Use of 3D printing in head and neck surgery

Zastosowanie druku 3D w chirurgii głowy i szyi

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*Zatrudnienie w momencie wysłania pracy do druku

ABSTRACT

Currently, 3D printing in medicine does not comprise only prostheses or implants, but also medical modelling and surgical planning. The future of 3D printing is printing combined with tissue bioengineering (bioprinting). Scaffolds made in 3D technology containing living cells are a step to creating tissues and organs. Three-dimensional printing in surgery is now considered the future of reconstructive and regenerative medicine. Head and neck surgery also benefits from advances in 3D printing. In this article, we will describe some of the possibilities offered by 3D printing in the aspect of education, training, and printed prostheses for the needs of head and neck surgery.

KEY WORDS

3D printing, otolaryngology, head and neck, surgery, education, reconstruction

STRESZCZENIE

Obecnie druk 3D w medycynie oznacza nie tylko protezy czy implanty, ale także modelowanie medyczne i planowanie chirurgiczne. Przyszłością będzie druk 3D połączony z bioinżynierią tkankową (bioprinting). Ruszowania wykonane w technologii 3D zawierające żywe komórki są krokiem do tworzenia tkanek i narządów. Druk trójwymiarowy w chirurgii uważany jest obecnie za przyszłość medycyny rekonstrukcyjnej i regeneracyjnej, a z dookoła na tym polu korzysta także chirurgia głowy i szyi. W prezentowanym artykule opisujemy niektóre możliwości, jakie daje druk 3D w aspekcie edukacji, szkoleń oraz drukowanych protez na potrzeby chirurgii głowy i szyi.

SŁOWA KLUCZOWE

druk 3D, otolaryngologia, głowa i szyja, chirurgia, edukacja, rekonstrukcje
The technology of 3D printing like, called additive manufacturing or rapid prototyping, already has a long and interesting history. The first reports on 3D printing technology come from the work of Hideo Kodama from the Nagoya Municipal Industrial Research Institute in 1981 [1,2], who developed the basics of the 3D printing process. In 1986, Charles Hull patented the stereolithographic 3D printing process and introduced 3D printers to the commercial market [3]. Since then, an expansion of 3D printing can be observed in many branches of the economy. Currently, medicine is considered the largest beneficent of 3D printing.

Various materials are used in 3D printing like, among others, titanium, plastic, natural and synthetic polymers such as PLA (polylactide), ABS (acrylonitrile butadiene styrene), photopolymers [4] and bioink. The actual 3D printing process can vary, depending on the properties of the starting material used for printing. The first patented method was stereolithography [2]. The principle of its operation is curing 2D layers of resin material with ultraviolet light. An advantage of this method is the possibility of receiving very precise shapes, while the price of photopolymers is its disadvantage [4]. FDM (fused deposition modelling) technology uses thermoplastic in filament form as the starting material, which melts when it passes through the nozzle and in liquid form it is applied on the table surface. In FDM technology, the "building" of a three-dimensional object consists in applying subsequent layers of thermoplastic. Nonetheless, before the next layer is applied, the previous one needs to solidify (cool). SLS/SLM (selective laser sintering/selective laser melting) is a 3D printing technology based on sintering metallic powders with a laser. In this technology, powder grains are applied to the worktable surface with a roller. Next, a laser gun generates an energy beam, which sinters spherical powder grains selectively or melts them locally. When using SLM technology, one can create objects of a much higher density than when using SLS technology. The advantage of this method is that it does not require any additional elements to stabilize the structure. The support material is unsintered powder, which can be reused in the process. The printing process itself is systematically improved and presently various types of printers can be distinguished on the market. According to the printing system, there are printers based on the following technologies: SLS/SLM, FDM, 3DP, stereolithography, or biplotter [2,4]. The materials used in 3D printing such as plastics (polycarbonate, polyamide, polylactide), waxes, metals (titanium) or photopolymers, are presently defined as standard materials.

Another type of printing is inkjet printing, in which the printer head deposits small droplets of raw material layer upon layer, creating a 3D object. These droplets can be obtained by various techniques such as piezoelectric, thermal, or electromagnetic methods [4]. The models are made relatively fast and at a low cost, but they are not as durable as those made with SLS technology. Due to the possibility of receiving very precise shapes, while the price of photopolymers is its disadvantage [4].
to the very high quality of printing this method provides the possibility of using living cells as "ink material" and this technique is applied in "bioprinting", which is used in regenerative medicine in attempts to produce tissues and even organs. Printers using materials such as bioink or tissue spheres are new in this area. Bioink is a water-based liquid [5], consisting of proteins such as collagen, gelatine, algatines, chitosan [6], enzymes [7] and cells suspended in a nutrient or saline solution [8]. The bioinks available on the market have different properties, depending on their composition: osteoinductive, angiogenic, chondrogenic, imitating natural ECM. After printing, the cells are supported by a neutral gel and the geometry of the printing is maintained as the cell model matures [9]. With a high precision, the printer puts subsequent cell layers, placed singularly or as aggregates on a gel substrate. Then, during cell differentiation into tissues, the biodegradable hydrogel diminishes [10]. Bioprinting has an advantage in producing scaffolds used in tissue engineering due to its fast production and a high precision of printing [11]. However, 3D bioprinting processes are limited to scaffolds supporting cells and simple body parts such as bones. Currently, the majority of the inks for 3D bioprinting is limited to collagen, gelatin, fibrin, ceramics, thermoplastics, or light-cured composites [11]. Nonetheless, this method is still at the stage of intensive research because it encountered significant difficulties in proper vascularization of the tissues made of those materials. Currently, 3D bioprinting is used in prostheses and bone implants as they can be adjusted to the exact shape of the patient's body defect. Scientists are also working on using bioprinting for printing veins and arteries. The ultimate goal in tissue engineering and regenerative medicine is the direct production of organs by means of 3D bioprinting technology, i.e. printing a complete organ which can be directly transplanted into the human body [12,13,14,15,16,17]. Currently, intensive research is underway, among others in bioprinting neoplastic tumours. Thanks to this, it will be possible to model, to some extent, the natural structure of the tumour and treat it with, e.g. chemotherapeutic agents [18].

How can a model be printed for medical purposes? The data for model printing are obtained from CT scans, MRI, ultrasound, or a non-contact scanner [4]. Digital printing technology requires a representation of the geometric data obtained from these tests in STL or other formats [19]. They are used to make 3D objects from computer-aided designs (CAD). The development of polymer technology and, above all, the continuous improvement of 3D printing methods enables the development of materials printed in sterile conditions, which is important in the case of surgical procedures. Before the output data is converted into the STL format, i.e. the format that allows printing of a virtual object, they are subjected to computer processing using CAD software, for example Materialise Mimics or 3D doctor. A CT scanner allows the mapping of a three-dimensional...
nal model of the human body. Nevertheless, in order to obtain an image directly from the scanner that could be printed in 3D technology, it should be first converted into a format understood by a 3D printer. A universal extension used in 3D printing is STL. The process of obtaining such a ready-to-print file involves several stages:

1. The first step is to extract the tissue of interest from the CT image. It can be bone tissue, but also skin, blood vessels, or adipose tissue. Each tissue has a different density and most software for opening DICOM files present them in the form of graphic cross-sections. Therefore, the result of isolating a specific tissue is a two-dimensional bitmap, consisting of thousands – hundreds of thousands of cross-sections. These cross-sections, when put one on top of the other, create a 3D image.

2. The second stage is to create the so-called "model outlines." Using the bitmap, the software outlines and closes the outer edges of each cross-section, thus creating the contour and interior for a given layer.

3. The third stage consists in putting the subsequent layers onto each other to create the "outer shell" of the model and to build its internal structures.

4. Once the model has been assembled into a whole, the obtained "shell" shall be converted by placing a mesh of triangles on its outer surfaces. The more triangles, the more precise our 3D model will be. The finished mesh can then be saved in a format understandable to printers, i.e. STL.

5. Before starting the printing process, it must be ensured that the obtained model is a closed figure. There is special verification software used for that purpose. An algorithm examines the model and checks whether there any unclosed surfaces. Eventual defects are automatically fixed. At this stage, the density of the mesh of triangles obtained in the previous stage can also be optimized. Too high a density of the mesh may result in an artificially high weight (calculated in Mb) of the 3D model. Too low a density of the mesh will, in turn, result in poor quality of the print surface and an inaccurate reproduction of the model compared to the CT scan (Fig. 1).

3D printing combined with tissue bioengineering is the future. Printing scaffolds containing living cells is the first step to creating tissues and organs. Three-dimensional printing is presently considered to be the future of reconstructive and regenerative medicine. In this paper, some of the possibilities that 3D printing provides in the aspects of education, training and prostheses for neck and head surgery purposes will be described.
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3D printing in education and training

Today, simulation using models is one of the main methods of teaching and improving manual skills [20, 21]. Pre-operative three-dimensional models are also used, among others, in thoracic surgery and orthopaedics. Orthopaedists use the models to plan surgical procedures for complicated fractures, while thoracic surgeons use them to plan how to best surgically access tumours in the thoracic cage.

In order for the training to fulfil its task, the 3D printed models must be of high quality and to the highest extent reflect not only the anatomy but also the mechanical properties of the simulated structure. Particularly noteworthy is the possibility of obtaining paediatric models and those of rare, untypical anatomical variants or pathologies [22]. Szkolenia chirurgów są ważne ze względu na fakt, iż po treningach skraca się czas zabiegu, a tym samym czas trwania znieczuleniu i kosztownego pobytu na sali operacyjnej [23]. Modele 3D mogą być też użytkowe w nauczaniu anatomicznych komplikowanych struktur około-ściennych i szymy, takich jak kość skroniowa czy zatoki oboczne nosa. Sander i wsp. stworzyli wielomateriałowy model zatok obocznych nosa, aby łatwiej i dokładniej wytłumaczyć pacjentom, na czym polega ich choroba i jakie mają opcje leczenia [24]. Wyniki ich pracy wykazały, że dokładne zrozumienie przez pacjenta planu leczenia, dzięki pokazowi na modelu 3D, poprawiło ostateczne wyniki leczenia [24].

Podczas planowania operacji chiurgicznych lekarz, próbując lokalizować zmianę, bazuje przede wszystkim na badaniach obrazowych i ewentualnych rekonstrukcjach, co w niektórych przypadkach nie jest wystarczające. Stworzenie modeli 3D w skali 1:1 lub większej pozwala na zaplanowanie przez chiurga dokładnych procedur w czasie operacji, zwłaszcza w zabiegach rekonstrukcyjnych, gdzie istotne jest odtworzenie pożądanych kształtów i symetrii. Pierwszy przeszczep twarzy w Polsce dokonany przez zespól chirurgów z Instytutu Onkologii w Gliwicach także był wspomagany modelami czaszki pochodzącymi z drukarek 3D. Modele te drukowano na bieżąco zarówno przed, jak i podczas operacji i służyły zespołowi chirurgów za
demonstration on the 3D model, improved the final results of the treatment [24].

When planning surgical operations, in order to locate the lesion, the physician relies primarily on imaging examinations and alternatively, reconstructions. In some cases, that may not be sufficient. Creating 3D models in a 1:1 or larger scale allows the surgeon to plan detailed procedures for surgery, especially in reconstructive procedures, where it is important to reproduce the desired shape or recreate the symmetry. The first face transplant in Poland, performed by a team of surgeons of the Institute of Oncology in Gliwice, was supported by skull models from a 3D printer as well. These models were printed continuously, before and during the surgery and served the surgeons as a model to recreate the desired skull geometry of the patient with an extensive frontal skull trauma [25]. Already in 2015, physicians of the Voivodeship Hospital for Children in Bydgoszcz were the first in Poland to perform a laryngological surgery demonstration on a head model from a 3D printer. Temporal bone models were used to improve the methods of inserting cochlear implants in children [26].

The internal structure of the temporal bone is extremely complex. For years attempts have been made to create a model that would allow laryngologists to receive high-quality training on procedures in the temporal bone area, such as labyrinthectomy. Currently, the "gold standard" is training on bones from corpses. Paediatric temporal bones and bones with rare anomalies are very difficult to access [22]. Attempts to train on animal bones were unsuccessful because they significantly differ from the anatomy of human bones. Similarly, synthetic temporal bones made of plastics, ceramics or resin did not meet expectations due to their poor anatomical realism and little similarity in the mechanical properties of the used materials in relation to those of bones from a corpse [22].

The first model of a temporal bone for microsurgery that used 3D printing was made by Vorwerk and Begall in 1998. Using CT scans of temporal bones, anatomical preparations and CT scans of patients, they were able to reconstruct 3D images with a CAD workstation. In order to reproduce the anatomical features of the temporal bone as accurately as possible, the prints were made using the stereolithographic technique [22].

Using 3D printing, Monfared et al. created a surgical middle ear simulator (SMS) from two different materials simulating bone tissue and soft tissues. The simulator consisted of a box with the dimensions of an adult person’s external auditory meatus and an internal inlay based on an otosclerosis model. The simulator was assessed by otologists from 6 academic centres. The SMS was judged to have exact dimensions by 83.3% of the respondents and 66.6% of them considered its tactile feedback to be precise. According to 78% of physicians, practicing stapedotomy with a simulator translates into improved surgery techniques. During such training, it is possible to see and "feel virtually" contact with a bone, but these simulators are not able to precisely recreate the pressure exerted on the bone, e.g. when drilling du-
ring surgery [27]. An enormous challenge for the printing was faithful reproduction of the internal structure and mechanical properties of a bone. Difficulties were caused by the artefacts arising after removing the structures supporting the model and creating empty spaces of air [27]. An important improvement was obtaining a cochlear lumen, which is essential for cochlear implantation training [28]. In practice, the model produced by the German Phacon company, was used. Data for its development were obtained by scanning normal human temporal bones using CT. The model was created employing a 3D printer using a powder and binding agent, adding colour, and removing cast powder from anatomically hollow structures. The tympanic membrane was replaced by a silicon sheet and the auditory ossicles were cast as one rigid structure. The facial nerve, sigmoid sinus and carotid artery were printed as empty channels, which were then filled with coloured wires [22]. De Cruz and Francis investigated the usefulness of temporal bones printed with the 3D technique from composite materials to serve as tools for preoperative training for residents. The residents performed such procedures as mastoidectomy, epitympanectomy, posterior tympanotomy and ossiculoplasty. After completing the training, the participants filled in a form consisting of questions answered on a five-point Likert scale, where a score of 3 meant at least acceptable and 5 at least an equivalent resemblance to real temporal bone. Everyone assessed the bone anatomical realism as comparable to corpse bones. In particular, the depth perception (4.7), anatomical precision (4.3) and tactile feedback (4.0) were assessed favourably. The assessment of drilling in a bone (3.7) and colour contrasts (3.2) were slightly worse. Model training itself was assessed as at least equal to training on corpses. Exercises on the lateral parts of the temporal bone model were assessed as especially useful; those on the medial parts were rated slightly worse. It was also noted that in comparison with using human bones from corpses, model training was useful not only for learning (score of 4.8) but it also facilitates the planning of surgical tasks (4.8), improves hand-eye coordination (4.8) and serves to improve surgery techniques (4.5). As a general training tool, the models were rated 4.7. Otolaryngologists training with the models found the synthetic temporal bones recommendable (4.8) and the acquired skills transferable to block operations (4.7), model training was considered worthy of including in the curriculum (4.8), however, the proposal to replace all training with 3D models was not so positively assessed (3.5) [22].

In the research of Hochman et al., based on an algorithm a model in the form of layers was first developed and then assembled into a three-dimensional model of a temporal bone, with removal of the content from places of air space. With such prepared models otolaryngologists trained, whose earlier experience gained during training on corpses was sufficient to evaluate the artifi-
cral temporal bones. A 7-point Likert scale was used for assessment, which covers the similarity of anatomical structure, usefulness for developing surgical skills, and educational value. The results showed that the physical properties of the 3D model are quite similar to those of bones, especially in the aspect of drilling in bones. The internal structure was satisfactory (range 4.9–6.2). The model was considered a beneficial training tool for all kinds of mastoidectomy (range 5.9–6.6), posterior tympanotomy (6.5 ± 0.71). Training with the models printed in the 3D technique improves confidence (6.7 ± 0.68) and surgical efficiency (6.7 ± 0.48) [29]. The research by Rose et al. also confirmed that temporal bone models printed in 3D have a potential benefit in terms of surgical training, preoperative simulation in difficult otolaryngologic cases and standardised testing of surgical skills for temporal bone surgery. A multicoloured, multi-material temporal bone model printed in the incremental technique was used for the tests [30].

The Phacon company improved temporal bone models, and Mick et al. demonstrated that the models are suitable for training residents in their 1–3 years of specialisation, although the tympanic membrane, auditory ossicular chain mobility, facial nerve and colour contrasts need to be improved [31].

A good way to learn ear surgery with access through the external auditory canal (transcanal endoscopic ear surgery – TEES) can be training with simulators printed thanks to 3D technology, which ensure high faithfulness of anatomical structures. According to Nagendran et al., research on the use of box laparoscopic simulators for surgeons shows improvement in technical skills, especially in trainees with little experience in endoscopic ear surgery [32]. In the described study, the external auditory meatus of the simulator was designed according to anthropometric measurements and reproduced an anatomically consistent middle ear entry. A composite material was used to create the simulator, and it was printed by an inkjet printer using dye. The test area – the middle ear space, was designed in the shape of a dome. The auditory canal can be connected with the middle ear at any angle, and the dome shape provides the possibility for any access. The dome floor corresponded to the surface of the medial wall of the tympanic cavity space and was flat with two small grooves that enabled easy replacement of module test platforms. The auditory canal entered the middle ear space at a 45° angle. On the front surface the dome was equipped with a movable door that enabled the exchange of module test platforms to switch the tasks of the simulator. The test was carried out using a 3D simulator, rigid endoscopes, and microsurgical equipment. The participants were surgeons, who were divided into two groups, depending on their level of experience. The simulator task was to move three rings from one peg to the other and back. To do that, forceps and an endoscope were used. The task consisted of three serial attempts with the dominant hand and three serial attempts with the non-dominant hand. After having completed the task, there were questions concerning the level of surgical properties in the case of all kinds of mastoidectomy (zakres 5.9–6.6) and tympanotomy (6.5 ± 0.71). Training on models drukowanych w technice 3D poprawia pewność (6.7 ± 0.68) i sprawność operacyjną (6.7 ± 0.48) [29]. Badania Rose i wsp. także potwierdziły ich potencjalną korzyść w zakresie szkolenia chirurgicznego, symulacji przedoperacyjnej w trudnych przypadkach laryngologicznych i standaryzowanego testowania umiejętności chirurgicznych dotyczących zabiegów wykonywanych na kości skroniowej. Do testów wykorzystali oni wielokolorowy, wielomateriałowy model kości skroniowej wydrukowany techniką przyrostową [30].

Firma Phacon udoskonaliła modele kości skroniowej, a Mick i wsp. wykazały, iż są one odpowiednie do szkolenia rezydentów na 1–3 roku specjalizacji, mimo że poprawy wymaga jednak blony bębenkowej i okrągła, ruchomość łańcucha kosteczek słuchowych, nerw twarzowy oraz kontrasty kolorów [31].

Dobrym sposobem do nauki chirurgii ucha z dostępu przez przewód słuchowy zewnętrzny (transcanal endoscopic ear surgery – TEES) mogą być ćwiczenia na symulatorach wydrukowanych dzięki technice 3D, zapewniających wysoką wierność struktur anatomicznych. Według Nagendran i wsp. w badaniach nad wykorzystaniem pudełkowych laparoskopowych simulatorów dla chirurgów stwierdzono poprawę umiejętności technicznych osób, zwłaszcza stażystów mających niewielkie doświadczenie w operacjach endoskopowych ucha [32]. W opisywanym badaniu przewód słuchowy zewnętrzny-simulator został zaprojektowany według pomiarów antropometrycznych i odwzorował anatomicznie zgodne wejście do ucha środkowego. Do stworzenia symulatora wykorzystano materiał kompozytowy, a wydruk wykonano na drukarce atramentowej z użyciem barwnika. Obszar testowy – przestrzeń ucha środkowego – został zaprojektowany w kształcie kupały. Przewód słuchowy może lączyć się z uchem środkowym pod dowolnym kątem, a kształt kupały zapewnia możliwość dowolnego dojścia. Podloga kupały odpowiadała powierzchni przyśrodkowej ściany jamy bębenkowej i była płaska z dwoma rowkami, które umożliwiały łatwą wymianę modułowych platform testowych. Przewód słuchowy wchodził do przestrzeni ucha środkowego pod kątem 45°. Kupała na przedniej powierzchni posiadała ruchome drzwiczki umożliwiające wymianę modułowych platform testowych w celu przełączania zadań symulatora. Badanie przeprowadzono za pomocą symulatora 3D, sztywnych endoskopów i sprzętu mikrochirurgicznego. Uczestnikami byli lekarze chirurgi, których podzielono na dwie grupy, w zależności od poziomu doświadczenia. Zadaniem symulatora było przeniesienie trzech obręczy z jednego kołka na drugi i z powrotem. W tym celu użyto kleszczyków i endoskopu. Zadanie obejmowało trzy seryjne próby ręką dominującą i trzy seryjne próby ręką niedominującą. Po wykonaniu zadania pytania dotyczyły doświadczenia chirurgicznego i oceny pracy z symulatorem. Wraz ze wzrostem liczby wykonywanych prób ulegał skróceniu średni czas ich wykony-
Endoscopic sinus surgery presents a significant surgical challenge due to its complexity and anatomical variability, as well as the risk of serious complications. Simulation models have proved to be effective in gaining endoscopic skills and training operational procedures. Research has shown that a simulator may be useful as a questionnaire before and after the simulation. All the participants agreed that the skills acquired during the simulation will be useful during a real operation. The study involved 10 residents (5 with less experience, 5 with more experience), who were first shown an instructional video on placing a TEP with explanations provided by an expert. The participants completed a questionnaire before and after the simulation. All the participants agreed that the skills acquired during the simulation will be useful during a real operation. The younger residents particularly benefited from the simulation. The elements printed in 3D technology were not damaged during repeated simulations and the use of squid tissues provided very realistic tactile feedback, similar to that of oesophageal mucosa without increasing the costs. An additional advantage of the models is their precision, with the possibility of achieving resolution up to 20 micrometres [46]. To sum up, three-dimensional TEP simulators provide the opportunity to train this complicated procedure. Thanks to their low production costs and high quality, they can be used on a large scale, which will significantly accelerate resident training and increase their skills in the operating room.

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a training and educational tool in sinus operations as well as in training for rhinologic operations [47]. Three-
dimensional models are used in teaching endoscopic sinus surgery (ESS) as well. The study used a printed 3D model that simulated bone structures and soft tissues. Residents and rhinologists performed, among others, antrostomy and removal of the frontal recess on the simulator. The use of simulators has been highly rated in terms of acquiring basic skills in endoscopy [48,49]. Sander et al. described the education of patients with paranasal sinus diseases. For this purpose, they created a model of a paranasal sinus, which was printed in the advanced 3D polyjet method to develop a precise, anatomically faithful replica of the sinuses. The educational 3D model is an effective tool for otolaryngologists to educate their patients by explaining the patient’s anatomy, medical condition, and treatment options [50].

3D printing in reconstructions

To repair defects and correct the nose and nasal cavity, 3D printing can be used. In the case of nasal septum perforation, on the basis of CT scans 3D templates of the exact shape of the perforation can be printed. In patients with an irregular nasal bone contour, forms obtained thanks to 3D printing can be used, and with the help of silicone injected into them, a specific implant can be obtained for rhinoplasty [51].

Microtia is a rare congenital defect which consists in the deformation of one earlobe and hearing impediments, while the other earlobe usually develops normally. Earlobes are hard to reproduce by standard methods due to their complex structure, which is why 3D printing seems promising in this field. Chen et al. conducted their study on 6 children with one-sided microtia. Thanks to the presence of one proper earlobe, a mirror image was created by computer, which then enabled the making of a scaffold by means of 3D printing for surgical reconstruction of the lacking earlobe. The final shape of the prosthesis was made by a 3D printer from porous polyethylene (MEDPOR, Stryker, Kalamazoo). The microtia ear was removed and a one-stage reconstruction was performed consisting in the formation of a cutaneous fascial lobe on the printed scaffold. In one of the six patients, the reconstruction was not successful due to vascularisation problems. In two patients, a temporary issue of alopeia in the operated area was observed. The creation of such a prosthesis made it possible to reconstruct the deformed lobe during one operation, whereas up till now a series of operations was needed. The use of this method enables recreation of the patient’s unique ear morphology and the end effect of the surgery is very aesthetic, and the earlobes look symmetrical. However, this method requires further research and standardisation [52].

Zopf et al. are conducting promising research on laser printing prostheses of polycaprolactone that would contain agents stimulating chondrogenesis [53].

w zakresie umiejętności endoskopowych i treningu procedur operacyjnych. Badania wykazały, że symulator może być przydatny jako narzędzie szkoleniowe i edukacyjne w operacjach zatok oraz w treningu do operacji rynologicznych [47]. Modele 3D wykorzystywane są również w nauczaniu chirurgii endoskopowej zatok (ESS). W badaniach zastosowano model 3D, który symuloł struktury kostne i tkanki miękkie. Na symulatorze rezydenci i rynolodzy wykonali m.in. antrostomię i usunięcie zachłynia czołowego. Badania wykazały, że symulator może być przydatnym narzędziem szkoleniowym/edukacyjnym w operacjach zatok. Ich stosowanie zostało wysoko ocenione w zakresie nabywania podstawowych umiejętności w endoskopii [48,49].

Sander i wsp. opisali edukację pacjentów z chorobami zatok przynosowych. W tym celu stworzyli model zatok obocznych nosa, który został wydrukowany z użyciem zawieszanej metody 3D polyjet celem opracowania ich dokładnej, wiernej anatomicznie repliki. Wyjaśnienie pacjentowi anatomici, stanu chorobowego i opcji leczenia z wykorzystaniem edukacyjnego modelu 3D stanowi skuteczne narzędzie, z którego lekarze laryngolodzy mogą korzystać w celu edukacji chorych [50].

Druk 3D w rekonstrukcjach

Druk 3D możemy wykorzystać do naprawy defektów i korekcji nosa oraz jamy nosowej. W przypadku perforacji przegrody jamy nosowej na podstawie obrazów tomografi komputerowej możemy wydrukować szablony 3D o dokładnym kształcie perforacji. U pacjentów z neregularnym konturem kości nosowej można zastosować formy uzyskane dzięki drukowi 3D i za pomocą wstrzykiwanego do nich silikonu uzyskiwać specyficzny implant w celu zaprowadzenia plastyki nosa [51].

Microtia jest rzadką wadą wrodzoną, która polega na deformacji małżowiny usznej z powodu głębokiego uszka, a także niedorozwoju słuchu. Przy czym druga małżowina często rozwija się prawidłowo. Małżowiny uszne są trudne do odtworzenia standardowymi metodami, ze względu na swoją złożoną strukturę, dlatego druk 3D wydaje się obiecujący w tej dziedzinie. Chen i wsp. przeprowadzili swoje badanie u 6 dzieci z jednostronną mikrotią. Dzięki obecności jednej prawidłowej małżowiny stworzono anatomicznie prawidłową replikę na drukarce 3D. W przypadku perforacji przybyły druk 3D ułatwia operację w celu zakończenia niepowodzenia z powodu problemów z zatokami, a także w przypadku perforacji zatok zakończyła się niepowodzeniem z powodu problemów z unaczynieniem. U dwóch pacjentów zaobserwowano przejściowy problem z łysieniem operowanej okolicy. Stworzenie protezy umożliwiło rekonstrukcję zdeformowanej małżowniny podczas jednego zabiegu, zamiast...
Markstedt et al. rozwinęli bioink, który zrównoważyło atrybuty algylu (NFC) ze względu na rozległość odniesień morfologicznych ucha pacjenta, a końcowy efekt zabiegu cechuje się dużą estetyką i symetrycznym wyglądem obu małżów usznych. Metoda ta wymaga jednak dalszych badań i standaryzacji [52].

Zopf i wsp. prowadzą obiecujące badania nad lasero-wym drukiem protez z polikaprolaktonu, zawierających czynniki stymulujące chondrogenię [53].

Markstedt i wsp. opracowali bioink, który zrównoważyło atrybuty algylu (NFC) ze względu na rozległość odniesień morfologicznych ucha pacjenta, a końcowy efekt zabiegu cechuje się dużą estetyką i symetrycznym wyglądem obu małżów usznych. Metoda ta wymaga jednak dalszych badań i standaryzacji [52].

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was then filled with a composite hydrogel of fibrillated collagen. The thus prepared tympanic membranes were compared with tympanic membranes from fresh human corpses and with temporal fascia from corpses. Their acoustic and mechanical properties were assessed using digital opto-electronic holography (DOEH) and laser Doppler vibrometry (LDV), as well as dynamic mechanical analysis (DMA). It was shown that the tympanic membrane made in the 3D technique is much more similar to the human tympanic membrane than the temporal fascia. Comparing transplants made of 8 or 16 fibres, minimal differences in DOEH and LDV were found for the tested frequencies. The more fibres there were, the more resistant the transplant was to mechanical strain, which is especially positive in comparison with the temporal fascia, which lost 70% of its capability to transfer sound wave vibrations during mechanical tests. Although the study was carried out in vitro, it proves that the acoustic and mechanical properties of tympanic membranes printed in 3D technology are better than those of temporal fascia used up-to-date. This gives hope for better results of myringoplasty in the future [59].

Kuo et al. attempted to repair a tympanic membrane by means of 3D bioprint based on images obtained from ear endoscopy. The effectiveness of traditionally performed tympanoplasty, i.e. by transplanting cartilage, largely depends on the surgeon's skills to manually reproduce the shape of the graft matching the defect in the tympanic membrane. Therefore, personalised implants printed in 3D technology, based on images from endoscopy, tailored to the shape of the defect of a given patient might be better than those manually created by a surgeon. A study was conducted in chinchillas, in which scaffolds bioprinted in the 3D technique coated with fibroblasts and epidermal growth factor (EGF) were transplanted to defects in the tympanic membrane. Complete healing of the tympanic membrane was obtained, while preserving good acoustic properties. This method needs further studies, though, it shows the possibilities of using 3D bioprinting not only in otolaryngology but also in other fields of medicine [60].

Total removal of the larynx still remains a method of choice in treating advanced cancer of this organ. Voice production loss is one of the dominant manifestations of disability after this surgery. There have been attempts to transplant larynx from donors, although regretfully recent reports show that despite the success of the transplanted larynx starting to work, there was a gradual process of its rejection, which ultimately led to the necessity of its removal after 10 years [61].

A transplant of this type always requires long-term use of immunosuppressive drugs and yet it is often not permanent. Another method involves the use of an artificial larynx prosthesis that does not provide all the functions of the organ, e.g. the lack of sound vocalisation, although it allows breathing without a tracheostomy tube and prevents the aspiration of food into the respiratory tract [62]. Three-dimensional models of the larynx are already being created using 3D printing, Uszkodzenie błony bębenkowej jest często powikłaniem przewlekłych zapałek ucha lub skutkiem urazu. Obecnie jej odbudowa polega na rekonstrukcji przy użyciu materiału pobranego od pacjenta. Najczęściej jest to ochronista, cienki fragment chrząstki pobrany z małżowni usznej lub powięź mięśni skroniowego. Materiały te nie są jednak doskonale, z uwagi na czynność błony bębenkowej. Kozin i wsp. wykorzystali druk 3D do stworzenia sztucznej błony bębenkowej. Wykonał je z ruszkowania złożonego z 8 lub 16 włókien wydrukowanych z polidimetylosiloksanu (PDMS), polikaprolaktonu (PCL) i kwasu polietylenowego (PLA), a następnie wypełnił kompozytowy hydrożel z kolagenem fibrynowym. Tak przygotowane błony bębenkowe zostały porównane z błonami pochodzącymi ze świeżych zwłok ludzkich oraz z powięzi skroniowej ze zwłok. Oceniano ich właściwości akustyczne i mechaniczne za pomocą cyfrowej holografii optoelektronicznej (DOEH) i wibrometrii laserowej dopplerowskiej (LDV) oraz dynamicznej analizy mechanicznej (DMA). Wykazano, że błona wykonana techniką 3D ma właściwości dużo bardziej zbliżone do ludzkiej błony bębenkowej niż powięź skroniowa. Porównując przeszczepy wykonane z 8 lub 16 włókien, wykazano minimalne różnice w DOEH i LDV dla badanych częstotliwości. Wraz z liczbą włókien rosła jednak oporność na obciążenie mechaniczne przeszczepu, co jest bardzo dobrą informacją w porównaniu z właściwościami powięzi skroniowej, która traciła 70% zdolności do przenoszenia dźwięku fali dźwiękowej podczas testów mechanicznych. Mimo iż badanie to przeprowadzono in vitro, udowadnia ono, że właściwości akustyczne i mechaniczne wydrukowana w technologii 3D błony bębenkowej są lepsze niż stosowanej do tej pory powięzi skroniowej, co pozwala mieć nadzieję na lepsze rezultaty myringoplastyki w przyszłości [59].

Kuo i wsp. podjęli próbę naprawy błony bębenkowej za pomocą biodruku 3D na podstawie obrazów uzyskanych z endoskopii ucha. Skuteczność tympanoplastyki wykonywanej standardową techniką przeszczepu chrząstki zależy w dużej mierze od umiejętności chirurga w ręcznym otworzeniu kształtu przeszczepu do pasowanego do ubytku w błonie bębenkowej. Dlatego implanty wydrukowane w technologii 3D na podstawie obrazów z endoskopii, spersonalizowane, dopasowane do kształtu ubytku błony danego pacjenta mogą być lepsze, niż te tworzone ręcznie przez chirurga. Badanie przeprowadzono na szynszyłach, którym przeszczepiono na ubytki w błonie bębenkowej pokryte fibroblastami i naskórkowym czynnikiem wzrostu (EGF) ruszkowania wykonane techniką biodruku 3D, uzyskując całkowite wygwojenie błony z zachowaniem dobrych właściwości akustycznych. Metoda ta potrzebuje dalszych badań, ale ukazuje możliwości wykorzystania biodruku 3D nie tylko w otolaryngologii, lecz także w innych dziedzinach medycyny [60].

Całkowite usunięcie krzta wciąż pozostaje metodą z wyboru w leczeniu zaawansowanego raka tego narządu. Utrata funkcji głosotwórczej jest jednym z do-
mapping individual tissues, allowing the testing of treatment methods of some diseases of the larynx such as vocal fold paralysis that require laryngoplasty injection [63]. 3D printing allowing the reproduction of individual elements of the larynx is currently in the sphere of research which is primarily aimed at the most accurate representation of individual differences in the construction of patients’ larynx, in addition to acquiring precise knowledge on the mechanics of its elements. Although 3D printing technology has been successively developed over the years, it has not yet been successfully applied in larynx reconstruction. Attempts have been made to create 3D models of laryngeal cartilages based on high-resolution computerized tomography (HRCT). This allowed 3D visualisation of individual laryngeal cartilages and their mutual topographic relations to be obtained [64].

The next stage was to analyse the laryngeal joint mechanics, above all, those of the cricothyroid joint. This was conducted using HRCT as well and Mimics software to determine changes in the position of the vocal folds caused by larynx movements [65]. Perhaps using 3D printing based on already obtained models of laryngeal cartilages would enable more in-depth analysis of their operation. Subsequent, increasingly more precise models allow better visualisation of the elements that model a larynx, while taking into account their function, and their use as training models at the same time and in the future, also as reconstructive models [66]. A forecast of larynx prototyping using 3D printing is a study conducted by Reszke et al. using Macrolon 2600 polycarbonate with good biocompatibility and corrosion resistance. Thyroid, cricoid and arytenoid cartilages mapped thanks to MR examination were printed on a 3D printer. The printed cartilages were promising, although in some cases the precision that would allow reproduction of the smallest details was lacking [67]. 3D printing, provided that appropriate material similar to cartilage properties or cartilage itself is used as part of bioprinting, can be used in the future for larynx reconstruction after a partial laryngectomy. For some time now, autotransplants of tissue fragments for larynx reconstruction after a partial laryngectomy is used as part of bioprinting, can be used in the future material similar to cartilage properties or cartilage itself was lacking [67]. 3D printing, provided that appropriate material similar to cartilage properties or cartilage itself is used as part of bioprinting, can be used in the future for larynx reconstruction after a partial laryngectomy. For some time now, autotransplants of tissue fragments for larynx reconstruction after a partial laryngectomy is used as part of bioprinting, can be used in the future material similar to cartilage properties or cartilage itself was lacking [67]. 3D printing, provided that appropriate material similar to cartilage properties or cartilage itself is used as part of bioprinting, can be used in the future for larynx reconstruction after a partial laryngectomy is used as part of bioprinting, can be used in the future material similar to cartilage properties or cartilage itself was lacking [67]. 3D printing, provided that appropriate material similar to cartilage properties or cartilage itself is used as part of bioprinting, can be used in the future for larynx reconstruction after a partial laryngectomy is used as part of bioprinting, can be used in the future material similar to cartilage properties or cartilage itself was lacking [67]. 3D printing, provided that appropriate material similar to cartilage properties or cartilage itself is used as part of bioprinting, can be used in the future for larynx reconstruction after a partial laryngectomy is used as part of bioprinting, can be used in the future material similar to cartilage properties or cartilage itself was lacking [67]. 3D printing, provided that appropriate material similar to cartilage properties or cartilage itself is used as part of bioprinting, can be used in the future for larynx reconstruction after a partial laryngectomy is used as part of bioprinting, can be used in the future material similar to cartilage properties or cartilage itself was lacking [67].
planted them in four rabbits. In follow-up tests after 4 and 8 weeks, neither CT scans nor endoscopy indicated transplant failure. The histopathology indicated that the prosthesis integrated with the adjoining trachea without the formation of granulation tissue. Examination under a scanning microscope confirmed the regeneration of cilia with a proper structure and function on the respiratory mucosa, which covered the entire surface of the transplant and did not differ from the mucosa of the remaining parts of the trachea. Chondrocyte regeneration sufficient to maintain airway patency was demonstrated as well. PCL scaffolds manufactured by the 3D printing method are inexpensive and enable the production of individual trachea prostheses. The study only covered a period of 8 weeks after the transplantation, therefore further long-term research is needed to assess trachea regeneration [69]. Works are being continued, and their result is the use of a similar method in a 46-year-old patient with tracheostenosis caused by bronchial tuberculosis. After measuring both the length and width of the trachea based on the patient’s CT scan, a constricted model of the narrowed trachea was created to facilitate the preparation of the element required for the transplantation. Polycaprolactone (PCL) was used due to its biocompatibility and biodegradability. By mapping the shape of the tracheal cartilage, an external scaffold was printed from it – a 6 cm long splint placed around the stenosis to which the tissue of the narrowed trachea was attached in order to provide the desired width. After 3 months of observation, no adverse side effects were found in the patient. Moreover, the patient’s breathing capacity and physical condition improved significantly.

The use of biodegradable materials and tailored to the individual patient, which the 3D printing method allows, is very important from the point of view of procedures requiring an unusual approach due to the location of the defect in the respiratory tract, as well as in children, enabling size adjustment and eliminating the need to replace the element during growth of the patient [70]. Another approach to the use of 3D printing is to prepare ready-made transplants to replace the lacking part of airways after its surgical removal. In a pilot study performed on pigs in 2017, Bhor et al. tested a transplant model made of a polycaprolactone scaffold printed in 3D technology and a layer of extracellular matrix collagen. The transplants were designed based on CT scans of the experiment animals and implanted in the place of an earlier removed fragment of the larynx. The length of the prepared implant included 4 tracheal cartilages and the time of preparation from obtaining the CT scans to sterilising before implantation, was 36 hours. Although the initial results were promising, the longest time of survival was 34 days. The cause that ultimately led to the death of the tested animals was the appearance of granulation tissue, which narrowed the trachea and disabled breathing. Interestingly, the animals who were implanted with a 360° round closed tube survived longer than those with a 270° open tube, theoretically more similar to real tracheal cartilage. Therefore, it is not an ideal method because, in the case of transplant in a child, the implant will be replaced twice, once with a closed tube and then with an open tube. In the event of bronchial tuberculosis, the length of such a replacement may be much longer than those with a 270° open tube, theoretically more similar to real tracheal cartilage. Therefore, it is not an ideal method because, in the case of transplant in a child, the implant will be replaced twice, once with a closed tube and then with an open tube. In the event of bronchial tuberculosis, the length of such a replacement may be much longer.
ting small fragments covering only a part of a trachea excised from the existing organ, its hypertrophy affecting the adjoining epithelial tissue in vivo is possible, which was found in earlier studies. For larger fragments of the organ, it will likely be necessary to use epithelial culture on the surface of the printed transplant prior to its implantation [71].

**SUMMARY**

Using 3D models in the education of physicians is significantly less expensive than practising on human corpses. Simulators of this type can also reduce the problem of obtaining standard preparations. A great advantage of 3D printing is the possibility of obtaining individual prostheses. They are "made to measure", which allows them to be adjusted to any patient's anatomical conditions. This creates new treatment opportunities for those patients that require particularly precise, individually tailored implants. Further expansion of 3D printing technology in the future will contribute to a significant reduction in the costs of treating patients with neoplastic lesions. It will also be an important support in the education of future head and neck surgeons.

**CONFLICT OF INTEREST**

The authors state that there is no conflict of interest in connection with the published work.

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**Author's contribution**

Study design – W. Likus
Data collection – R. Wilk, K..Nechoritis, A. Różycka-Nechoritis, K. Przytulakandzia
Manuscript preparation – K. Nechoritis, A. Różycka-Nechoritis, R. Wilk, W. Likus, W. Gawel, A. Hudecki
Revised – J. Markowski

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Wykorzystywanie modeli 3D w edukacji lekarzy jest znacznie tańsze niż ćwiczenia na ludzkich zwłokach. Tego typu symulatory mogą również zmniejszyć problem z pozyskiwaniem standardowych preparatów. Dużą zaletą druku 3D jest możliwość otrzymywania indywidualnych prototyp. Są one tworzone „na wymiar”, przez co mogą być dopasowane do najróżniejszych warunków anatomicznych pacjenta. Stwarza to nowe szanse leczenia pacjentów wymagających szczególnie precyzyjnych, indywidualnie dopasowanych implantów. Dalsza ekspansja technologii druku 3D w przyszłości przyczyni się do znacznego obniżenia kosztów leczenia pacjentów dotkniętych zmianami nowotworowymi, a także będzie istotnym wsparciem w nauce przyszłych chirurgów głowy i szyi.

**KONFLIKT INTERESÓW**

Autorzy stwierdzają brak konfliktu interesów w związku z publikowaną pracą.

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REFERENCES

1. Kaye R, Goldstein T, Zeltman D, Grande D A, Smith L P. Three dimensional printing: A review on the utility within medicine and otolaryngology. Int. J. Pediatr. Otorhinolaryngol. 2016; 89: 145–148, doi: 10.1016/j.ijporl.2016.08.007.

2. Zadpoor A., Malda J. Additive Manufacturing of Biomaterials, Tissues, and Organs. Ann. Biomed. Eng. 2017; 45(1): 1–11. doi: 10.1007/s10439-016-1719-9.

3. Marietti N, Serrano C, van den Brink H, Pineau J, Prognon P, Borget J, El Batti S. Advantages and disadvantages of three-dimensional printing in surgery: A systematic review. Surgery. 2016; 159(6): 1485–1500, doi: 10.1016/j.surg.2016.07.012.

4. Kim S.E., Lee J., Kim H., Yang D.H., Kim Y.H., Kyung Y.S., Kim C.S., Choi S.H., Bai J., Ha H., Kwon S.U., Kim N. Three-Dimensional Printing: Basic Principles and Applications in Medicine and Radiology. Korean J. Radiol. 2016; 17(2): 182–197, doi: 10.3348/kjr.2016.17.2.182.

5. Cui X., Boland T., DiMaio D.D., Lotz M.K. Thermal inkjet printing in tissue engineering and regenerative medicine. Recent. Pat. Drug. Deliv. Formul. 2016; 12(1): 1–8, doi: 10.2174/1574885111712010002.

6. Jang D., Kim D., Moon J. Influence of fluid physical properties on inkjet printability. Langmuir. 2009; 25(5): 2626–2635, doi: 10.1021/la900059m.

7. Khan M.S., For D., Li X., Tian J., Forasyth J., Garnier G., Shen W. Bioreactor engineering through inkjet printing. Colloids Surf. B. Biointerfaces 2010; 79(2): 441–447, doi: 10.1016/j.colsurfb.2009.09.032.

8. Christensen K., Xu C., Chai W., Zhang Z., Fu J., Huang Y. Freeform inkjet printing of cellular structures of artificial organs. Biotechnol. Bioeng. 2015; 112(5): 1047–1055, doi: 10.1002/bit.25501.

9. Gopinathan J., Noh I. Recent trends in bioinks for 3D printing. Biomater. Res. 2016; 20(1): 19, doi: 10.1186/s40824-016-0058-2.

10. Datta P., Ozbolat O., Ayan B., Dhanaw A., Ozbolat I.T. Bone tissue bioprinting for craniofacial reconstruction. Biotechnol. Bioeng. 2017; 114(11): 2424–2431, doi: 10.1002/bit.26349.

11. Datta P., Ayan B., Ozbolat I.T. Bioprinting for vascular and vascularized tissue biofabrication. Acta Biomater. 2017; 51: 1–20, doi: 10.1016/j.actbio.2017.03.035.

12. Heller M., Bauer H.K., Goetze E., Gielsch G., Ozbolat I.T., Moncal K.K. 3D printing to facilitate anatomic study, device development, simulation, and planing in thoracic surgery. J. Thorac. Cardiovasc. Surg. 2015; 149(4): 973–979, doi: 10.1016/j.jtcvs.2015.04.005.

13. Lohel K., Lin S., Tytgat L., Van Velzenbergh S., G. L., Ovsianikov A. Bioink properties before, during and after 3D bioprinting. Biofabrication. 2016; 8(3): 032002, doi: 10.1088/1758-5080/8/3/032002.

14. Lohel K., Choi D.J., Park S.J., Kim M.S., Kang C.M., Kim C.H. 3-dimensiol bioprinting for tissue engineering applications. Biomater. Res. 2016; 20: 12, doi: 10.1186/s12048-016-0058-2.

15. Horgan N., Yang G.H., Lee J., Kim G.J. 3D bioprinting and its in vivo application. Biomed. Mater. Res. B. Appl. Biomater. 2018; 106(1): 444–459, doi: 10.1002/bibm.2018.23826.

16. Ozbolat I.T. Bioprinting scale-up tissue and organ constructs for translantation. Trends Biotechnol. 2014; 32(8): 773–785, doi: 10.1016/nature.2015.04.005.

17. Datta P., Ozbolat O., Ayan B., Dhanaw A., Ozbolat I.T. Bone tissue bioprinting for craniofacial reconstruction. Biotechnol. Bioeng. 2017; 114(11): 2424–2431, doi: 10.1002/bit.26349.

18. Cui X., Boland T., DiMaio D.D., Lotz M.K. Thermal inkjet printing in tissue engineering and regenerative medicine. Recent. Pat. Drug. Deliv. Formul. 2016; 12(1): 1–8, doi: 10.2174/1574885111712010002.

19. Trachtenberg J.E., Plaックe J.K., Smith B.T., Piard C.M., Santoro M., Scott D.W., Fisher J.P., Mikos A.M. Effects of Shear Stress Gradients on Ewing Sarcomas. Annals of Biomedical Engineering. 2016; 2(20): 1771–1780.

20. Kurenov S.N., Ionita C., Sammons D., Demmly T.L. Three-dimensional printing to facilitate anatomic study, device development, simulation, and planning in thoracic surgery. J. Thorac. Cardiovasc. Surg. 2015; 149(4): 973–979, doi: 10.1016/j.jtcvs.2014.12.059.

21. Zheng B., Wang X., Zheng Y., Feng J. 3D printed model improves clinical assessment of surgeons on anatomy. J. Robot. Surg. 2013; 18(1): 61–67, doi: 10.1007/s11766-012-0809-2.

22. Wersz S.M., Zeichner S.J., Berg B.I., Zeilhofer H.F., Thieringer F. 3D Printed Surgical Simulation Models as educational tool by maxillofacial surgeons. Eur. J. Dent. Educ. 2018; 22(3): e005-e005, doi: 10.1111/eje.12332.

23. De Cruz M.J., Francis H.W. Face and content validation of a novel three-dimensional printed temporal bone for surgical skills development. J. Laryngol. Otol. 2015; 129(Suppl 3): S23–S29, doi: 10.1177/0778160815501346.

24. Barber S.R., Kozin E.D., Demdon M., Lin B.M., Lee K., Sinha S., Black N., Remscheider A.K., Lee D.J. 3D printed pediatric endoscopic car surgery simulator for surgical training. Int. J. Pediatr. Otorhinolaryngol. 2016; 90: 113–118, doi: 10.1016/j.ijporl.2016.08.027.

25. Sander I.M., Leepert T.T., Doney E.L., Leevy W.M., Liepert D.P. Patient education for endoscopic sinus surgery: preliminary experience using 3D-printed clinical imaging data. J. Funct. Biomater. 2017; 8(2): E13, doi: 10.3390/jfb8020013.
48. Hsieh T.Y., Cervenka B., Dedthia R., Strong E.B., Steele T. Assessment of a Patient-Specific, 3-Dimensionally Printed Endoscopic Sinus and Skull Base Surgical Model. JAMA Otolaryngol. Head Neck Surg. 2018; 144(7): 574–579, doi: 10.1001/jamaoto.2018.0437.

49. Alarsheedi A.S., Nguyen L.H.P., Mongeau L., Funnell W.R.J., Tevfil M.A. Development and validation of a 3D-printed model of the ostiomeatal complex and frontal sinus for endoscopic sinus surgery training. Int. Forum Allergy Rhi- nol. 2017; 7(8): 837–841.

50. Sander J.M., McGoldrick M.T., Helms M.N., Betts A., van Avermaete A., Owens E., Doney E., Liepert T., Nieburg B., Liepert D., Levey W.M. Three-dimensional printing of X-ray computed tomography datasets with multiple materials using open-source data processing. Anat. Sci. Educ. 2017; 10(4): 383–391, doi: 10.1002/ase.1682.

51. Unkovskiy A., Spintzyk S., Brom J., Huettig F., Keutel C. Direct 3D printing of silicone facial prosthetics: A preliminary experience in digital workflow. J. Prosthet. Dent. 2018; 120(2): 303–308, doi: 10.1016/j.prosdent.2017.11.007.

52. Chen H.Y., Ng I.S., Chang C.S., Lu T.C., Chen N.H., Chen Z.C. Pansuising Mirror Image Reconstruction in Unilateral Microtia: Customizing Auricular Framework by Application of Three-Dimensional Imaging and Three-Dimensional Printing. Plast. Reconstr. Surg. 2017; 139(6): 1433–1443, doi: 10.1097/PRS.0000000000001374.

53. Zofop D.A., Mitas A.G., Flanagan C.L., Wheeler M., Green G.E., Hollister S.J. Computer aided-designed, 3-dimensionally printed porous tissue biocar- folds for craniofacial soft tissue reconstruction. Otolaryngol. Head Neck Surg. 2015; 152(1): 57–62, doi: 10.1177/0194599814520065.

54. Markstedt K., Mantas A., Tournier I., Martinez Ávila H., Hägg D., Gatenholm P. 3D Bioprinting Human Chondrocytes with Nanocellulose-Alginate Bioink for Cartilage Tissue Engineering Applications. Biomacromolecules 2015; 16(5): 1489–1496, doi: 10.1021/acs.biomac.5b00188.

55. Danij S., D’Alessandro D., Pietrabissa A., Petrini M., Berrettini S. Development and validation of tissue-engineered substitutes of the ear ossicles: PORP-shaped poly(propylene fumarate)-based scaffolds cultured with human mesenchymal stromal cells. J. Biomed. Mater. Res. A. 2009; 92(4): 1343–1356, doi: 10.1002/jbm.a.32447. doi:10.1002/jbm.a.32447.

56. Xiong Y., Chen P., Sun J. Studies on personalized porous titanium implant fabricated using three-dimensional printing. forming technique. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi 2012; 29(2): 247–250.

57. Li X.S., Sun J.J., Liang W., Liu X. Effect on cheekula function by tissue-engineering ossicle prostheses containing controlled release bone morphogenetic protein 2 transplanted into acoustic build in guinea pig. Chin. J. Otorhinolaryn- gol. Zhonghua Er Bi Yan Hou Tou Jing Wai Ke Za Zhi 2009; 44(6): 490–493.

58. Philippi J.A., Miller E., Weiss I., Huurd J., Waggoner A., Campbell P. Microenvironment engineered by inkjet bioprinting spatially direct adult stem cells toward image- and bone-like subpopulations. Stem Cells. 2008; 26(1): 127–134, doi: 10.1634/stemcells.2007-0520.

59. Kozin E.D., Black N.L., Cheng J.T., Colter M.J., McKenna M.J., Lee D.J., Lewis A.A., Rouwski J.J., Remmerscheider A.K. Design, fabrication, and in vitro testing of novel three-dimensionally printed tympanic membrane grafts. Tissue Res. 2016; 340: 191–203, doi: 10.1016/j.heares.2016.03.005.

60. Kuo C.Y., Wilson E., Fuson A., Gandhi N., Monfaredi R., Jenkins A., Romero M., Santoro M., Fisher J.P., Cleary K., Reilly B. Repair of Tympanic Membrane Perforations with Customized Bioprinted Ear Grafts Using Chinc- chilla Models. Tissue Eng Part A. 2018; 24(5–6): 527–535, doi: 10.1089/ten.tea.2017.0246.

61. Lorenz R.R., Strome M. Total laryngeal transplant explanted: 14 years of lessons learned. Otolaryngol. Head Neck Surg. 2014; 150(4): 509–511, doi: 10.1177/0194599813519748.

62. Debry C., Dupret-Bories A., Vranu N.E., Hemar P., Lavalle P., Schultz P. Laryngeal replacement with an artificial larynx after total laryngectomy: the possibility of restoring larynx functionality in the future. Head Neck. 2014; 36(11): 1669–1673, doi: 10.1002/hed.23621.

63. Hamdan A.L., Haddad G., Haydar Y., Hamade R. The 3D printing of the Paralyzed Vocal Fold: Added Value in Injection Laryngoplasty. J. Voice. 2018; 32(4): 499–501, doi: 10.1016/j.jvoice.2017.07.011.

64. Storck C., Gugatschka M., Friedrich G., Sorantin E., Ebner F., Fischer C., Wolfensberger M., Juergens P. Developing a 3D model of the laryngeal car- tilages using HRCT data and MIMICS’s segmentation software. Logopedics Phoniatrics Vocology. 2010; 35(1): 19–23, doi: 10.3109/14015430903525378.

65. Storck C., Gebrer R., Fischer C., Wolfensberger M., Honegger F., Friedrich G., Gugatschka M. The role of the cricothyroid joint anatomy in cricothyroid approximation surgery. J. Voice. 2011; 25(5): 632–637, doi: 10.1016/j.jvoice.2010.06.001.

66. Zhang Y., Shi T. The research of laryngeal joints to reconstruction and modeling. Biomed. Mater. Eng. 2014; 24(6): 2627–2634, doi: 10.3233/BME-141079.

67. Rezke M., Štolduška M., Paluch J., Jasiuk K., Öhka H., Gabor J., Lępiński M., Swarenare B., Swarenare A. Proba rekonstrukcji krtny przy użyciu technic prototypowania 3D z wykorzystaniem poliwęglanu Makrolon 2600. Przetwórstwo tworzyw 2015; 6: 487–492.

68. Marquillas J., Wójtowicz P., Szafarowski T., Krzeski A. Vertical partial frontalcartilage with simultaneous pedunculated sternothyroid muscle flap reconstruction of the vocal fold - surgical proce- dure and treatment outcomes. Otolaryngol. Pol. 2018; 72(1): 23–29, doi: 10.5604/01.3001.0011.5938.

69. Chang J.W., Park S.A., Park J.K., Choi J.W., Kim Y.S., Shin Y.S., Kim C.H. 3D Printing of the Larynx: Lessons Learned. Ann. Otol. Rhy- nothyroid Muscle Flap Reconstruction of the Vocal Fold - Surgical Pro- cedure and Treatment Outcomes. Otolaryngol. Pol. 2018; 72(1): 23–29, doi: 10.5604/01.3001.0011.5938.

70. Hamdan A.L., Halab Y., Haddad G., Haydar Y., Hamade R. The 3D printing of the Paralyzed Vocal Fold: Added Value in Injection Laryngoplasty. J. Voice. 2018; 32(4): 499–501, doi: 10.1016/j.jvoice.2017.07.011.

71. Bhuta F.Y., Lewis E.E., Rohman S.S., Ayub A., Raad W., Al-Ayoubi A.M., Lebovics R.S. Circumferential Three dimensional – Printed Tracheal grafts: Research Model feasibility and early results. Ann. Thorac. Surg. 2017; 104(3): 958–963, doi: 10.1016/j.athoracsur.2017.03.064.