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Contribution of 3D printing technology for craniofacial surgery

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Abstract: This article summarizes technical aspects of preparing printable 3D anatomical models created from radiological data (CT, MRI) and discusses their usefulness in surgery of the human skull. Interdisciplinary approach to the capabilities of the 3D printers, and the materials used for manufacturing 3D objects oriented on replicating anatomical structures has created new possibilities for simulating and planning surgical procedures in clinical practice settings.

Keywords: 3D printing, mesh model, craniofacial surgery, computed tomography.

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Introduction

In medical applications, 3D anatomical models are usually created on the bases of the data obtained from CT or MRI. These radiological technologies play an important role in imaging of the internal anatomy of the human organs. The virtual 3D reconstructions and materialized 3D models have a much better influence on the perception of the observer than plain, two-dimensional images. They facilitate to orientate how the anatomical structures are embedded in the 3D space [1, 2]. This is particularly helpful for planning surgical operations and visualizing their final outcomes.

In recent years, data obtained from the radiological imaging have been frequently used for building 3D mesh models which were materialized as a physical models by additive manufacturing processes usually executed by the 3D printing technology. 3D printing models can be obtained by distinct technologies classified as: additive, subtractive or formative [3, 4].

Coincidence of virtual modeling, 3D printing technology and development of polymer engineering including biomaterials, has opened new perspectives in plastic and reconstructive surgery. Numerous studies demonstrated applications of 3D printing in medical disciplines mostly related to surgeries such as: plastic surgery, craniofacial surgery, orthopedic surgery, neurosurgery, vascular surgery, thoracic and abdominal surgery, and others e.g.: otolaryngology, urology [5–10].

Technical remarks on preparation 3D printable virtual models

Production of anatomical models for medical purpose starts with acquiring data from the medical imaging devices. In the beginning, CT cross-sectional images are viewed to find the region of interest, or all of the CT scans are chosen to be included in the model. At this stage, the anatomical structures can be reconstructed in the three-dimensional manner and visualized by volume or surface rendering techniques which display a 2D projection of the beforehand 3D sampled data set. Next, anatomical structures which have been chosen to be printed have to be delineated from the entire volume data by segmentation of the defined region of interest. Usually, image segmentation is performed through automatic or manual processes; however, in such cases as 3D models for surgical preparations, this may be a tedious and time consuming task.

Detailed descriptions of methods and software used for image segmentation were presented by Pham *et al.*, Sharma and Aggarwal, Withey and Koles [11–13]. Choosing the appropriate segmentation method is a crucial step in creating accurate anatomical models. Originally, virtual mesh models being the backbone for building their derivatives, the actual physical models manufactured by the 3D printers.

Anatomical regions delineated from the acquired image data are proceeded by the computer software in order to obtain binary data which serves to build the virtual 3D model of the segmented anatomical structure. This is attained by using a method of thresholds of image segmentation.

A grayscale image threshold method selects the appropriate gray values which are representative of the defined anatomical structure, and creates a binary image by replacing each gray pixel in the image with a black or white pixel depending on the defined criteria for the thresholding method [14, 15]. The next step in creating computer models, is an image-based meshing procedure which transforms segmented data into 3D mesh models which are usually stored in a stereolithographic file; therefore, the model is also termed a stereolithographic model.

Technical limitations in creating high quality medical models manufactured using rapid prototyping described Winder and Bibb. They concluded that quality of medical models depends chiefly on the imaging parameters and image processing than the method of manufacture [16].

An example of the mesh model imitating the plate of the parietal bone is shown in Fig. 1. At this step of preparing the virtual model for further reproduction, it is advisable to decimate the mesh (reduce number of triangles which create the mesh) using filtering tools implemented in the computer software dedicated for mesh processing. Mesh decimation significantly reduces the file size which stores the 3D model. The file size also depends on the resolution of the data used for creating the mesh model. For example, file size of the mesh model for the temporal bone created from micro-CT data may exceed even 1GB, whereas file size of the same model created from the medical CT data is much smaller (in the range of hundreds kilobytes). This results from spatial resolution of applied imaging modalities. Micro-CT scanners have ability to capture anatomical details with voxel size even of 1 micron, whereas most of the CT scanners used in clinical practice attain resolutions under 1 mm, usually no more than 0.25–0.5 mm per voxel.

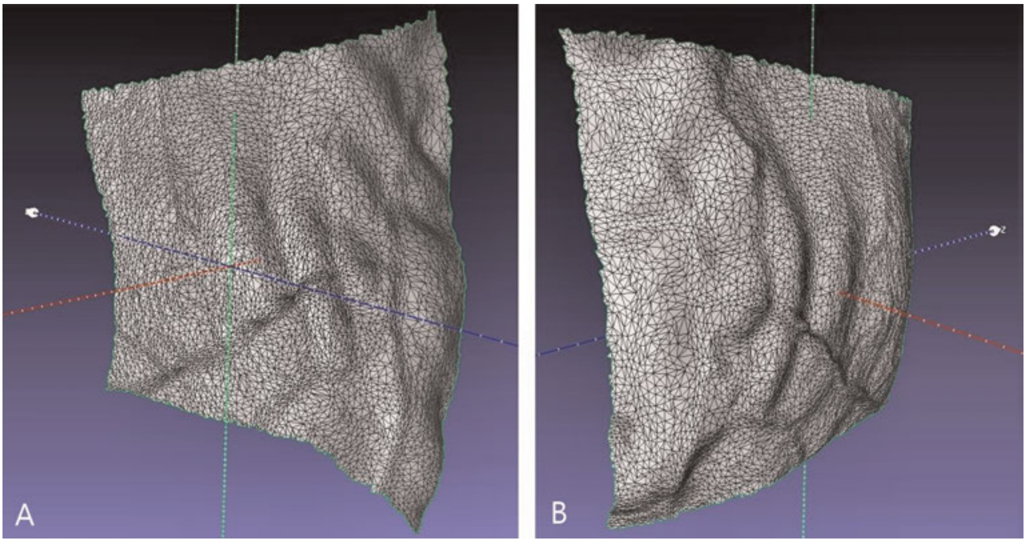

Fig. 1. An example of the 3D mesh model (A — positive, B — negative) of the endocranial surface (parietal bone) recreated from CT scans of the human skull. Concave grooves reflect the course of the dura matter vessels (A); convex folds correspond to the arrangement of the cerebral gyri (B).

Created 3D mesh model often needs refinement (elimination of the errors from the mesh which approximate geometry of the modeled object) before it becomes a printable 3D solid model. This is performed by using computer software designed for inspection of the mesh quality. The essential steps include: eliminating holes in the mesh, removing non manifold edges, re-meshing to obtain unique triangles in the mesh, and mesh simplification if the number of triangles is excessive (Fig. 2). Mesh

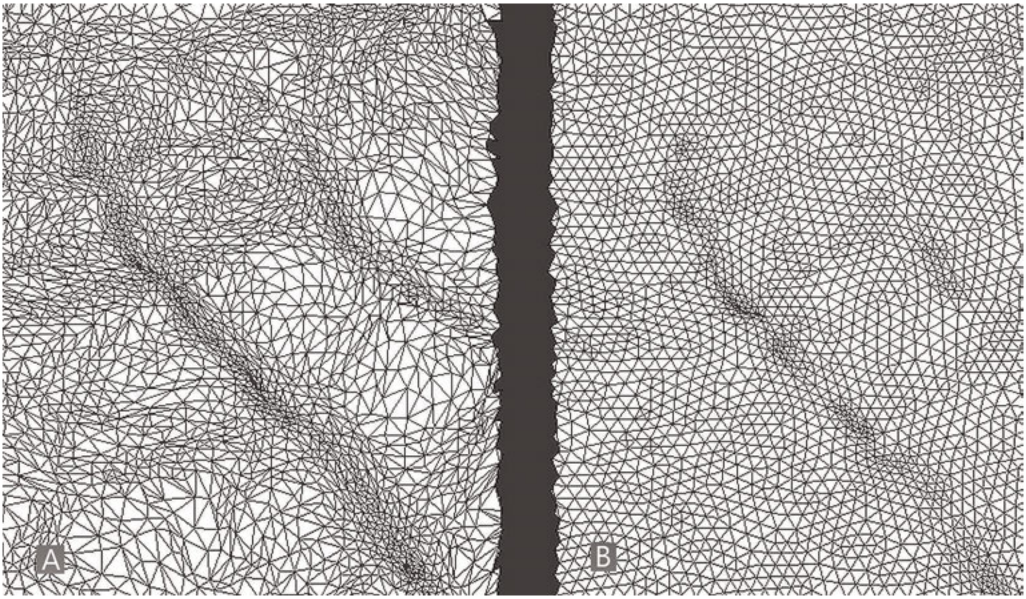

Fig. 2. Effect of remeshing improved mesh triangulation; regular connectivity between the triangles. A — input mesh of uneven triangles, B — resultant mesh of equilateral triangles.

smoothing is recommended for better visual perception of the virtual model designed for rapid prototyping (3D printing), whereas mesh simplification reduces the size of the 3D model stored in the computer file (usually stl or obj format).

Role of the 3D printing models in craniofacial reconstructions

Preoperative planning based on stereolithographic models created from CT and MR image data has been used in the craniofacial surgery for almost 30 years [17, 18]. These models gave opportunity for surgeons to analyze the external and internal anatomy in the three-dimensional aspect prior to surgery [19]. Since that time, computer-generated three-dimensional models and their materialized replicas have become helpful tool in the planning of surgical reconstructions of craniofacial malformations, and preparing implants and prosthesis [20, 21]. Development of 3D printing technologies has facilitated solving problems of accurate fitting of prosthesis to patient's demands. Customized prosthetics or implants constructed with a 3D printer fit perfectly in the deteriorated places of the skull [22]. In craniofacial surgery, CT-guided stereolithography provided acrylic models which replicated exactly the original structures, thus allowing for optimal preoperative planning and adaptation of a reconstructive plates [6, 23, 24].

Numerous examples of successfully created cranial prosthesis using 3D printing technology comes from people who suffered from cancerous bone deterioration or head trauma, and their skulls required bone replacement. In the year 2013 year surgeons have managed to replace 75% of a man's skull with a custom-designed polymer cranium [25]. Creation of computer-generated 3D models of the cranial bones followed by their 3D printing opened new perspective in the field of reconstructive craniofacial surgery. With the aid of rapid prototyping technologies and the use of biomaterials, the ability to supplement individualized cranial bones for patients is possible through quick manufacturing with high precision. Hence, the 3D printed models can mimic to some degree natural anatomical features of the human skull, particularly if their replicas are made of biomaterials which are capable of preserving protective role just like the natural cranial bones. According to Sunderland *et al.* application of patient-specific alloplastic implants in cranioplasty, decreases operative time, minimizes risk of contamination, and improves morphological results [26].

The 3D printed models provide spatial visual information about anatomical structures, moreover, they are tactile object which can be manipulated with hands (e.g.: cut, trim, and drill), contrasting to the volumetric reconstructions which can be only displayed on the computer screen as rotated or translocated objects observed in the virtual space. Both surgeons and patients stated that printed 3D models improved understanding of the cranio-surgical procedures, particularly in complex operations (e.g.: resection of cranial tumours and skull reconstruction) when templates and implants are necessary to replace resected bone. In this case, printed templates can serve for comparison to obtain the desired shape of the implant, as well as to check if it matches with the resection line [27–30].

Computer-aided surgery in conjunction with rapid prototyping technology gained a significant advantage because any defect of the skull can be quickly compared to the 3D printed model as well as used for accurate reposition of the malformed part of the head. Combination of these techniques enhances attaining better esthetic effects after craniofacial reconstruction and reduces the risk of a secondary operations because an inaccuracy in the 3D implant shape can be corrected before surgery [31].

The 3D reconstructions based on CT scans of the head give the possibility to build virtual 3D models of the patient's skull, and expose their individual anatomy which can be materialized by 3D printers. In surgical applications printed models obtained from CT or MRI have to represent anatomy at a scale of 1:1 and precisely reproduce anatomical details. Contemporary 3D printers are capable of reproducing accurately complex shapes which makes the entire model anatomically realistic, as well as reflects the patient's specific morphological features with high accuracy [32]. This view supports measurements performed between anatomical landmarks demarcated on the original dry skulls and their printed replicas. Choi *et al.* estimated that the mean deviation between 16 linear measurements was 0.62 ± 0.35 mm (0.56 ± 0.39%)

[33]. The measurements of the skull performed by Barker *et al.* yielded differences ranging maximum +4.62 mm, minimum +0.1 mm, mean +0.85 mm, representing an accuracy of 97.7–99.12% [34]. In turn, Chang *et al.* found that mean differences in dimensions between the reproduced 3D models and skull specimens varied from 1.2–1.9 mm, depending on the cranial region [35]. Nizan *et al.*, compared four human adult skulls with their replicated models which revealed 0.08% of difference with a standard deviation of 1.25% considering eight linear measurements (vertical, medio-lateral and antero-posterior) [36].

Thereby, relatively low errors established between reproduced and original skulls permit application of the 3D printed replicas in medical applications.

Perspectives of 3D printing technology

The 3D printing technology has offered access to printable biomaterials utilize to fabricate scaffolds for tissue engineering [37–39]. Researches in biomaterials are promising for future development and progress in distraction osteogenesis. Their application can reduce treatment time, enhance quality of bone formation and consolidation in bone defect [40, 41].

Constantly increasing number of publications reporting application of 3D printing technologies in medicine indicates that 3D printing technology gained quick success.

Ballard *et al.* retrieved the PubMed database (maintained by US National Library of Medicine National Institutes of Health) using the term "3D printing" and found only six publications in the year 2000 [42]. Ten years later there were 61 publications, but in 2016 more than 1100 publications have been recorded. In 2019, I personally found 5614 publications in the PubMed including the term "3D printing". In turn, Chepelev *et al.* analyzed popularity of referencing to the following terms: "3D printing", "rapid prototyping", "additive manufacturing" in the period from 2012 to 2015. They found that since the year 2014, the term "3D printing" surpassed "rapid prototyping" and accounted for 64% of all papers in the domain, whereas "rapid prototyping" and "additive manufacturing" accounting for 29% and 11%, respectively [43].

A systematic review on the applications of 3D printing in plastic and reconstructive surgery has been performed by Bauermeister *et al.* [44]. They retrieved three popular medical databases: PubMed, Ovid Medline, and Google Scholar including university websites, and found 1092 articles discussing applications of 3D printing in medicine, whereas surgical applications were identified in 226 articles. Many researchers remain in accordance with the view that 3D printing technology has considerably promoted fabrication of accurate anatomical models used for surgical purposes (e.g. reconstruction of the orbital injures and defects or other craniomaxillofacial post-traumatic deformities) but also started to support tissue engineering and regenerative medicine [45, 46].

Thereby, the 3D printing technology became a standard procedure in the medical applications like craniofacial surgery and other surgical disciplines utilizing biomaterial for reconstructive therapy, and anatomical printed models for stereotactic navigation.

Conclusions

Retrieval of different internet databases like PubMed, Ovid Medline, Google Scholar delivers evidences that applications of 3D printing technology in medical sciences is still in the scope of interests of many researchers. Interdisciplinary approach to the capabilities of the 3D printers and materials used for manufacturing 3D objects oriented on replicating anatomical structures caused a considerable revolution in clinical practice, and gave new possibilities for simulating and planning surgical procedures.

Conflict of interest

No conflict of interest nor any financial interest.

References

1. *Ameil M., Delattre J.F., Cordobes B., Flament J.B.*: Computerized reconstruction of an anatomical structure based on digitized sections. Anat Clin. 1984; 5 (4): 261–264. doi: 10.1007/BF01798749.
2. *Vannier M.W., Marsh J.L., Warren J.O.*: Three dimensional CT reconstruction images for craniofacial surgical planning and evaluation. Radiology. 1984; 150 (1): 179–184. doi: 10.1148/radiology.150.1.6689758.
3. *Groth C., Kravitz N.D., Jones P.E, Graham J.W., Redmond W.R.*: Three-dimensional printing technology. J Clin Orthod. 2014; 48 (8): 475–485. PMID: 25226040.
4. *Onuh S.O., Yusuf Y.Y.*: Rapid prototyping technology: applications and benefits for rapid product development. J Intell Manuf. 1999; 10 (3–4): 301–311. doi.org/10.1023/A:1008956126775.
5. *Anderson J.R., Thompson W.L., Alkattan A.K, Diaz O., Klucznik R., Zhang Y.J., Britz G.W., Grossman R.G., Karmonik C.*: Three-dimensional printing of anatomically accurate, patient specific intracranial aneurysm models. J Neurointerv Surg. 2016; 8: 517–520. doi:10.1136/neurintsurg-2015-011686.
6. *Anderl H., Zur Nedden D., Mühlbauer W., Twerdy K., Zanon E., Wicke K., Knapp R.*: CT-guided stereolithography as a new tool in craniofacial surgery. Br J Plastic Surg. 1994; 47 (1): 60–64. doi:10.1016/0007-1226(94)90121-x.
7. *Eltorai A.E., Nguyen E., Daniels A.H.*: Three-dimensional printing in orthopedic surgery. Orthopedics. 2015; 38 (11): 684–687. doi:10.3928/01477447-20151016-05.
8. *Hoch E., Tovar G.E., Borchers K.*: Bioprinting of artificial blood vessels: current approaches towards a demanding goal. Eur J Cardiothorac Surg. 2014; 46 (5): 767–778. doi:10.1093/ejcts/ezu242.

9. *Kamali P., Dean D., Skoracki R., Koolen P.G., Paul M.A., Ibrahim A.M., Lin S.J.*: The current role of three-dimensional printing in plastic surgery. Plast Reconstr Surg. 2016; 137 (3): 1045–1055. doi: 10.1097/01.prs.0000479977.37428.8e.
10. *VanKoevering K.K., Hollister S.J., Green G.E.*: Advances in 3-dimensional printing in otolaryngology: a review. JAMA Otolaryngol Head Neck Surg. 2017; 143 (2): 178–183. doi:10.1001/jamaoto.2016.3002.
11. *Pham D.L., Xu C., Prince J.L.*: Current methods in medical image segmentation. Annu Rev Biomed Eng. 2000; 2 (1): 315–337. doi:10.1146/annurev.bioeng.2.1.315.
12. *Sharma N., Aggarwal L.M.*: Automated medical image segmentation techniques. J Med Phys. 2010; 35 (1): 3–14. doi: 10.4103/0971-6203.58777.
13. *Withey D.J., Koles Z.J.*: A review of medical image segmentation: methods and available software. Int J Bioelectromagn. 2008; 10 (3): 125–148.
14. *Pal N.R., Pal S.K.*: A review on image segmentation techniques. Patt Rec. 1993; 26 (9): 1277–1294. doi.org/10.1016/0031-3203(93)90135-J.
15. *Sahoo P.K., Soltani S.A. Wong A.K.C.*: A survey of thresholding techniques. Comput Vis Graph Im Proc. 1988; 41 (2): 233–260. doi.org/10.1016/0734-189X(88)90022-9.
16. *Winder J., Bibb R.*: Medical rapid prototyping technologies: state of the art and current limitations for application in oral and maxillofacial surgery. J Oral Maxillofac Surg. 2005; 63 (7): 1006–1015. doi:10.1016/j.joms.2005.03.016.
17. *Fleiter T., Hoffmann R., Niemeier R., Claussen C.D.*: Preoperative planning and follow-up with spiral CT and stereolithographic models in craniofacial surgery. In Advances in CT III. Springer, Berlin, Heidelberg 1994; 149–156.
18. *Mankovich N.J., Cheeseman A.M., Stoker N.G.*: The display of three-dimensional anatomy with stereolithographic models. J Digit Imaging. 1990; 3 (3): 200–203. doi: 10.1007/BF03167610.
19. *Stoker G.N., Mankovich N.J., Valentino D.*: Stereolithographic models for surgical planning: preliminary report. J Oral Maxillofac Surg. 1992; 50: 466–471. doi: 10.1016/s0278-2391(10)80317-9.
20. *Eppley B.L., Sadove A.M.*: Computer-generated patient models for reconstruction of cranial and facial deformities. J Craniofac Surg. 1998; 9 (6): 548–556. doi: 10.1097/00001665-199811000-00011.
21. *Müller A., Krishnan K.G., Uhl E., Mast G.*: The application of rapid prototyping techniques in cranial reconstruction and preoperative planning in neurosurgery. J Craniofac Surg. 2003; 14 (6): 899–914. doi: 10.1097/00001665-200311000-00014.
22. *Singare S., Yaxiong L., Dichen L., Bingheng L., Sanhu H., Gang L.*: Fabrication of customised maxillo-facial prosthesis using computer-aided design and rapid prototyping techniques. Rapid Prototyp J. 2006; 12 (4): 206–213. doi: 10.1108/13552540610682714.
23. *Kermer C., Lindner A., Friede I., Wagner A., Millesi W.*: Preoperative stereolithographic model planning for primary reconstruction in craniomaxillofacial trauma surgery. J Craniomaxillofac Surg. 1998; 26 (3): 136–139. doi: 10.1016/s1010-5182(98)80002-4.

24. *Kernan B.T., Wimsatt J.A.*: Use of a stereolithography model for accurate, preoperative adaptation of a reconstruction plate. J Oral Maxillofac Surg. 2000; 58 (3): 349–351. doi:10.1016/s0278-2391(00)90071-5.
25. *Ehrenberg R.*: Plastic implant replaces three-quarters of man's skull. Science News. March 11, 2013.
26. *Sunderland I.R., Edwards G., Mainprize J., Antonyshyn O.*: A technique for intraoperative creation of patient-specific titanium mesh implants. Plast Surg (Oakv). 2015; 23 (2): 95–99. doi: 10.4172/plastic-surgery.1000909.
27. *Bell R.B., Markiewicz M.R.*: Computer-assisted planning, stereolithographic modeling, and intraoperative navigation for complex orbital reconstruction: a descriptive study in a preliminary cohort. J Oral Maxillofac Surg. 2009; 67 (12): 2559–2570. doi: 10.1016/j.joms.2009.07.098.
28. *D'Urso P.S., Atkinson R.L., Lanigan M.W., Earwaker W.J., Bruce I.J., Holmes A., Barker T.M., Effeney D.J., Thompson R.G.*: Stereolithographic (SL) biomodelling in craniofacial surgery. Br J Plast Surg. 1998; 51 (7): 522–530. doi: 10.1054/bjps.1998.0026.
29. *D'Urso P.S., Redmond M.J.*: A method for the resection of cranial tumours and skull reconstruction. Br J Neurosurg. 2000; 14 (6): 555–559. doi:10.1080/02688690020005581.
30. *Erickson D.M., Chance D., Schmitt S., Mathis J.*: An opinion survey of reported benefits from the use of stereolithographic models. J Oral Maxillofac Surg. 1999; 57 (9): 1040–1043.
31. *Cui J., Chen L., Guan X., Ye L., Wang H., Liu L.*: Surgical planning, three-dimensional model surgery and preshaped implants in treatment of bilateral craniomaxillofacial post-traumatic deformities. J Oral Maxillofac Surg. 2014; 72 (6): 1138-e1-14. doi: 10.1016/j.joms.2014.02.023.
32. *Frühwald J., Schicho K.A., Figl M., Benesch T., Watzinger F., Kainberger F.*: Accuracy of craniofacial measurements: computed tomography and three-dimensional computed tomography compared with stereolithographic models. J Craniofac Surg. 2008; 19 (1): 22–26. doi: 10.1097/scs.0b013e318052ff1a.
33. *Choi J.Y., Choi J.H., Kim N.K., Kim Y., Lee J.K., Kim M.K., Lee J.H., Kim M.J.*: Analysis of errors in medical rapid prototyping models. Int J Oral Maxillofac Surg. 2002; 31.(1): 23–32. doi: 10.1054/ijom.2000.0135.
34. *Barker T.M., Earwaker W.J., Lisle D.A.*: Accuracy of stereolithographic models of human anatomy. Australas Radiol. 1994; 38 (2): 106–111. doi: 10.1111/j.1440--1673.1994.tb00146.x.
35. *Chang P.S., Parker T.H., Patrick C.W., Miller M.J.*: The accuracy of stereolithography in planning craniofacial bone replacement. J Craniofac Surg. 2003; 14 (2): 164–170. doi: 10.1097/00001665-200303000-00006.
36. *Nizam A., Gopal R., Naing N.L., Hakim A.B., Samsudin A.R.*: Dimensional accuracy of the skull models produced by rapid prototyping technology using stereolithography apparatus. Arch Orofac Sci. 2006; 1: 60–66.

37. *Chia H.N., Wu B.M.*: Recent advances in 3D printing of biomaterials. J Biol Eng. 2015; 9 (1): 4. doi: 10.1186/s13036-015-0001-4.
38. *Hsieh T.Y., Dedhia R., Cervenka B., Tollefson T.T.*: 3D Printing: current use in facial plastic and reconstructive surgery. Curr Opin Otolaryngol Head Neck Surg. 2017; 25 (4): 291–299. doi: 10.1097/MOO.0000000000000373.
39. *Jakus A.E., Rutz A.L., Shah R.N.*: Advancing the field of 3D biomaterial printing. Biomed Mater. 2016; 11 (1): 014102. doi: 10.1088/1748-6041/11/1/014102.
40. *Poukens J., Haex J., Riediger D.*: The use of rapid prototyping in the preoperative planning of distraction osteogenesis of the cranio-maxillofacial skeleton. Comput Aided Surg. 2003; 8 (3): 146–154. doi: 10.3109/10929080309146049.
41. *Wang Y., Ni M., Tang P.F., Li G.*: Novel application of HA-TCP biomaterials in distraction osteogenesis shortened the lengthening time and promoted bone consolidation. J Orthop Res. 2009; 27 (4): 477–482. doi:10.1002/jor.20782.
42. *Ballard D.H., Trace A.P., Ali S., Hodgdon T., Zygmont M.E., DeBenedectis C.M., Smith S.E., Richardson M.L., Patel M.J., Decker S.J., Lenchik L.*: Clinical Applications of 3D Printing: Primer for Radiologists. Acad Radiol. 2018; 25 (1): 52–65. doi: 10.1016/j.acra.2017.08.004.
43. *Chepelev L., Giannopoulos A., Tang A., Mitsouras D., Rybicki F.J.*: Medical 3D printing: methods to standardize terminology and report trends. 3D Print Med. 2017; 3 (1): 4. doi: 10.1186/s41205-017-0012-5.
44. *Bauermeister A.J., Zuriarrain A., Newman M.I.*: Three-dimensional printing in plastic and reconstructive surgery: a systematic review. Ann Plast Surg. 2016; 77 (5): 569–576. doi: 10.1097/SAP.0000000000000671.
45. *Pham D.L., Xu C., Prince J.L.*: Current methods in medical image segmentation. Annu Rev Biomed Eng. 2000; 2 (1): 315–337. doi: 10.1146/annurev.bioeng.2.1.315.
46. *Waran V., Devaraj P., Hari Chandran T., Muthusamy K.A., Rathinam A.K., Balakrishnan Y.K., Tung T.S., Raman R., Rahman Z.A.*: Three-dimensional anatomical accuracy of cranial models created by rapid prototyping techniques validated using a neuronavigation station. J Clin Neurosci. 2012; 19 (4): 574–577. doi: 10.1016/j.jocn.2011.07.031.