The Usability of 3D-printed Medical Devices in Emergency and Military Disaster Medicine Care

Thesis

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Introduction

The Development of Military and Disaster Medicine

The scientific discipline of addressing mass casualties and disaster situations emerged during the Industrial Revolution, when large-scale conflicts, wars and industrial accidents exposed organisational weaknesses in mass casualty care. Over the course of the 20th century, the principles of modern disaster medicine were developed, beginning with World War I, drawing on military experience to lay the foundations for the rapid triage of mass casualties, emergency care protocols and organised logistical systems. These have become global guidelines (e.g. NATO). These encompass protocols for initial territorial or battlefield-level care (ROLE-1) and for more complex interventions in regional centres (ROLE-2 and ROLE-3). International organisations continuously adapt these guidelines to meet evolving challenges. One of the greatest challenges in emergency medicine is establishing a hierarchical and organised system for preparing for complex mass-casualty events and rapidly restoring the supply chain. Protocols are continually refined based on wartime and civilian experience, technological advances and the diversity of environmental crises, with the aim of achieving rapid, effective yet proportionate interventions. Technological progress in the 21st century has fundamentally shaped the possibilities of disaster medicine. Modern tools for on-site care, such as helicopters, mobile container hospitals and portable imaging and diagnostic equipment, enable rapid and targeted interventions and stabilisation at the scene. Structured protocols (e.g. MARCH and ABCDE) and organised response, together with technological innovations such as 3D printing, artificial intelligence and portable diagnostic devices, have become indispensable in effective mass casualty care. The increasingly complex challenges we face (e.g. biological and nuclear incidents, terrorist attacks and pandemics) demand continuous adaptation and the development of organised, flexible strategies that can be rapidly integrated with technology.

Theoretical Foundations and Possibilities of Application of 3D Printing in Disaster Medicine and Emergency Care

3D printing is an additive manufacturing process that became technologically available in the 1980s. The first method was stereolithography (SLA), which uses photopolymerisation with UV light. This was followed by the Fused Filament Fabrication (FFF) method, also known as Fused Deposition Modelling (FDM), which builds objects layer by layer from melted plastic filaments. Thanks to a rapid technological development, it has become possible to produce

complex geometric structures, such as anatomical models, patient-specific implants and even tissues and organs made from biocompatible materials. This technology is based on material layering and computer control, enabling the rapid production of highly precise, customised devices. Through multiparameter control (speed, temperature and layer thickness), the mechanical and biological properties of prints can be fine-tuned for use in medical applications such as bone substitutes, dental prosthetics, tissue modelling and the manufacture of medical devices.

A Wide Range of Applications in Healthcare

Thanks to advances in biotechnology, 3D printing now plays a significant role in regenerative medicine, including tissue modelling, organoids and the experimental printing of functional tissues (e.g. skin, bone and teeth), as well as the production of patient-specific devices such as orthoses, prostheses and custom surgical implants. In disaster medicine, applications include rapidly produced device systems such as Mayo tubes, diagnostic instruments, and surgical aids, as well as the printing of items such as custom scissors, scalpel handles, dental forceps, and stethoscopes. This technology is particularly valuable in areas where conventional manufacturing or storage capacity is lacking, or where the supply chain is unreliable or disrupted.

Summary of the Problem and Research Challenges

In both domestic and international disaster medicine, ensuring an adequate supply of equipment in areas where traditional manufacturing and supply chains are unreliable or damaged is a significant challenge. The same issue arises in emergency medicine during periods such as an ongoing pandemic.

This is particularly true in conflict zones and remote or isolated areas, where the availability of equipment, transport times and manufacturing capacity make achieving a continuous, stable supply almost impossible.

One key solution is to develop adaptive, locally manufacturable, customised medical devices that can be produced quickly and cheaply. The essential technological basis for this is 3D printing, which enables the realisation of the self-sufficiency and rapid response paradigm. However, the practical application of this technology, especially with regard to structural strength, sterilizability and technical reliability, is a complex research question. Finding the

answer could significantly increase the effectiveness of disaster medicine. An additional challenge is that devices produced using additive manufacturing must meet clinical and regulatory requirements, such as mechanical strength and biocompatibility of the devices made using FDM or CFR technology.

Objectives:

- Our objectives included identifying manufacturing technologies that would ensure the structural integrity and expected load capacity of devices used in disaster medicine.
    - We tested a 3D-printed stethoscope based on the Glia model developed by Pavlovsky et al., as well as the MAYO tubes we modelled in a simulated environment to determine how our devices perform in practice at the patient's bedside.
    - In our investigations, we also sought to determine - without considering cost-effectiveness - whether consistent and equivalent devices could be manufactured using additive manufacturing technology.
- The long-term goal of our work is to lay the foundations for complex healthcare development, whereby digital 3D models of devices used in care can be accessed anywhere in the world via a cloud-based service, provided there is suitable internet connection available.

Materials and Methods

The materials under investigation were tested in accordance with International Organisation for Standardisation (ISO) standard ISO 527, which specifies the tensile properties of plastics and plastic composites under defined conditions. Additional measurements were performed on the specimens, including tensile testing, two-point bending fatigue testing, torsional fatigue testing and Shore D hardness measurement, to supplement these tests. These specimens, which are required for mechanical testing and analysis prior to user testing, were made from polymer and/or composite materials. The results obtained during these material technology measurements were necessary for developing the final version of the devices we wanted to characterise. Results obtained with our test devices for simulated patient airway management; condition assessment or tooth extraction were recorded on a standardised evaluation sheet. At the same time, we conducted a user satisfaction survey. In our work, we

examined the following technologies: FFF, CFR, SLS and SLA. During the material measurements, we compared Herz filament polylactic acid (PLA) printing filament without additives with Polymaker Polymide PA-6cf Onyx carbon fibre composite test specimens from 3Dee Technologies Hungary Kft. The material used was continuous fibre reinforcement (CFR) microcarbon fibre polyamide, printed by a Markforged X7, which is reinforced with continuous carbon fibre (CFR). The printing settings were calibrated for each model; therefore, the settings differed between individual devices and test specimens during testing. In 3D printing, the most important parameters in terms of the result are the printing temperature, layer thickness, and fill ratio. After the material tests, we needed to model and design some of our devices.

Our 3D-printed dental forceps are a 1:1 scale replica of a tool used for extracting upper right first molars. We digitised the original tool using an Artec Space Spider industrial scanner (Artec 3D). In order to do this, it was necessary to completely disassemble the tool and ensure that all its surfaces were non-reflective. This process involves using a special handheld 3D scanner to transfer the parameters of the sample piece to the editing software without touching it. This is followed by converting the obtained images into a digital model. During the design phase, we made minor modifications to the geometric structure to achieve the desired properties. We reinforced the fibre pulling technique with carbon fibre to increase the load capacity. Due to the expected load factors, we increased the pivot point by an additional 3 mm so that the jaws are in contact with each other when closed, providing sufficient force for tooth extraction.

For the stethoscope examination, we used and optimised a device from a previous study. Minimal modifications were made to the Glia model after processing, such as thinning the upper part for increased comfort, adding an olive and removing a non-functional component. The soft parts of the stethoscope were made of silicone tubing, and the membrane was made of standard nitrile rubber. In the case of MAYO tubes, there was no previous digital 3D model or accessible literature. First, we digitised the device using an Artec Space Spider industrial scanner. Then, using Rhino – Rhinoceros 3D design software –, we refined the design and made minor modifications, such as thickening the rim or wall. After slicing, we created the final MAYO tube designs in PreForm software and saved them in .stl format. Five dentists and oral surgeons, who were actively working in the clinic and had at least 2, but not more than 20 years of professional experience, tested and evaluated the dental forceps using an anonymised, standardised questionnaire.

In accordance with ethical guidelines and with written consent, a total of 26 participants agreed to test the 3D-printed stethoscope and MAYO tubes. Participants were divided into two groups based on their knowledge and experience of disaster and emergency medicine. The first group consisted of participants with relevant clinical experience, including resident physicians, specialists and paramedics in emergency medicine or anaesthesia with at least three years' clinical or prehospital experience (Group1 = 16). The second group comprised medical students from the Faculty of Medicine at the University of Pécs (Group2 = 10), who had the theoretical knowledge necessary to perform the simulation task, but lacked relevant clinical experience in emergency medicine. The selection criterion for the medical students was the successful completion of their third year of study. Participants were able to express their subjective opinions about the tools used in the study via an anonymous, standardised, paper-based questionnaire.

Our 3D-printed MAYO tubes were tested using simulated situational tasks, which mimicked patient care. Participants had to use the necessary clinical skills to secure the airway on the Laerdal Airway Management Trainer (LATM). The procedure was considered successful if it was performed correctly using all three 3D-printed MAYO tubes and a control, factory-made MAYO tube, achieving the same result each time. The time taken to insert each of the four devices was measured individually. For the skill to be considered successful, two out of three bag-valve mask (BVM) ventilations had to be performed successfully, meaning that at least 450 ml of air had to be delivered to the LATM lungs twice. A maximum of 2 minutes was allowed for inserting the four MAYO devices and performing the three ventilation attempts. If ventilation was unsuccessful, or if the LATM's stomach became distended, the task for that device was considered unsuccessful. The task was evaluated by independent technicians invited to participate in the study, who used a standardised evaluation sheet.

For the stethoscope task, participants had to recognise physiological and pathological lung sounds. For this task, the TCCS-S patient simulator (Operative Experience) was set up in a pre-randomised manner. Participants then had to determine the corresponding diagnosis using a familiar diagnostic procedure (auscultation of the lungs). A Littmann Classic II stethoscope was used as the control instrument because it is one of the most commonly used types by emergency services and hospitals in Hungary. The TCCS-S simulated either normal breathing sounds or weaker/incomplete breathing sounds associated with pneumothorax. Participants performed one auscultation with each stethoscope and reported the results to an observer. The auscultation experiment was considered successful if the participant correctly identified the

breathing sounds and reported them to the observer. The time available for both devices was a maximum of 3 minutes. If the time limit was exceeded or an incorrect auscultation result was obtained, the experiment was considered unsuccessful. During the study, we measured the time taken to perform auscultation (in seconds) and diagnostic accuracy (whether the diagnosis was correct or incorrect) based on a standardised evaluation sheet.

Statistical analysis and curve fitting were performed using Origin 2018 software (developed by OriginLab Corporation). SPSS 26.00 was used to analyse the results for MAYO tubes and phonendoscopes. The type of statistical test used depended on the results of the normality test. We used the Shapiro–Wilk normality test and Levene's test in all cases and then selected the appropriate parametric (ANOVA) or non-parametric (Wilcoxon, Mann–Whitney or Kruskal–Wallis) statistical test. The chi-square test was used to evaluate categorical variables.

Results

Material testing:

To assess the suitability of PLA and Onyx–carbon fibre materials for developing medical devices, specimens were prepared from both materials and subjected to bending fatigue tests to evaluate their resistance to forces arising from two-point bending loads. For the PLA specimens, the resulting fatigue curve matched those previously characterised and reported in the literature. The specimen did not fail in the bending fatigue test, so flexural strength could not be determined. However, although the PLA specimen did not break under the standard test load, it failed under long-term fatigue (125,000 cycles).

The carbon fibre-reinforced Onyx composite material exhibited consistent strength values between 10 mm and 30 mm deflection, with a gradual decrease observed up to 20,000 cycles. There was an almost linear correlation between deflection and measured strength values between 10 mm and 40 mm, but after 5,000 cycles, linearity was only observed between deflection distances of 10 mm and 30 mm. At a deflection of 10 mm, the measured forces were 15.37 N in the first cycle and 17.06 N in the 5,000th cycle. At a deflection of 30 mm, the measured forces were 34.22 N in the first cycle and 37.99 N after 5,000 cycles. When the test was performed until failure, the bending strength was measured at 51.16 N and the deflection at 50.56 mm.

Following the fatigue tests, we observed that test specimens with a deflection of 35 mm or more exhibited a small bulge at the bending point and underwent permanent deformation, remaining in a bent state.

The torsion fatigue test measures a material's resistance to twisting, rotating or rolling movements and forces. In the case of PLA test specimens, fracture occurred within 800 cycles at 35° torsion; however, at 30° torsion they withstood over 5,500 cycles without permanent deformation. At 25° torsion fracture occurred after 11,700 cycles.

During the torsion fatigue test, the carbon fibre material exhibited bending-like trends, and no fatigue pattern in the classical sense was detectable. After 200–300 cycles, the torque required to rotate the carbon fibre test specimen stabilised at a constant value with only a slight decrease. After completing the test over 20,000 cycles, we observed that the torsional flexibility of the specimen was proportional to the maximum rotation angle. The resistance of the carbon fibre specimens remained unchanged in both radial and axial directions. Permanent distortion of the specimens began after 40° of rotation. Notably, Shore D hardness measurements revealed no significant difference ($p<0.05$) between polylactic acid and the composite material.

Following the bending and torsion fatigue tests, tensile strength tests were performed on the Onyx carbon fibre specimens. In line with previous measurements, a significant difference was observed in the bending test results ($p < 0.05$). The average tensile strength value at a deflection of 30 mm was 258.30 MPa ± 10.79 MPa, with fracture occurring in the form of a V at the rounded end. Above a deflection of 30 mm, the average value was 71.00 MPa ± 19.92 MPa, with straight fractures most noticeable at the protruding points. Additionally, tensile tests were performed on the specimens used for the torsion fatigue test. The average tensile strength was 118 MPa ± 2 MPa, with fractures typically forming a V-shape at the rounded point, similarly to the bending test specimens. The difference between the values was not statistically significant.

User tests:

The dental forceps produced using additive technology were tested by dentists with between 2 and 20 years of clinical experience. First, the specialists performed the following tests using traditional metal forceps: they simulated the extraction force on a 3D-printed tooth model using a biaxial material tester. One test mimicked the traditional extraction process, while the other was performed with maximum force. They then repeated the same procedure with the 3D-printed forceps. This time, however, we asked them to apply maximum force only, without mimicking the normal process. The measured data served as a control for evaluating the 3D-printed medical device. Based on the results, no significant difference was observed in the maximum forces exerted with the forceps during either the normal tooth extraction simulation ($p = 0.15$) or the high-force tooth extraction simulation ($p = 0.10$). On average, the

maximum force exerted with the desktop 3D-printed dental forceps was 70.30 N ± 4.41 N, whereas with traditional dental forceps it was 84.8 N ± 16.96 N.

After completing the above test, each dentist was asked to fill out a questionnaire evaluating the 3D-printed forceps. Based on their responses, only two of the five dentists would currently use the device for actual dental procedures. However, with a few minor modifications, all of them would use it for patient care.

We compared different MAYO tubes based on the time taken for simple airway securing, success rates in airway management and subjective user evaluations. Clinical experience (expert versus student) had no significant effect on the time taken for intubation with the different tubes. Therefore, concerning the experience, there was no significant difference in procedure time between the MAYO tube variants ($p = 0.798$). Also, there was no significant difference in the success rate of securing the airway between the various MAYO versions ($p = 0.163$).

User experience after airway attempts was assessed using a Likert-scale questionnaire. Analysis of subjective user opinions showed that the stereolithography-produced Flexible V2 MAYO variant received significantly lower scores than all the other MAYO variants (median ± SD: conventional MAYO tube: 4.57 ± 0.487 vs. TPU A-95: 4.28 ± 0.52 vs. Flexible V2: 3.6 ± 0.54 vs. Flexa Black: 4.28 ± 0.66; $p < 0.001$). The conventional MAYO tube, TPU A-95 and Flexa Black variants rated equally well.

Despite being reproduced from the original design with minimal or without modification, users rated the devices differently. Ratings were determined by the perceived similarity in form and structure to the original MAYO tube rather than by function and usability (mean ± SD: conventional MAYO tube: 4.48 ± 0.82; TPU A-95: 4.28 ± 0.54; Flexible V2: 4.0 ± 0.7 vs. Flexa Black: 4.16 ± 0.7; $p = 0.104$).

We compared the stethoscopes based on auscultation duration, diagnostic accuracy and subjective evaluation by the participants. Overall, our results showed no difference in auscultation time between the control and 3D-printed stethoscopes, regardless of group categorisation (median ± SD: Littmann Classic 29 ± 21.46 seconds vs. 3D-printed stethoscope 27 ± 14.43 seconds; $p = 0.864$). Additionally, we observed that individual experience could significantly impact auscultation time beyond the criteria used to define the groups, as the SD values for each group were generally higher. No significant difference was found when comparing the time intervals for expert and student users with each stethoscope (Littmann Classic: $p=0.115$; 3D-printed stethoscope: $p=0.216$), indicating that the duration of diagnostic

auscultation did not differ significantly among the studied user groups (expert group: 25 ± 10.41 sec vs. 25 ± 10.31 sec; p=0.460; medical student group: 29.5 ± 29.5 sec vs. 32 ± 18.36 sec; p=0.552).

Each auscultation experiment resulted in a correct or incorrect diagnosis based on predetermined criteria, enabling the measurement of diagnostic accuracy. Despite the small sample size, no data were lost during the diagnostic trials, as the controlled conditions and participant numbers enabled focused attention on task execution. Interestingly, using the 3D-printed stethoscope slightly improved diagnostic accuracy, although this difference was not statistically significant (correct/incorrect diagnosis ratio: Littmann Classic II: 14:11 vs. 3D-printed stethoscope: 18:7; $p = 0.248$).

We used a Likert-scale questionnaire to provide a subjective, multidimensional assessment of user experience following the auscultation experiments. Based on this, the overall evaluation of the 3D-printed stethoscope was significantly lower than that of the Littmann Classic II (Median ± SD: Littmann Classic II 4.3 ± 0.62 vs. 3D-printed stethoscope 3.5 ± 0.59; $p < 0.001$). According to user feedback, the plastic rigidity of the 3D-printed device did not affect usability any more than that of the original instrument. User assessments generally aligned with the overall results.

Discussion

Based on our results and a comparison with the existing literature, we expect 3D printing technologies to transform everyday life, including the healthcare sector. Numerous international studies have discussed how additive manufacturing can support prevention and diagnostics, and provide opportunities for innovative, customised dental and surgical interventions. Furthermore, they can provide solutions to resource shortages during disasters and wars, as well as to the challenges posed by expeditionary medicine. As 3D printers become more accessible, their use in everyday clinical care, emergency medicine and military medicine is becoming a realistic possibility. However, despite ongoing research and development in this field, the manufacture of handheld medical devices using these technologies remains limited. In our work, we have taken steps to address this issue and promote the adoption of this technology. The uniqueness and importance of our research is supported by the fact that devices manufactured using the continuous fibre reinforcement (CFR) process have not previously been developed for emergency or military medical purposes, nor have the fatigue properties of the raw materials used been considered.

In addition, our research group has produced the first practical dental forceps using a desktop 3D printer. Previous studies that informed our work suggested that fibre-based manufacturing technology (FFF/FDM) could be suitable for producing handheld medical devices. However, no detailed structural or mechanical characterisation has yet been performed. While polylactic acid has a wide range of practical applications, the Onyx carbon fibre composite material that we developed and tested does not exhibit classic fatigue properties, which could be advantageous in the context of 3D printing. Based on our findings, we concluded that continuous fibre reinforcement technology can produce stronger medical devices that are more resistant to mechanical forces, consistent with international experience.

In the case of the polylactic acid material, the fatigue curve obtained corresponded with those of previous studies in which the material was analysed in detail. This included investigating the effects of different layer thicknesses, printing speed and fill density on fatigue fracture. Torsion and bending measurements were also performed in these studies. Our assumption that Onyx carbon fibre-reinforced devices are more resistant than traditional polylactic acid devices was confirmed. While polylactic acid (PLA) deflects and deforms, flexural fatigue tests on Onyx carbon fibre composites showed that a deflection of 30 mm can be considered the limit value, as a significant decrease in tensile strength was measured above this value. The torsion fatigue test showed permanent deformation after 40° of rotation, presumably due to damage to the cohesion between the polymer matrix and the carbon fibre. However, the carbon fibres remained intact as the axial and radial resistance did not change up to 90° during the tests. The Shore D hardness values were consistent with those in previous studies.

Based on our results, we can conclude that continuous fibre reinforcement technology is a suitable raw material for medical devices that exert greater force, such as dental forceps, and surgical hooks. However, the flexibility of polylactic acid can be a disadvantage in instruments that require greater force. Therefore, based on our results, we do not consider polylactic acid-based instruments to be suitable for procedures such as tooth extraction, without reinforcement. Tooth extraction is a complex process involving gripping, twisting and pulling in order to expand the tooth socket and break the fibres of the periodontal ligament. This requires forceps with the appropriate geometry, whose ergonomic design enables them to moderate the force applied.

Based on the results of our mechanical and load tests, we used inverse engineering methods to design and 3D-print the first upper molar forceps from a continuous carbon fibre-reinforced material. These were then critically evaluated by dentists and compared to a

traditional metal version. Using a unique, full-size tooth model, we verified that the carbon fibre dental forceps can exert sufficient force to remove a tooth under clinical conditions. However, it is important to note that success in practice may depend largely on the anatomy and current health of the patient's teeth. While our results may seem limited, they are consistent with previous literature data measuring vertical tooth extraction forces on real patients. It can be concluded that forces below 100 N should be applied during tooth extraction to avoid bone damage, a finding supported by existing literature. Depending on the type of forceps, our results were below the expected value: the average was between 70 N and 84 N. Based on feedback from dentists, our device could be used in real clinical conditions with a few minor modifications. Based on their experience, further reductions in flexibility would be necessary, as would strengthening the jaws and increasing the ribbing of the internal profile. These modifications could be implemented using 3D technology, presenting a potential development opportunity for additive manufacturing in the medical device sector. In addition to the aforementioned areas, the main target groups for devices produced using additive manufacturing technology are those in specific locations or for specific tasks where a continuous supply of medical devices cannot be guaranteed, such as on medical humanitarian missions in developing countries, or space expeditions. Several recent studies have highlighted the potential of 3D printing as a solution in global crisis situations and pandemics, as well as in the creation of personal protective equipment. Our results demonstrate that medical devices produced using continuous fibre reinforcement technology can be used multiple times, with their mechanical properties ensuring good durability. Furthermore, these devices are lightweight and easily customisable and can be manufactured without any special infrastructure requirements. Our detailed mechanical characterisation revealed that it will be crucial in the future to investigate and adjust chemical, mechanical or thermal disinfection procedures for 3D-printed medical devices to ensure they do not cause permanent damage to the material properties of the devices. Additionally, a cost-effectiveness analysis may be necessary, since the device will only offer real advantage if its costs do not significantly exceed the cost of currently used devices. We intend to further develop our dental instruments in the near future based on suggestions from participating dentists, and we plan to conduct further studies to achieve more detailed characterisation and increased durability.

Our long-term goals include developing innovative solutions for use in expeditionary medicine. Participant evaluations and feedback are also important to us as they improve the adaptability and ease of use of our devices, building on the experience gained from testing mechanical properties. This paper discusses the suitability of 3D printing technology for

manufacturing emergency medical care devices in the event of a supply shortage, and the fact that the usability of these devices is independent of the experience of the practising physician. In the case of MAYO tubes and stethoscopes, no significant differences were observed in terms of insertion time or diagnostic accuracy. A satisfaction survey showed that participants preferred the devices with which they were familiar from their practical work but were also open to testing new devices.

One of the greatest advantages of the increased use of 3D-printed medical devices is that the infrastructure required for their production can be easily mobilised, making manufacturing more flexible from a logistical point of view. Using the ABCDE approach to examine patients allows for the localised, on-demand production of point-of-care diagnostic and therapeutic devices. For example, airway devices can be produced using mobile 3D printing on expedition missions, and mechanically pressure-operated infusion pumps can be printed in disaster-stricken areas. This could potentially minimise the logistical complexity and cost implications of the supply chain. For instance, rather than waiting for prefabricated oropharyngeal tubes, a supply team operating at a remote base could produce sterile, size-accurate devices directly on site. Similarly, in an earthquake-stricken area where hospitals have been destroyed, infusion pumps or even temporary bandages could be manufactured immediately. This decentralised manufacturing model can improve the efficiency of clinical decision-making in environments with limited resources. These devices can be produced using 3D printing technology to a nearly identical standard, albeit with certain compromises (e.g. the mechanical and technical properties discussed above). 3D-printed devices are among the most advanced in terms of manufacturing technology, and many of the raw materials used have special mechanical, structural or biological properties. Another major advantage is that composite materials can be used to achieve an even higher quality and special functions if necessary. Their engineering design allows them to be manufactured with greater accuracy and customisation.

In this study, we compared a high-quality Littmann Classic III stethoscope with a desktop 3D-printed stethoscope. The diagnostic examination took nearly the same amount of time for both devices. Surprisingly, there was no significant difference in diagnostic accuracy between the two devices; in fact, the 3D-printed device tended to show better accuracy. Despite the improving trend in diagnostic accuracy, satisfaction was significantly higher in both user groups in favour of traditional clinical devices. This may be due to aesthetic differences between 3D-printed devices and the fact that they often felt unfamiliar and uncomfortable to users. We obtained similar results for MAYO tubes. However, we found no significant

difference in correct positioning or procedure duration. The insertion and evaluation duration were independent of the manufacturing technology used (except for Flexible V2) and depended more on clinical experience.

It was observed that experienced caregivers had better manual dexterity and were more confident, even when using unfamiliar devices. In terms of user evaluation, the traditional device was considered to be the best, though both the TPU A95 and the FlexaBlack performed well. There was no difference between these two versions, while the Flexible V2 performed the worst. There was no significant difference in airway management. Based on user feedback, our 3D-printed devices are not currently suitable for everyday use. However, with further refinements and modifications, they could be used in practice in the future. Several participants rated the stethoscope among our desktop 3D-printed devices as uncomfortable compared to the Littmann Classic II, but found its performance to be equivalent, so its clinical use is also conceivable in the future. Overall, further comprehensive studies are needed to establish the use of 3D-printed devices in everyday practice, but they could provide a viable alternative in emergency situations. We plan to repeat the studies with more participants and develop and compare other similar devices with our research group.

3D-printed medical devices have significant potential due to their accessibility, versatility and customisability, which offer almost limitless possibilities in patient care. These characteristics mean they can be quickly adapted to almost any healthcare situation. The desktop 3D-printed stethoscope is as effective as traditional devices. As for the opinions of the study participants, they preferred the original instruments. With the exception of one (SLA), MAYO tubes manufactured using different 3D printing technologies (FFF, SLA and SLS) performed similarly well during simulated procedures. Notably, no other research group has previously manufactured devices suitable for simple airway management using additive manufacturing technology. During material testing, the devices also showed adequate resistance to the erosive forces that may occur during patient care. Based on our investigations, we concluded that stethoscopes and MAYO tubes can be successfully designed and manufactured using 3D technologies.

One of the strengths of the study is that we were among the first to test the devices in simulated conditions. The aim was not just to test the materials and assess ergonomics, but also to validate adaptability and usability in everyday prehospital and hospital practice. Furthermore, our work showed that composite materials can be suitable for instruments used in high-force procedures; for example, we demonstrated this with dental forceps. Based on the results, the practical usability of the tools we made was similar to that of the types used in the clinic.

However, they fell short in terms of ergonomics and user preference, areas which require further development. This is supported by the fact that they scored lower in the subjective evaluation than the instruments routinely used in the clinic. However, this subjectivity is irrelevant in an emergency situation.

Overall, we can conclude that the technological advances employed can greatly benefit the military and disaster medical supply chains, as well as the field of expeditionary medicine.

One limitation of our study was the impact of the ongoing global pandemic, which is the main reason for the low number of cases. The experiments and reviews were organised in accordance with the university's pandemic measures, the coordination of which required significant human, organisational and spatial resources. To minimise the risk of contamination for the study participants, the number of people who could be involved and the organisation of the schedule posed a serious challenge during the study period. The simulated environment and the relatively small number of participants meant that the study was not entirely accurate. The study did not evaluate the cost-effectiveness of 3D-printed devices.

List of Own Publications and Conference Participations:

Publications Serving as the Basis for the Thesis:

1. **Ferenc Molnar**, Matyas Rendeki, Szilard Rendeki, Balint Nagy, Viktor Bacher, Peter Bogar, Adam Schlegl, Arnold Koltai, Peter Maroti, Gergely Marovics; Validation of 3D printed MAYO tubes and stethoscope in simulated medical environment – Tools fabricated with additive manufacturing for emergency care. (**2023**) *Heliyon*, https://doi.org/10.1016/j.heliyon.2023.e20866.
2. Roland Told, Gyula Marada, Szilard Rendeki, Attila Pentek, Balint Nagy, **Ferenc Jozsef Molnar**, Peter Maroti; Manufacturing a First Upper Molar Dental Forceps Using Continuous Fiber Reinforcement (CFR) Additive Manufacturing Technology with Carbon-Reinforced Polyamide. **(2021)** *Polymers*, https://doi.org/10.3390/polym13162647

Publications not Serving as the Basis for the Thesis:

1. Miklós Siptár, Krisztina Tóth, Alexandra Csongor, Zsuzsanna Németh, **Ferenc Molnar**, György Tizedes, Zsombor Márton, Sándor Márton; Efficacy of laparoscopic sleeve gastrectomy on morbidly obese patients. **(2023)** *Orvosi Hetilap,* https://doi.org/10.1556/650.2023.32918.
2. Zsuzsanna Németh, Miklós Siptár, Natália Tóth, Krisztina Tóth, Csaba Csontos, Zoltán Kovács-Ábrahám, Alexandra Csongor, **Ferenc Molnar**, Zsombor Márton, Sándor Márton;

Indications for Sleeve Gastrectomy—Is It Worth Waiting for Comorbidities to Develop? (**2023**) *Medicina,* https://doi.org/10.3390/medicina59122092

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