %	0.02 %	0.35 %	4.54 %

Table IV deals with the volume of the intersections, i.e. the cell in the  $i$ -th row and the  $j$ -th column tells which part of the volume of the objects of the  $i$ -th layer is inside objects from the  $j$ -th layer. For example, the 1<sup>st</sup> number in the 1<sup>st</sup> row implies that the volume of the intersections between the objects of skeletal layer is about 0.07 % of the total skeletal volume. The next number in the same row tells that the intersections between the objects of skeletal and muscular layers have volume about 9.17 % from the total volume of skeletal layer. Similarly, the 1<sup>st</sup> number in the 2<sup>nd</sup> row indicates that about 2.84 % of the volume of the muscles is inside skeletal layer. The calculations of objects volumes were done using plugin to Blender – NeuroMorph [12].

Several numbers presented in Tables III and IV are really high (intersections skeletal – muscles, skeletal – connective, circulatory – skeletal, nervous – skeletal, etc.). This indicates that a lot of overlapping objects exist in the analysed model. The preliminary qualitative analysis showed that there exist several reasons for these numbers:

- automatic holes filling – the procedure fills a hole with minimal number of triangles; this approach is not always suitable, particularly for objects with big holes (e.g. muscles on the head (Fig. 10));
- objects with no thickness – typical instance is the skull, which is modelled as one solid object; because of that, everything inside it (the brain and blood vessels) are recognized as overlapping objects (Fig. 11); the same problem occurs if we want to analyse intersections between the skin and objects from other layers – the skin is modelled as an object without thickness, i.e. it has only outer face, what causes that the presented approach will identify all objects from the other layers as objects

that are inside the skin (because of that, we have not performed this analysis in this paper);

- muscles are terminated inside bones and not on their surface (Fig. 12),
- inaccurate positions of objects (Fig. 13).

#### IV. RELIABILITY ESTIMATION

Reliability has to be one of the important characteristics of the UGRA-simulator [7, 13–15]. From point of view of reliability engineering, the UGRA-simulator (as any other healthcare system) is complex and heterogeneous.

Reliability is defined as failure-free operation over time. In healthcare, this definition connects to several aims according to [15]: effectiveness (where failure can result from not applying evidence), timeliness (where failure results from not taking action in the required time), and patient-centeredness (where failure results from not complying with patients' values and preferences). Therefore, reliability analysis has to be performed for various types of objectives. This requires reliability investigations for separate parts (components) of healthcare systems. In [16], reliability is defined to refer to an individual patient's experience over time. The qualitative analysis by Failure Modes and Effects Analysis (FMEA) is considered. A lot of investigations of reliability in healthcare are provided for the medical devices/equipment and human factor [17, 18]. Methodology of medical equipment and devices (as technical part of healthcare) is developed in [17]. Influence of human factor is investigated in [18]. These results have been developed in [19–22]. Methods of reliability analysis (qualitative and quantitative) allow estimating time-depend properties [17, 18], critical states for medical errors [19, 20, 22], influence of different factors on medical errors [21].

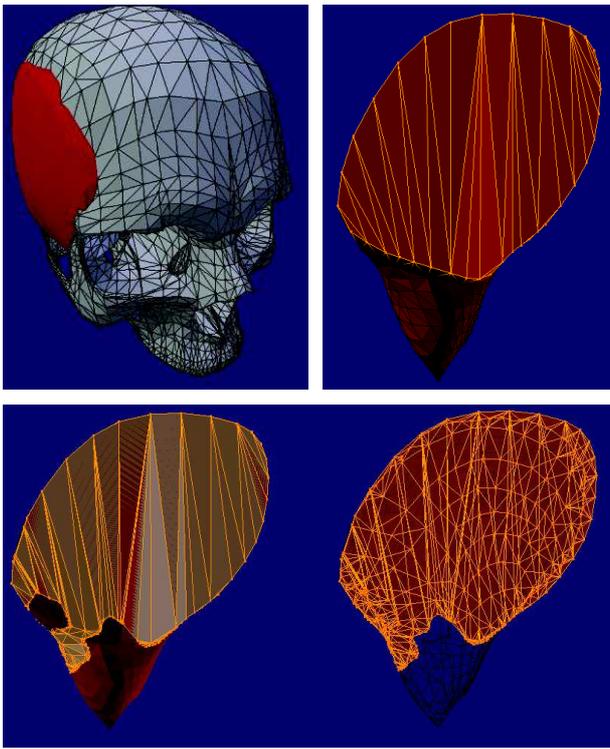


Figure 10. Zygote male – the skull, the masseter muscle and their intersection. One of the reasons that the intersection is quite big is that the muscle contains a big hole that has to be filled (the selected triangles in the upper picture). If we fill the hole using other methods, the intersection will be different.

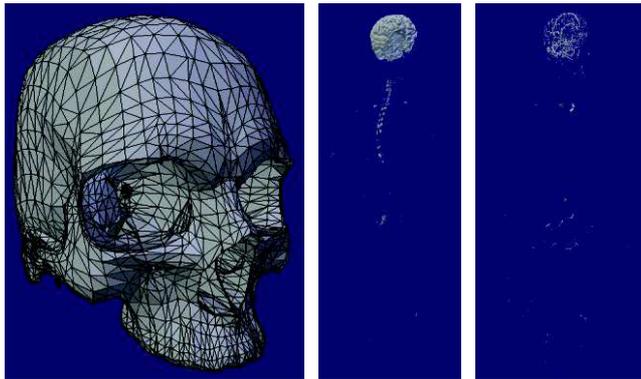


Figure 11. Zygote male – model of the skull and intersections between skeletal and nervous and skeletal and circulatory layers.

Qualitative evaluation aims to identify, classify, and rank failure modes or combinations of events that would lead to system failures. It is the first step in the analysis of reliability/risk of a given system that identifies the hazards associated to its operation. The output of this task consists of a list of the sources of potential danger (component failures, process deviations, external events, etc.) that have the probability of occurrence different from zero and that can give rise to significant consequences. These sources and initial data about behaviour of reliability of the system are used for quantitative evaluation in terms of probabilities for reliability, availability, safety, and similar attributes. Next, special measures allow creating a strategy for improving system reliability [17, 18, 23].

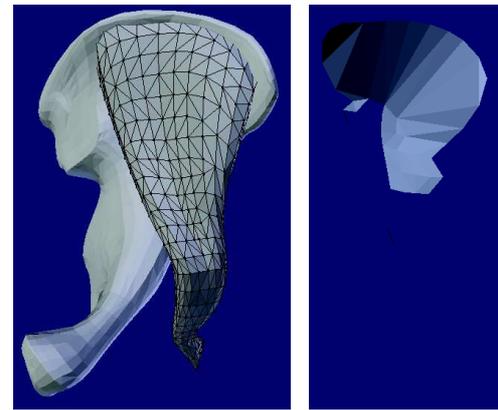


Figure 12. Zygote male – the pelvis and the iliac muscle terminated inside it and their intersection.

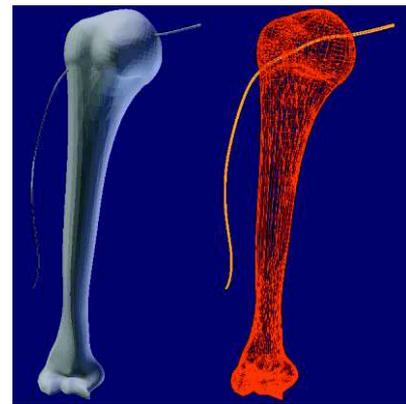


Figure 13. Zygote male – lymphatic vessel goes through a bone.

VPH-based model is an important part of UGRA-simulator. Therefore, improprieties of this model can cause error and failures in use of the simulator. Different types of improprieties are in 3D anatomical models [8, 24]. As shown above, the intersections of different layers in anatomical model are a real problem for the development of VPH-based model for the simulator. The provided analysis of intersections in Zygote Male Human Anatomy Collection v.4.0 can be used for simple reliability evaluation of this model. Typically, such investigation is implemented for the system in the step of testing. The qualitative analysis of faults in the system design is a complex problem because the definition of fault in acceptable form for reliability analysis is impossible [17, 23]. Therefore, assumptions for the faults indication and definition have to be considered. We propose to consider inconsistencies and incorrectness in the anatomical model for the UGRA-simulator because this model determines the quality of the simulator dominantly.

In the case of anatomical model, we consider it as investigated object that is formed by a triangle mesh (Fig. 6). This mesh is composed of 3 types of elements – vertices, edges between vertices, and faces (triangles) bounded by edges and vertices. The faults of this model can be interpreted as overlaps of different layers (Fig. 1). So, investigation of the intersections in Zygote used for development of anatomical model for UGRA-simulator can be considered as fault rates [25].

The results of the qualitative analysis of intersections in the anatomical model are used in preliminary estimation of reliability of the anatomical model by simple measure known as failure rate. The failure rate can be used in initial estimation of reliability of the simulator in design and preparation of recommendation to improve this system from reliability point of view [23, 25]. Typically, the fault rate represents the numerical characteristic as the frequency or probability of a specific fault and allows us to calculate the failure rate of system [25]. The data about intersections in the anatomical model are characterized as constant fault rates because this model is investigated as time-independent object. A system failure rate is defined in this case as follows [23, 25]:

$$F = \xi(\text{fault rate } 1, \text{fault rate } 2, \dots, \text{fault rate } N), \quad (1)$$

where  $N$  is a number of faults; and  $\xi$  is a function representing the correlations/connections of faults and their influence on system failure.

The function  $\xi$  in (1) is defined based on topological or structural properties of the system and represents result of the analysis of influence of possible faults on system failure [23, 25]. Let us propose the simple version of this function for the analysis of intersection in the anatomical model based on the statistics presented in section III. The intersections in the anatomical model are independent events (a given intersection has no influence on existence of other intersections occurring in the model). However, topology or structure of this model as a system from reliability point of view is not known. In such situation, we can consider two boundary failure rates, i.e. the failure rates for parallel and series structures. In case of the parallel structure, the failure rate is computed using the following formula [23]:

$$F = \prod_{i=1}^N q_i, \quad (2)$$

where  $q_i$  is the probability of fault  $i$ ; and for the series structure this measure is calculated as follows:

$$F = 1 - \prod_{i=1}^N (1 - q_i). \quad (3)$$

The calculation of failure rates for every layer in the anatomical model is implemented based on (2) and (3) and the data in Tables III and IV that are transformed into the probabilities of faults. The results of the evaluation for failure rates are shown in Tables V and VI. The data in these tables show that the layer of muscles has maximal failure rates for both variants of the analysis. It means that this layer is considered as the first for the improving of the model for the UGRA-simulator, i.e. the intersections of muscles with other layers has to be eliminated. The minimal failure rate has lymphatic layer and, therefore, elimination of the intersections between this layer and others will have minimal impact on the model improving.

Need to say that the interpretation of function  $\xi$  as the function for parallel and series structures is very simplified and can be considered as boundary assessments of failure rate of the anatomical model only.

## V. CONCLUSION

The VPH-based model is an important part of the RASim. 3D anatomical model Zygote was considered for the model elaboration. However, the model for the simulator developed based on Zygote Male Human Anatomy Collection v.4.0 is insufficient due to inconsistency, a lack of anatomical correctness, and missing structures like the fascia. In this paper, we presented results of the preliminary analysis of such model from point of view of reliability engineering. We tried to quantify its inconsistencies by detection of the intersections between the structures/layers that the model is composed of. We also identified the main causes of these intersections and, using some methods of reliability analysis, we investigated influence of individual layers on reliability of the used Zygote male model.

Need to say that the presented results are based mainly on the analysis of the layers from physical point of view, i.e. we investigated whether the layers are composed of objects modelled as manifolds without boundaries and whether intersections between them exist. However, the analysis does not

TABLE V. FAILURE RATE OF INTERSECTIONS BETWEEN OBJECTS OF TWO LAYERS (FOR PARALLEL STRUCTURE)

	Skeletal	Muscular	Connective	Lymphatic	Circulatory	Nervous
Intersections between objects for joint volume	6.0728·10 <sup>-7</sup>	1.5911·10 <sup>-5</sup>	5.0412·10 <sup>-10</sup>	9.2081·10 <sup>-19</sup>	5.8140·10 <sup>-11</sup>	1.4264·10 <sup>-13</sup>
Intersections between objects for inner vertices	2.6021·10 <sup>-9</sup>	9.2534·10 <sup>-8</sup>	1.4007·10 <sup>-12</sup>	7.7280·10 <sup>-20</sup>	3.3706·10 <sup>-13</sup>	4.8175·10 <sup>-13</sup>

TABLE VI. FAILURE RATE OF INTERSECTIONS BETWEEN OBJECTS OF TWO LAYERS (FOR SERIES STRUCTURE)

	Skeletal	Muscular	Connective	Lymphatic	Circulatory	Nervous
Intersections between objects for joint volume	0.5801	0.6606	0.4699	0.1242	0.1708	0.1253
Intersections between objects for inner vertices	0.2082	0.3789	0.1772	0.0349	0.1386	0.2155

consider all anatomical aspects because several kinds of intersections can exist in a human body (e.g. blood vessels and muscles). This and other issues will be addressed in the next research.

## REFERENCES

- [1] E. Ortiz and C. M. Clancy, "Use of Information Technology to Improve the Quality of Health Care in the United States," *Health Services Research*, vol. 38, no. 2, pp. xi–xxii, Apr. 2003.
- [2] G. Makransky et al., "Simulation based virtual learning environment in medical genetics counseling: an example of bridging the gap between theory and practice in medical education," *BMC Medical Education*, vol. 16, no. 1, pp. 1–9, 2016.
- [3] M. Graafland, J. M. Schraagen, and M. P. Schijven, "Systematic review of serious games for medical education and surgical skills training," *British Journal of Surgery*, vol. 99, no. 10, pp. 1322–1330, 2012.
- [4] T. K. L. Costa, L. S. Machado, A. M. G. Valença, and R. M. Moraes, "Architecture to Portals of Serious Games and Virtual Environments with Performance Evaluation during Sequences of Activities," in *2016 IEEE 4th International Conference on Serious Games and Applications for Health*, 2016.
- [5] The RASimAs project (Regional Anaesthesia Simulator and Assistant), <http://www.rasimas.eu/>.
- [6] T. M. Deserno, J. E. E. de Oliveira, and O. Grottko, "Regional Anaesthesia Simulator and Assistant (RASimAs): Medical Image Processing Supporting Anaesthesiologists in Training and Performance of Local Blocks," in *2015 IEEE 28th International Symposium on Computer-Based Medical Systems*, 2015, pp. 348–351.
- [7] J. E. E. de Oliveira, P. Giessler, and T. M. Deserno, "Image Registration Methods for Patient-specific Virtual Physiological Human Models," in *Proceedings of the Eurographics Workshop on Visual Computing for Biology and Medicine*, 2015, pp. 31–40.
- [8] M. L. Neal and R. Kerckhoffs, "Current progress in patient-specific modeling," *Briefings in Bioinformatics*, vol. 11, no. 1, pp. 111–126, Jan. 2010.
- [9] V. Voski et al., "A State of The Art Virtual Physiological Human Model for Regional Anaesthesia," in *2016 Virtual Physiological Human Conference (VPH 2016)*, The Netherlands, 2016 (submitted).
- [10] Blender project, <https://www.blender.org/>.
- [11] S. Marschner, P. Shirley, *Fundamentals of Computer Graphics*, 4th ed. Boca Raton, FL: CRC Press, 2015.
- [12] A. Jorstad et al., "NeuroMorph: A Toolset for the Morphometric Analysis and Visualization of 3D Models Derived from Electron Microscopy Image Stacks," *Neuroinformatics*, vol. 13, pp. 83–92, Jan. 2015.
- [13] B. W. Johnson and J. H. Aylor, "Reliability and safety analysis in medical applications of computer technology," in *Engineering of Computer-Based Medical Systems, 1988., Proceedings of the Symposium on the*, 1988, pp. 96–100.
- [14] B. Chaudhry, J. Wang, S. Wu, M. Maglione, W. Mojica, E. Roth, S. C. Morton, and P. G. Shekelle, "Systematic Review: Impact of Health Information Technology on Quality, Efficiency, and Costs of Medical Care," *Annals of Internal Medicine*, vol. 144, no. 10, pp. 742–752, May 2006.
- [15] *Crossing the Quality Chasm: A New Health System for the 21st Century*. Institute of Medicine (US) Committee on Quality of Health Care in America. Washington, D.C.: National Academies Press, 2001.
- [16] T. Nolan, R. Resar, C. Haraden, and F. A. Griffin, *Improving the Reliability of Health Care*. IHI Innovation Series white paper. Boston: Institute for Healthcare Improvement, 2004.
- [17] B. S. Dhillon, *Medical Device Reliability and Associated Areas*. Boca Raton, FL: CRC Press, 2000.
- [18] B. S. Dhillon, *Human Reliability and Error in Medical System*. Singapore, SG: World Scientific, 2003.
- [19] J. Deeter and E. Rantanen, "Human Reliability Analysis in Healthcare," in *2012 Symposium on Human Factors and Ergonomics in Health Care*, 2012, pp. 45–51.
- [20] R.G. Fichman, R. Kohli, and R. Krishnan, "The Role of Information Systems in Healthcare: Current Research and Future Trends," *Information Systems Research*, vol. 22, no. 3, pp. 419–428, Sep. 2011.
- [21] E. Zaitseva, V. Levashenko, J. Kostolny, and M. Kvassay, "New Methods for the Reliability Analysis of Healthcare System Based on Application of Multi-State System," in *Applications of Computational Intelligence in Biomedical Technology*, R. Bris, J. Majernik, K. Pancerz, and E. Zaitseva, Eds. Cham: Springer International Publishing, 2016, pp. 229–251.
- [22] M. R. Chassin and J. M. Loeb, "High-Reliability Health Care: Getting There from Here," *The Milbank Quarterly*, vol. 91, no. 3, pp. 459–490, Sep. 2013.
- [23] E. Zio, *An Introduction to the Basics of Reliability and Risk Analysis*. Singapore, SG: World Scientific, 2007.
- [24] G. Widmann, R. Stoffner, and R. Bale, "Errors and error management in image-guided craniomaxillofacial surgery," *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*, vol. 107, no. 5, pp. 701–715, May 2009.
- [25] E. J. Henley and H. Kumamoto, *Probabilistic risk assessment: reliability engineering, design, and analysis*. New York, NY: IEEE Press, 1992.