

BRIGHT

Erasmus+ strategic partnership for Higher Education

BOOSTING THE SCIENTIFIC EXCELLENCE AND INNOVATION
CAPACITY OF 3D PRINTING METHODS IN PANDEMIC PERIOD

O5 - BRIGHT e-case study 2

Project Title	Boosting the scientific excellence and innovation capacity of 3D printing methods in pandemic period 2020-1-RO01-KA226-HE-095517
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1 Introduction

This is a documentation regarding the e-case study #2 of the BRIGHT project, which was focused on 3D printed and cast anatomical model of tongue with cancer tumor – a device used before and during life-saving cancer surgery. In this e-case study, all main stages of work are presented – design using medical data (DICOM), some strength simulations in CAE, manufacturing using FDM, SLA and PolyJet 3D printing technology and resin casting, also testing – both destructive (simulated surgery) and non-destructive.

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2 BRIGHT e-case study #2 – main ideas

2.1 Main concepts

Cancer of the tongue is one of the most common malignancies in the oral cavity. A tongue tumor can grow relatively quickly and spread deep into the muscles of the tongue. It is recommended that the resulting lesions undergo tumor resection. This procedure involves radical removal of the tumor, and the operation is highly demanding due to the difficulty of accessing the tumor, it may lead to trismus or massive bleeding. After tumor resection, a cavity remains, which must be reconstructed using the patient's tissues. The answer to the need for thorough preoperative planning is to create a personalized object that reflects the shape, size and mechanical properties of anatomical structures. One-to-one creation of an individualized model is possible and cost-effective thanks to the additive manufacturing technique.

That is the purpose of the second BRIGHT case study. It is an anatomical model of a tongue with cancer tumor (Figure 1). This type of model has a number of applications – first and foremost it is used as a pre-operative aid – for simulated surgery procedure. It is also used for mid-surgery support, to help with tissue reconstruction process (after sterilization, the model can be taken into the operating room). It can also be used for educational purposes (by students of medical universities) and for showing to the patient prior to the operation itself. The anatomical models of soft tissues can be produced either as hard models (for mid-surgery) or as soft ones (for simulated surgery before the operation).



Figure 1. Models of tongue with cancer tumor

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The product is customized basing on medical imaging – in the case of soft models, MRI is the most popular technique. Basic DICOM images require proper segmentation, then a 3D mesh is generated in STL format. It can be further processed – for hard 3D prints (using FDM, SLA, DLP or PolyJet) it can be used right away, but for soft resin, molds need to be created first and then they are printed (using FDM or PolyJet). A number of different software tools are used in the design process, starting from medical image processing software (Invesalius), through mesh processing software (GOM Inspect, MeshMixer etc.) and CAD software (Inventor).

2.2 Requirements and recipients

To realize a 3D printing and manufacture the product, the following is needed:

- 1) DICOM anatomical data of a given patient, preferably from MRI (soft tissues), with good (dense) resolution of images
- 2) FDM printer or preferably (for better surface) – SLA or PolyJet printer – for hard model and molds for casting
- 3) vacuum chamber and casting tools, for manufacturing soft models
- 4) additive (two-component) resin – a chemically cured material, with properly low hardness for tissue property simulation
- 5) basic tools for post processing (file, sandpaper, knife, driller etc.)

The recipients of the model could be as following:

- medical personnel realizing patient treatment (surgeons), for pre-operative work or for mid-surgery support in the reconstructive surgery,
- students of medicine, for education (visual and tactile assessment of cancer tumor, simulated surgery)
- patients and their families, for better knowledge before operation and for improved psychic comfort

Also, for students and 3D printing specialists, this is a good example of difficult work on human soft tissue images – as opposed to hard tissues (bones and cartilage), here segmentation and work with anatomical data is difficult and requires heavy expertise, preferably assistance from a skilled radiologist.

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2.3 *Plan of work and task distribution*

The model of the tongue was created as cooperation between Poznan University of Technology and one of the local hospitals. It is a part of a doctoral thesis of one of PUT's teachers. It was designed, produced, tested and clinically implemented. Out of this process, educational materials for BRIGHT were created – specifically, toolkit for O2 and input for O1 CAD model. The model was also selected for the webinars in O4 and a number of additional work was done then, for educational purposes (including CAE simulation and SLA printing) that have been realized with the contribution of all partners of the BRIGHT project consortium. The case was not implemented in neither of summer schools, due to high difficulty of working with DICOM imagery of oral cavity without prior experience. However, its educational value is esteemed as very high.

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3 BRIGHT e-case study #2 – realized work

3.1 Design

Create STL models

On the basis of cooperation between the Poznań University of Technology and the Clinical Hospital of Heliodor Świącicki of the Medical University of Karola Marcinkowski in Poznań, the data provided in the form of DICOM from MRI imaging for the conducted research was one of the patients. These photos show an MRI of the head, and the area of interest is the tongue and the tumor of the tongue. One of the first steps was to import data from imaging to InVesalius 3.1. It enabled the conversion of the file from the DICOM standard to the STL format and setting the parameters, the thickness of a single layer is 1 mm.

Segmentation of anatomical structures

Then in InVesalius 3.1. the segmentation of the structures of the tongue and its tumor was carried out. Various taskbars appear on the screen after the data is imported. On the left side you can see the image manipulation tools and on the right side there are windows showing the same three-dimensional image in 3 different planes. There are sliders next to each of the windows, which are used to change the viewed cross-section. Below in Figures 2 and 3 are given 3D images of a patient's skull with a tongue tumor along.

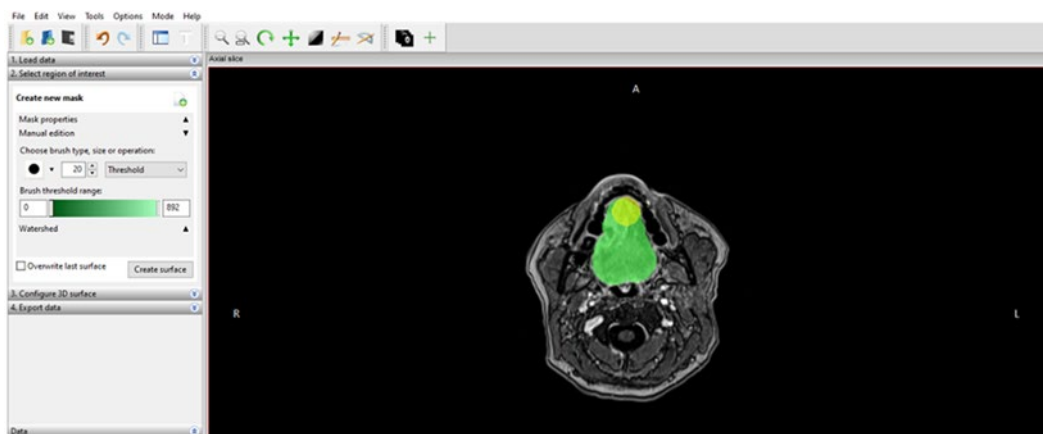


Figure 2. Screenshot taken during tongue segmentation

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The effects of the work described above are presented below:

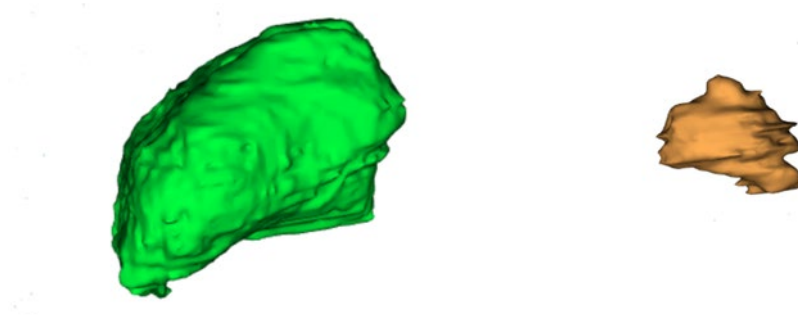


Figure 3. Segmented model of the tongue and its tumor

Processing the 3D model

In order to make the models as real as possible and to facilitate the printing of individual models, they were processed using the GOM Inspect Suite system. For this purpose, several functions were used, such as smoothing, selecting surface triangles, closing holes interactively/automatically. The most frequently used function when processing models was smoothing, it can be found by opening the operation options and going to the mesh, as shown in Figure 4

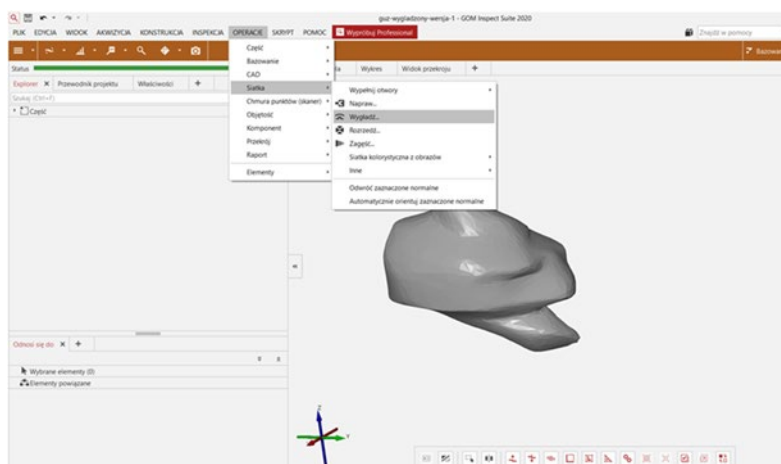


Figure 4. GOM Inspect Suite – smoothing the model

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The results of the operations performed for both models are presented in Figure 5.

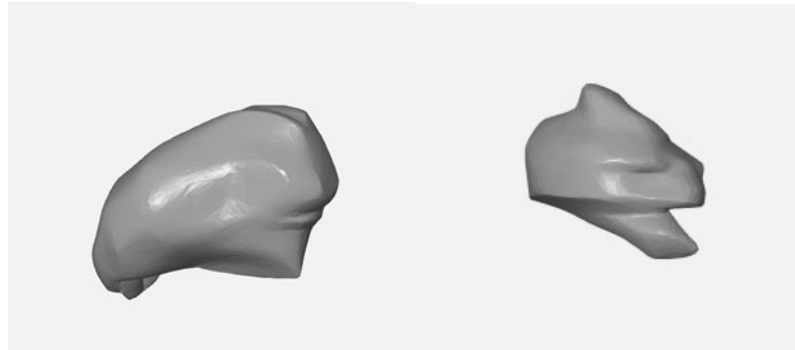


Figure 5. The final effect of machining the models from the left tongue on the right tumor

Design of molds

The last of the design elements was the preparation of molds for the tongue with the tumor and the tumor itself as shown in Figure 6. For this purpose, the Meshmixer program and the STL models designed at that time were used. In both cases, the first step was to import the designed models. Then, overflow and venting channels with a diameter of 6 [mm] were added to each of the models, located in the tops of the models, and infusions placed on the side and in the center of the models for the tongue form with a tumor with a diameter of 11 [mm], for the tumor the diameter was the same dimensions every transfer, that is, it measured 6 [mm]. For this purpose, the cylinder-shaped objects already in the program were added, and then they were sized and positioned in the appropriate places using the transform function in the edit function tools.

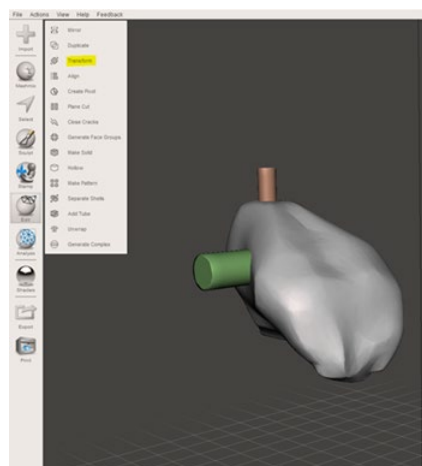


Figure 6. Designing an overflow using the transform function

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After creating the infusion and overflow, these elements were selected together with the model, open the edit option in the taskbar again, but this time the Make Solid option was selected, setting Solid Accuracy and Mesh Density to the maximum possible values as in Figure 7, if the object had any kind of holes this function could be performed. Setting these functions was required so that the next operation, which will be subtracting models, could be performed correctly.

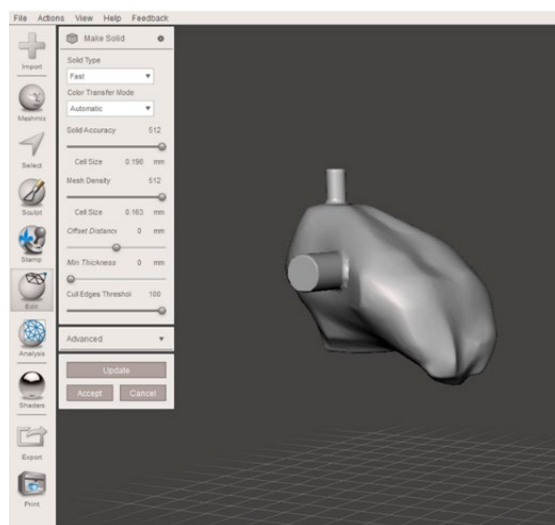


Figure 7. Design of the mold core

Once the mold core was prepared, a casting box had to be prepared. For this purpose, the shape was again obtained from the objects proposed by the Meshmixer program, and in the Meshmix options, both the tongue and the nodule were selected as cuboids. The main goal of designing the boxes was to keep the volume as small as possible, so that the printing was not time-consuming and financially optimal. The initial dimensions of the cuboid in the case of the tongue were 57x72x70 mm, and in the case of the tumor, the dimensions of the cuboid as well as its final dimensions of the form were 25x30x35 mm. The created objects also had to be subjected to the Make Solid function and set the aforementioned parameters.

When two objects were created for both the tongue and the tumor - a cuboid and a form, it was time to subtract one model from another. The program enables such an operation using the Boolean Difference function. For this purpose, in the Object Browser panel, the object was first selected, from which the next selected object was to be subtracted, as shown in Figure 8.

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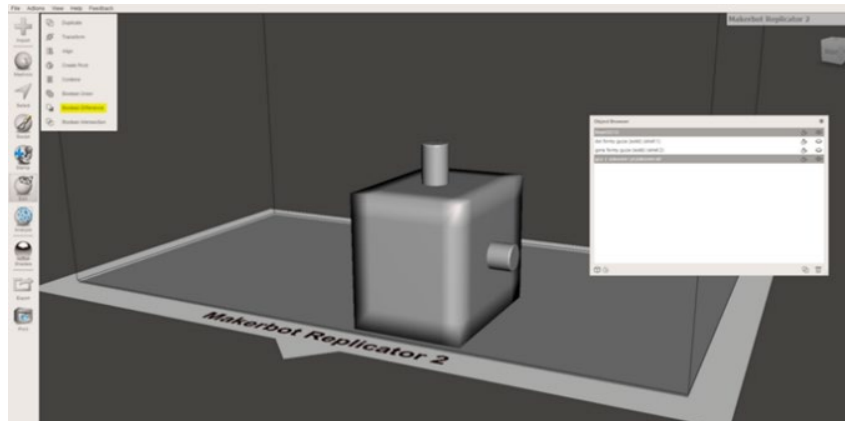


Figure 8. Using the Boolean Difference function to obtain the form of a tumor

In the case of the tumor matrix, the cuboid had too much unsuitable volume, so it was transformed. With the plane cut operation available in the edit functions, the volume of the mold was reduced as shown in the Figure 9.

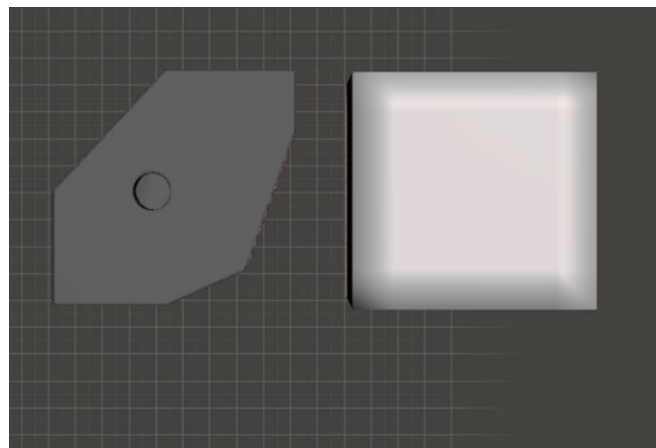


Figure 9. Comparison of the optimized object with its initial version

The final step was to use the plane cut function again to separate the molds into two parts so that the resulting castings could be easily removed. For this purpose, the division of the facilities was carried out through the overflow and venting channel.

In Figure 10 is presented how the designed and ready-to-print casting models look like for a tongue with a bump:

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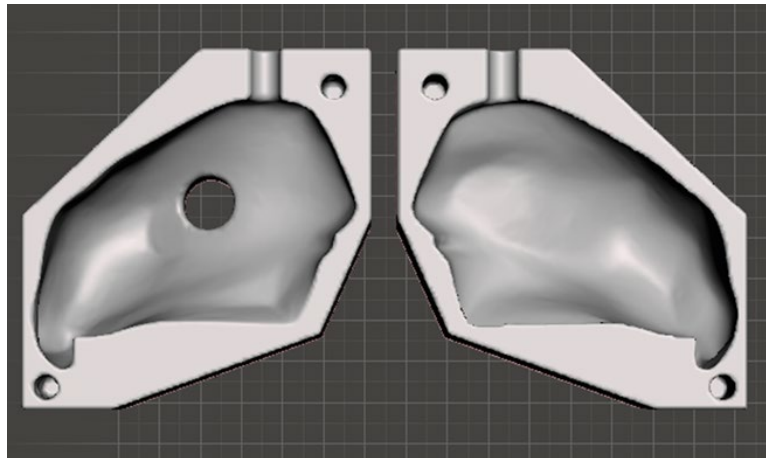


Figure 10. Casting form of a tongue with a tumor

In Figure 11 are presented casting molds designed to cast a tongue tumor:

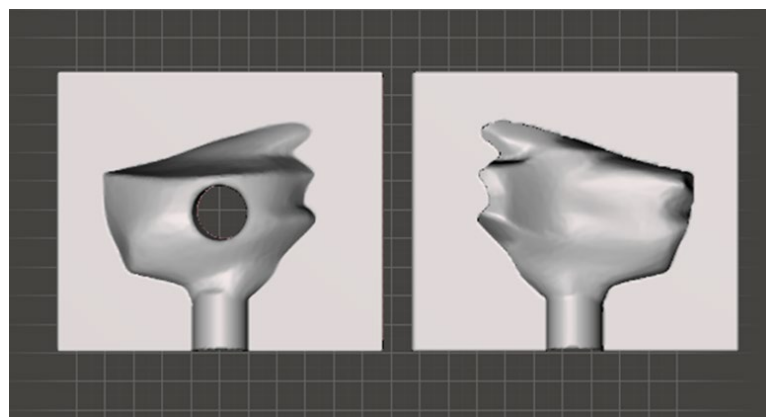


Figure 11. Tongue tumor matrix

3.2 CAE simulations

The main objective of the finite element analysis that was realized for the 3D model of the tongue casting mould shown in Figure 12 was to evaluate the strength characteristics of the mould used for casting the tongue model by simulating a pressurization test. The principle of the test is shown in Figure 13. As one may notice, the inner surfaces of the mould parts are loaded by pressure after being clamped between two rigid plates in their assembled configuration. The inner pressure gradually increases from 0 (zero) to 8 MPa.

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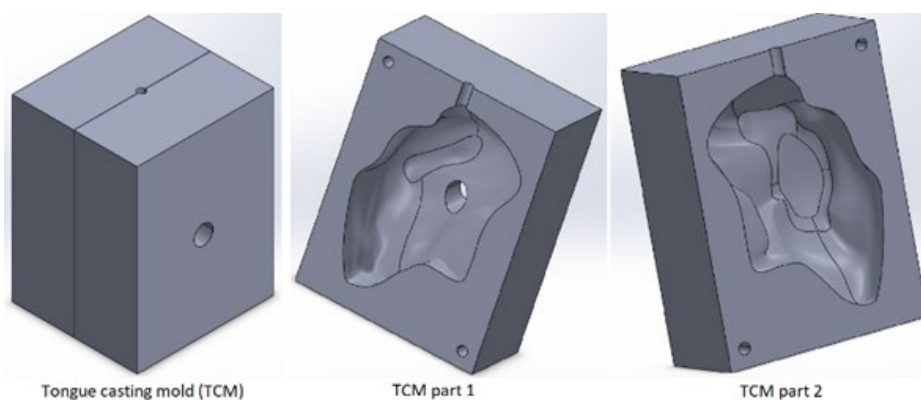


Figure 12. 3D model of the tongue casting mould

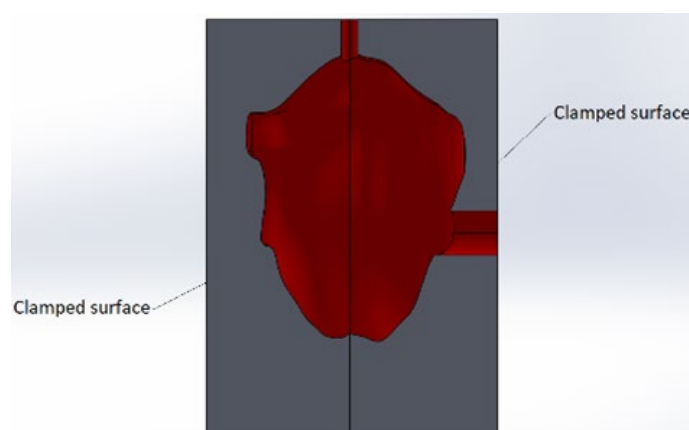


Figure 13. Principle of the pressurization test simulated for evaluating the strength characteristics of the tongue casting mould (inner pressure acting on the red surfaces)

The following assumptions have been made when preparing the finite element model of the pressurization test:

- a) Both mould parts are made from PLA exhibiting an isotropic linear elastic behaviour defined by the following parameters: elastic modulus $E = 3500$ MPa, Poisson's ratio $\nu = 0.36$, and yield strength $Y = 59$ MPa.
- b) The mould parts are bonded together along their contact surfaces.

The finite element model of the pressurization test has been elaborated and solved with SOLIDWORKS Simulation in the following sequence of steps (Figure 14):

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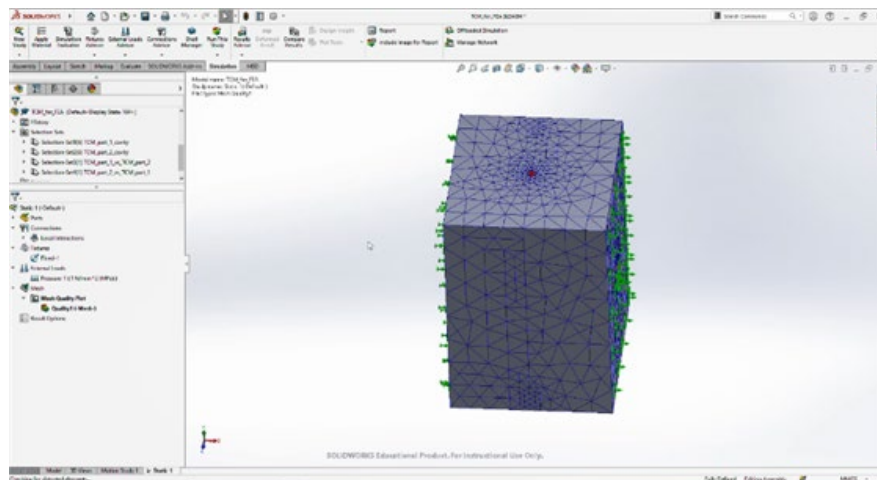


Figure 14. Finite element model of the pressurization test simulated for evaluating the strength characteristics of the tongue casting mould

- a) Associating the PLA material to both mould parts
- b) Specifying the contact interaction between the mould parts: bonded contact
- c) Enforcing a full locking kinematic constraint on the end faces of the mould parts
- d) Defining a unit pressure on the inner surfaces of the mould parts

Note: The actual values of this load have been specified later as load cases (step (f)).

- e) Specifying the dimension of finite elements and generating the mesh

- f) Specifying the actual values of the pressure applied to the inner surfaces of the mould parts: 2 MPa (load 1), 4 MPa (load 2), 6 MPa (load 3), and 8 MPa (load 4).

In Figures 15 and 16 are shown the most important results provided by SOLIDWORKS Simulation: distributions of the von Mises equivalent stress in the mould parts for the fourth load case (testing pressure of 8 MPa). The maximum values of the von Mises equivalent stress $\sigma_{eq,max}$ associated to different load cases are displayed on the diagram in last figure to show their dependence on the testing pressure p . The following conclusions have been formulated after examining the diagram given in Figure 17:

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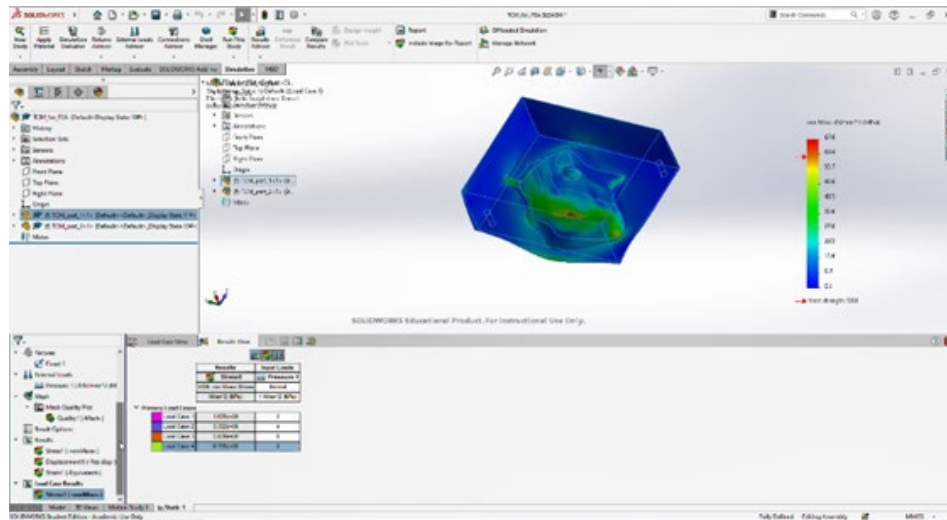


Figure 15. Distribution of the von Mises equivalent stress in the upper part of the mould for the fifth load case – testing pressure of 8 MPa

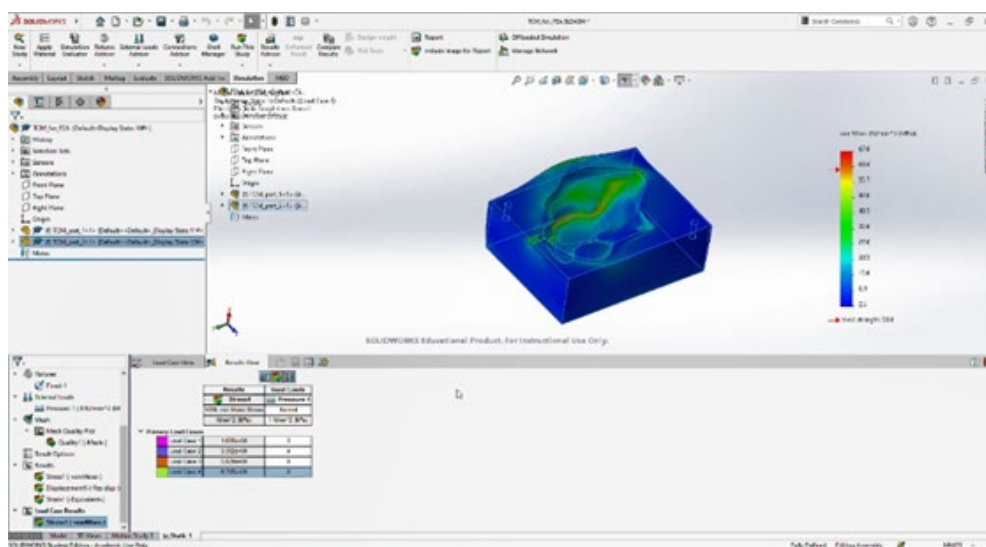


Figure 16. Distribution of the von Mises equivalent stress in the lower part of the mould for the fifth load case – testing pressure of 8 MPa

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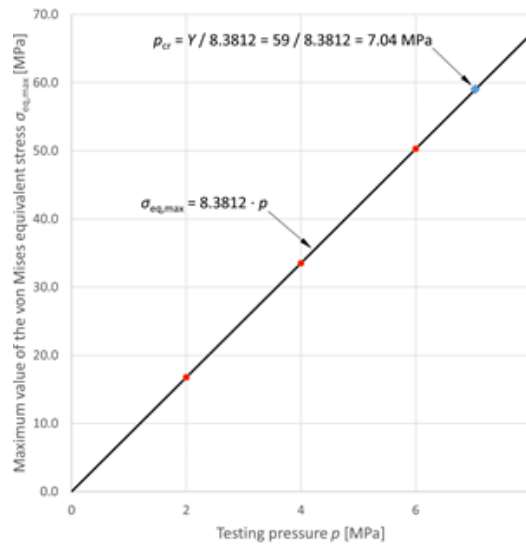


Figure 17. Maximum values of the von Mises equivalent stress associated to different testing pressures: red dots – numerical results; black path – linear regression; blue diamond – pressure at which the maximum value of the equivalent stress equals the yield strength

a) The mechanical response of the mould is well approximated by means of the linear regression $\sigma_{eq,max} = 8.3812 \cdot p$ (see the black path displayed on the diagram in Figure 17).

b) This regression can be used to determine the testing pressure at which the maximum value of the equivalent stress equals the yield strength of the PLA material: 7.04 MPa (see the blue diamond displayed on the diagram in Figure 17).

c) The finite element analysis shows that the mould exhibits a high strength when loaded by an inner pressure. The critical value of this parameter (7.04 MPa) is much greater than the greatest load that may occur during the casting process.

3.3 Manufacturing

3.3.1. Additive manufacturing

In the case of FDM tongue and tumor print (hard, operative model), the FlashForge Creator Pro machine was used (Figure 18). Low layer thickness (0.15 and 0.2) was used for tumor and tongue.

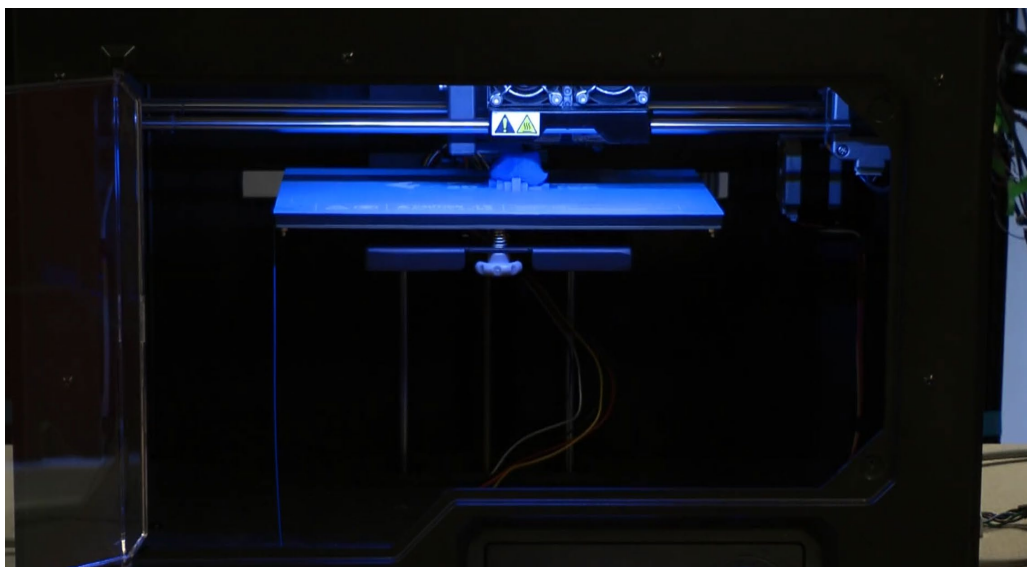


Figure 18. FDM 3D printing of tongue – FlashForge Creator Pro

Molds were printed with the Prusa i3 MK3S printer in the 3D printing laboratory at the Poznań University of Technology. In order to print the molds, the objects were imported into PrusaSlicer 2.3.3 (see Figure 19). Formerly known as Slic3r Prusa Edition and Slic3r PE, the program is an open source, feature-rich, frequently updated tool that gives y the ability to export print files for Original Prusa 3D printer.

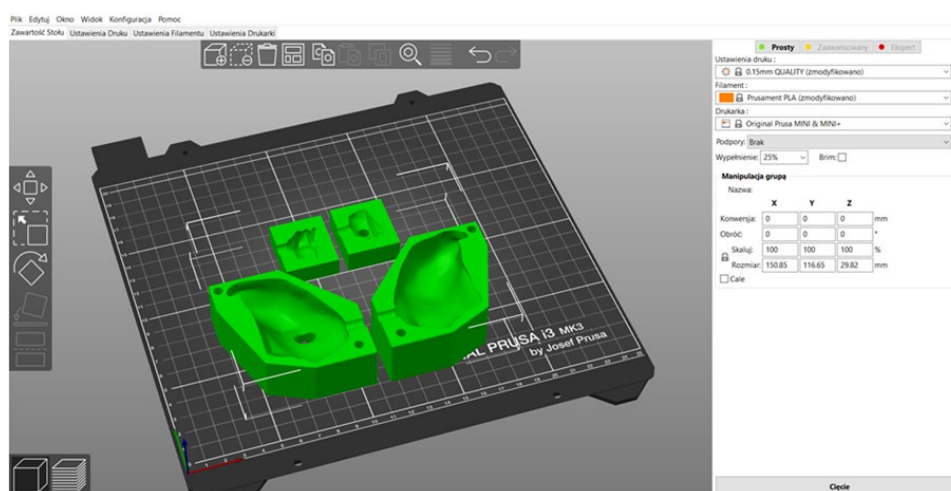


Figure 19. Screenshot of PrusaSlicer with casting

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The table with the printing parameters of the above-illustrated forms is presented in Figure 20.

Parameters	Values
Material	PLA
Filling	25%
Thickness	0,15 [mm]
Printing time	9 [h]
Volume	524,73 [cm ³]

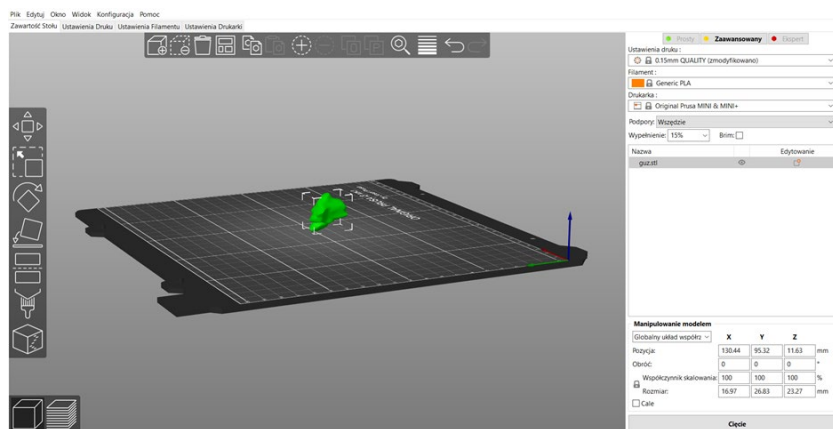


Figure 20. A screenshot of the PrusaSlicer program with a tumor

In Figure 20 is presented also one screenshot for the preparation of part for printing, there was a lump of the tongue. The object has irregular shapes and does not contain any element that could be considered as the basis for printing. In order for the printing process to run correctly, the model had to be printed with supports. The supports were made of the same material as the object itself – Fiberlogy PLA.

Few important details about the printing process (like time necessary for the printing (printing time), layer thickness, details about the material are given in Figure 21, along with the final result of the 3D printed casting molds of the tongue and its tumor. As one may notice in Figure 21, a mold of the tongue with a tumor is presented in the Figure and in the lower part of the Figure it is provided a form of a tumor of the tongue.

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Parameters	Values
Material	Fiberlogy PLA
Filling	15%
Thickness	0,15 [mm]
Printing time	27 [min]
Volume	10,59 [cm ³]

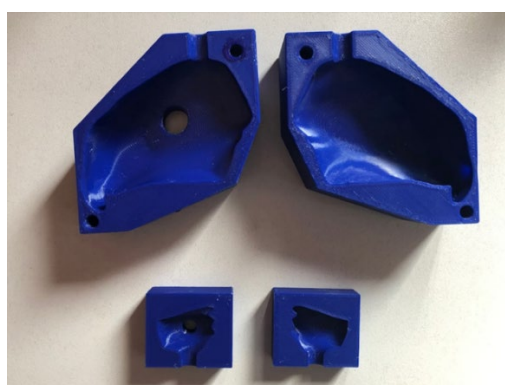


Figure 21. Casting molds of the tongue and its tumor

In the case of SLA technology, Anycubic Photon Mono was used (Figure 22). The machine operates in the LCD-based SLA technology. Anycubic Standard Resin+ material was used. The 0.1 mm layer thickness was used, The manufactured parts were post-cured using Anycubic Cure Plus Machine (Figure 23), in time of 5 minutes, after previous cleaning in isopropyl alcohol.

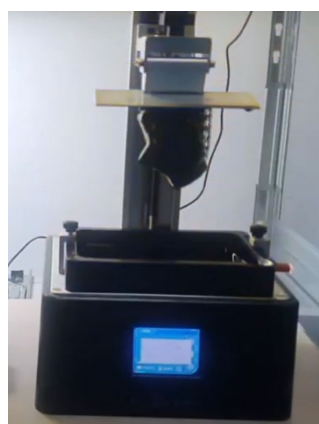


Figure 22. SLA printing of the tongue using Anycubic machine

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Figure 23. Anycubic SLA post-curing of the tongue model

In case of the PolyJet technology, MediJet J5 printer by Stratasys was used (Figure 24). Standard settings were utilized during the printing, with 18 micron layer thickness. For the tongue, transparent VeroUltra Clear S material was used. For the tumor, combination of four colors (VeroCyan, VeroMagent, VeroYellow and VeroBlack Plus) were used to obtain a dark red color (as visible in Figure 26). Also, a post processing station with water jet device was used (as visible in Figure 25). Support structures in PolyJet are soluble (synthetic wax) and can be removed just by pressurized stream of water.



Figure 24. PolyJet 3D printing using MediJet J5 printer (multimaterial)

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Figure 25. PolyJet 3D printing – post processing

Figure 26 presents final results of hard models 3D printing – FDM, PolyJet and SLA printouts after post processing, before sterilization and clinical use.



Figure 26. Hard 3D printed models of tongue with cancer – FDM, PolyJet and SLA technology

3.3.2. Casting

After printing the casting molds of the tongue and the tongue tumor, the next step was to cast the models. The goal was to obtain three models of the tongue with their tumors, where each tumor was made of different materials. In this section, we will describe the course of the foundry processes and show how various parameters can affect the final result.

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The first step in all the operations was to locate the tumor of the tongue in the cast mold. As the tumor is inside the tissue, its location was arbitrary, selected on the basis of photos taken during the design. The location of the tumors in a casting mold is shown in Figure 27. Further on the mold is prepared to be used for casting of the models like shown in Figure 28.



Figure 27. Placing the tumor model in larger mold



Figure 28. A mold prepared for the casting process

Ultimately, three different models of the tongue will be created along with its tumor. For realizing of the casting, the materials were selected in consultation with the medical staff, based on the presentation of samples of various materials. The semi-finished product intended for the casting of the tongue in all cases was - Sorta Clear 12. However, the tumors were made of materials such as Fiberflex (printed), Dragon Skin 10 and XTX 45 DRY (cast).

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The process of casting is presented in Figure 29, while the three models that have been obtained after the casting process are presented in Figure 30.



Figure 29. The resin casting process



Figure 30. Three cast models of tongue, with use of various materials

3.4 Testing

As part of the planned clinical evaluation, a simulated surgery process was performed followed by a survey. The clinical evaluation was attended by two surgeons working every day at the Clinical Hospital. Heliodor Świącicki of the Medical University of Karol Marcinkowski and a medical student from the Medical University of Karol Marcinkowski.

One of the first stages of the simulated operation was the preparation of surgical instruments, which included a surgical vice, surgical tweezers and surgical knives. Then the models were inspected and the selected area was marked with a marker, as it is usually done in the operating theatre as shown in Figure 31.

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Figure 31. Operation simulation - marking

The next step was to incision the area marked at that time and then excise the tumor model as shown in Figure 32. The operation was performed jointly by two surgeons on the tongue with the tumor cast from Dragon Skin 10 silicone material and the tumor cast from XTX 45 DRY silicone material (dyed).



Figure 32. Operation simulation - incision

The doctors who performed a simulated operation confirmed that the faults are not a problem if they are not in the desired location, in this case within the tumor and its margin.

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The color of the silicone models turned out to be a very important factor during the planning and during the simulated operation. The transparency of the tongue model together with its colored tumor allowed a better view of the tumor visibility and its correct excision. These types of models were assessed as very good in terms of didactic value, intended for students and less experienced doctors. However, the simulated operation on the transparent model is not very realistic. The operation carried out on the colored model was closer to the actual operation, it reflects the difficulty of the operation. In this case, the tumor was excised with too small a margin and part of it remained in the tongue. The hard, 3D printed models that are shown in Figure 33 were evaluated clinically, at the operating room, during actual surgery of the patient. The evaluation result was positive and the models greatly helped with patient treatment.



Figure 33. The tongue model together with its colored tumor after the simulated surgery

3.5 Dissemination results

The tongue model is first and foremost a topic of doctoral thesis of one of PUT's lecturers (Magdalena Żukowska). It is also a topic of cooperation between PUT and local hospital. The doctoral thesis is not yet finished as of closing this report, but it will be defended in 2023. The case study was also pursued as a student diploma (Master's) project in the year 2021, which has become a basis for O2 toolkit and also this report. The case was also used in numerous student projects realized during classes (exercise and project) at the PUT

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university and in cooperation with other higher educational institutions, like Technical University of Cluj-Napoca (TUCN) and University of Nis (UNI)

The case is very positively recognized by the doctors and future projects are going to be pursued regarding it. Educational materials made on its basis are very helpful to the students at all BRIGHT partner universities. It also helped integrating between PUT, TUCN and UNI in the process of printing, CAE simulation and testing.

On the basis of the case, several conferences and student event presentations were realized, many of them being published in important scientific journals with ISI impact factor, as it has been presented in the final dissemination report of the BRIGHT project. There is till also work in progress related to this particular case study that has been presented in this report, two articles being prepared to be submitted for the Springer book to be published in 2023.

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4 Conclusions

The presented case study pertains to an anatomical model that can be used during advanced surgical procedures. It was designed and prepared on the basis of medical cooperation, by representatives of Poznan University of Technology. The model was used in educational activities in BRIGHT project, first and foremost as a case study in the BRIGHT e-learning webinars. Of all case studies, this one requires the highest skill to realize and the manufacturing process is the most complex. This is also a unique case among the others, as the only one representing human internal tissues, examined by medical imaging (MRI).

For increased educational effect, all the stages were realized in product development, starting from design for specific patient, through CAE simulation, manufacturing (with use of many technologies), finalized with clinical evaluation. Positive feedback was obtained from the medical environment. The case was also used to integrate partners from PUT, TUCN, UNI and all others, during the O4 (webinar) and O2 (toolkit) activities.

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