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Review Article

Anaesthesia Section

A Narrative Review of 3D Printing Applications in Airway Management: Customised Solutions for Difficult Airways

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ABSTRACT

Difficulty in airway management continues to be one of the most significant problems of anaesthesia practice, where anatomical pathology or complexity may make traditional methods ineffective. Over the past decade, three-dimensional (3D) printing has emerged as a transformative technology, producing highly personalised solutions that bridge diagnostic imaging and therapeutic intervention. By converting patient-specific information into physical devices and models, 3D printing enables physicians to better understand individual airway anatomy, predict complications, and provide customised care. The uses of the technology are widespread in various fields, ranging from creating personalised airway stents, bioresorbable splints, and intubation devices to lifelike anatomical models for preoperative planning and procedural training. These innovations advance clinical outcomes and greatly enhance healthcare providers' preparedness and proficiency through experiential training. In preoperative planning, models printed with 3D printing have been found especially valuable in depicting complex reconstructions and practising high-stakes procedures, particularly in paediatric and oncologic patients. Though it has tremendous potential, widespread use of 3D printing in airway management is balanced by a few challenges, such as inconsistency in material properties, very high cost of production, limitations in sterilisation, and absence of regulatory standardisation. Improvements in bioprinting, artificial intelligence-based design, and integration with smart devices are progressively widening its clinical applicability and viability. This review aims to critically analyse the current applications and future prospects of three-dimensional printing in airway management. The present review consolidates current applications of 3D printing specifically in airway management, a niche yet critical area of anaesthesia.

Keywords: Additive manufacturing, Airway obstruction, Biocompatible materials, Intubation, Patient-specific modelling

INTRODUCTION

Successful airway management is an anaesthetic standard of practice, but is often complicated in patients with abnormal or complex airways. Craniofacial syndromes, neoplasia, trauma, and congenital anomalies make routine, uneventful airway management complicated by elevating the risk of difficult intubation and undesirable perioperative outcomes. Standard airway equipment and planning techniques are sometimes insufficient to manage the abnormal anatomic variants of such patients. Ever since the introduction of 3D printing technology, has emerged as a promising solution. By rendering Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) data into physical, patient-specific models, clinicians can model and visualise airway management techniques to a degree not previously achievable. This enables the creation of customised airway devices, stents, and splints using the specific anatomy of the individual patient to improve airway procedure safety and efficacy. A 3D printing has demonstrated in clinical settings that 3D-printed airway stents work. Patient-specific airway stents developed at the Cleveland Clinic, for example, have received approval by the US Food and Drug Administration (FDA) and are designed to replicate a patient's airway structure and minimise the complications of the traditional stents. Likewise, in tracheomalacia, external airway splints produced using bioabsorbable materials with 3D printing have been shown to maintain airway patency and allow primary growth, especially among children. Besides therapeutic use, 3D printing has been reported to be useful as a preoperative planning tool and an educational tool for medicine. The development of accurate anatomy models increases simulation of complex airway intervention, improving clinician readiness and patient outcomes [1-3].

This review article discusses 3D printing for airway management and its application to develop tailored solutions for difficult airways. The article outlines the technology background, clinical practice, benefits and limitations, and fields of future study on this novel approach and where it can revolutionise airway management guidelines.

LITERATURE REVIEW

Summary of key studies demonstrating the diverse applications of 3D printing in difficult airway management, ranging from preoperative planning and simulation training to personalised device creation is depicted in [Table/Fig-1] [1,2,4-7]. These studies highlight the growing clinical value of 3D printed airway models in enhancing anatomical understanding, improving communication, and reducing procedural risks.

Author names and year of study	Type of study	Intervention	Observations/Results
Iliff HA et al., 2023 [1]	Letter to the Editor	3D printing of airway models using PolyJet from CT imaging	Successfully produced scopeable, anatomically accurate models for endoscopic evaluation. Demonstrated potential to improve preoperative planning, equipment selection, and operator confidence.
Ormandy D et al., 2021 [2]	Descriptive Study	3D augmented reality with 3D printed airway models from CT scans	Enabled virtual airway navigation and fibreoptic simulation. Improved multidisciplinary communication and decision-making for complex intubations in head and neck cancer patients.
Ma L et al., 2023 [4]	Review Article	Artificial Intelligence (AI)-integrated 3D printing for organ model development and preoperative training	Highlighted AI's role in optimising image resolution, material selection, and print monitoring. Proposed AI as a key enabler of efficient, high-quality models for surgical skill development and patient understanding.

Segaran N et al., 2021 [5]	Review Article	Medical 3D printing for surgical preoperative planning	Identified limitations of 2D and basic 3D imaging. Emphasised the utility of 3D printed models in enhancing anatomical realism and simulation to better prepare surgeons for complex procedures.
Evans AZ et al., 2021 [6]	Case Series	3D printed anatomical models from CT data used in cardiothoracic, ENT, and general surgery	In a 9-patient series, models were reported to enhance anatomical understanding and surgical preparedness. Trainees benefited from simulation, and clinicians noted potential for reduced surgical time and complications.
Kamath AA et al., 2022 [7]	Experimental Study	Structured light scanning with iPhone X to create custom-fit 3D printed neonatal Continuous Positive Airway Pressure (CPAP) mask inserts	Structured light scanning was superior to other techniques for neonatal modeling. Customised inserts significantly reduced skin pressure and strap tension, suggesting improved fit and reduced risk of complications.

[Table/Fig-1]: Summary of studies demonstrating the use of 3D printing in difficult airway management across various clinical applications [1,2,4-7].

DISCUSSION

Overview of Airway Management Challenges

Airway management continues to be one of the most critical aspects of anaesthetic and emergency practice, especially in patients with difficult airways. A difficult airway is a clinical situation in which the skilled clinician is experiencing trouble with tracheal intubation and/or face mask ventilation. Difficult mask ventilation has been described at 1.4% to 7.5%, and difficult ventilation is about 0.15%. These situations are combined with the reality that anesthesiologists cannot always anticipate a challenging airway preoperatively, contributing significantly to the danger when an airway is being managed [8,9].

Airway assessment is a crucial component of preoperative and emergency airway management aimed at identifying potential difficulties before intervention. A comprehensive evaluation typically includes both clinical examination and predictive scoring systems. Common bedside assessments include the Mallampati classification, which evaluates the visibility of oropharyngeal structures; thyromental distance and sternomental distance measurements, which estimate mandibular space and neck extension; and mouth opening assessment to gauge access for intubation. Additional evaluations such as neck mobility, jaw protrusion, and the upper lip bite test help predict potential alignment or access challenges. Integrating these physical findings with patient history, such as prior difficult intubations, presence of obstructive sleep apnea, obesity, or cervical spine disorders, provides a more holistic risk profile. In recent years, ultrasound-based airway assessment has emerged as a non invasive and dynamic method to visualise airway anatomy, measure soft-tissue thickness, and identify anatomical variations that may complicate ventilation or intubation. A systematic and multimodal airway assessment approach enhances preparedness and informs appropriate device and technique selection, reducing the risk of airway-related complications [10,11].

Anatomic derangements such as neoplasms, facial trauma, craniofacial syndromes, or congenital malformations have been found to essentially alter the normal airway anatomy to an extent that impairs traditional airway equipment and techniques. Obstructive sleep apnea, obesity, and diminished cervical spine mobility are a few physiological conditions that further lessen the margin of safety of airway management. Non operating rooms or emergency environments offer situational challenges where compromised access to equipment, interruption of patient positioning, and speed demands can enhance the difficulty of airway intervention. The "Cannot Intubate, Cannot Oxygenate" (CICO) event is arguably the most dreaded complication [9,12].

Although rare, with an estimated range of putative prevalence of 0.003%, CICO has the potential to rapidly escalate to life-threatening complications like hypoxic brain injury or death if not immediately and effectively managed. Standardised airway assessment algorithms and equipment have been created to limit such danger. For instance, the American Society of Anaesthesiologists (ASA) gives guidelines that emphasise preoperative airway evaluation, availability of alternative devices, and stepwise management of the airway. While such guidelines exist, prediction and application are challenging, especially with tricky or complex situations [13,14].

This has increased interest in technology to facilitate increased patient-specific and precise airway management. Technologies like 3D printing and AI are becoming increasingly popular because of their ability to create patient-specific anatomical models on which clinicians can easily practice and plan interventions. These technologies have a promising future for managing difficult airways, hopefully optimising outcomes with enhanced preparation and personalisation [4].

Technological Backgrounds of 3D Printing

The use of 3D printing or additive manufacturing represents a new generation of fabrication techniques that build physical objects layer by layer from a Computer-aided Design (CAD) file. Unlike the conventional subtractive manufacturing process, where material is cut away or drilled out of a solid block, 3D printing builds an object from scratch with the ability to produce intricate and highly tailored geometries with minimal waste. It is increasingly applied across multiple industries, particularly medicine, where precision and patient-specific customisation are critical. The 3D printing process traditionally started with designing a virtual 3D model using CAD software. The model is then translated into a language that will be understood by the 3D printer, and is cut very thinly into horizontal layers by specialised software. Every slice instructs the printer to deposit material successively to create the physical object. The materials themselves are diverse, ranging from thermoplastics, photopolymer resins, and metals to bio-inks, depending on the particular technology and application [15-17].

Fused Deposition Modeling (FDM) is achieved by extruding molten thermoplastic material out of a hot nozzle and is prevalent due to its affordability and relatively low cost. Stereolithography (SLA) utilises the projection of a laser to fuse liquid resin, producing high-resolution prints with delicate details for models with minute details. Selective Laser Sintering (SLS) uses the laser principle to fuse powdered material and is primarily applied to rough and intricate parts that do not require support. Two other sophisticated techniques, Digital Light Processing (DLP) and Multi Jet Fusion (MJF), further enhance the scope of 3D printing with greater speed and accuracy [18].

Rapid prototyping becomes a reality, and the design-to-manufacturing cycle is significantly reduced. Its capability of delivering patient-specific models and devices benefits the medical sector in specific terms. Personalisation, cost benefits from low-series production, and less material usage are the primary advantages that make the technology more attractive in industries. Technology. Medicine has the potential to transform by 3D printing because it allows customised implants, prosthetics, surgical guides, and anatomical models for training and preoperative planning. As technology improves, use in clinical practice will increase, and procedural accuracy and patient outcomes will be enhanced [19,20].

Applications of 3D Printing in Airway Management

The most optimal use of 3D printing for airway management is airway splint and stent customisation. These are used primarily in patients with severe airway disease, including tracheobronchomalacia. Bioresorbable 3D-printed airway splints are used to rigidify the airways of infants with severe forms of the disease. These splints are molded to the patient's anatomy. They are made to eventually biodegrade, thereby obviating the need for surgical removal of splints and adaptive remodeling to accommodate growing paediatric patients [21,22].

Recent advancements have enabled 3D-printed custom stents beyond traditional tracheal stenosis or malacia. Krumm IR and Gesthalter YB demonstrated their successful application in rare, non malignant conditions such as extrinsic vascular compression and bronchopleural fistula, highlighting the versatility and precision of custom-designed stents in maintaining airway patency and managing complex anatomical challenges [23]. Alraiyes AH et al., emphasised the potential of 3D printing in overcoming the common limitations of factory-made stents, particularly the mismatch between stent and airway anatomy. Patient-specific 3D printed stents allow for more accurate sizing, reducing migration, erosion, or granulation tissue formation risks by minimising high-pressure contact points in deformed airways [24].

Through 3D printing of airway models, preoperative planning enables clinicians to visualise and rehearse complex interventions before working on patients. It is instrumental in a case of anatomical abnormality or tumour leading to shifting airway anatomy, when traditional imaging is often insufficient. By being trained on authentic replicas of a patient's airway, surgical teams can plan the best plan, decreasing operation time and enhancing outcomes. Medical simulation education and training have also been transformed using 3D printing technology. Anatomically accurate airway models are valuable training devices for gaining and developing airway manipulation skills such as intubation and tracheostomy. They facilitate realistic simulation-based training, increasing medical student and physician training without jeopardising the simulation over actual patients. In addition, 3D printing allows personalised-fit medical devices to be produced, including oropharyngeal airways and continuous positive airway pressure masks. Physicians can enhance comfort, effectiveness, and treatment protocol compliance by custom-producing the devices based on patients' unique anatomical features [5,7,25].

Personalised Airway Devices and Models

The 3D printing technology transformed airway management to create customised airway devices and anatomic models tailored to a patient's unique anatomy. Personalisation optimises the efficacy of intervention, especially in complex cases where traditional devices will be inadequate. Apart from stents, anatomically correct airway models are possible through 3D printing. They are most helpful in planning operations and simulation training. Physicians may utilise the replicas to rehearse intricate procedures, thereby being better equipped and possibly yielding better patient outcomes. With the help of 3D printing technology, physicians can print oral airways that are custom-made and printed according to a patient's anatomy to ensure successful intubation while minimising the risk of airway trauma [26-28].

Utilising 3D printing technology in airway management aligns with the trend toward more personalised medicine, where interventions are performed on a patient-specific basis to deal with a patient's unique anatomical and physiological features. With advancing technology, it is equally possible to improve airway management effectiveness and safety [29].

Preoperative Simulation and Planning

The 3D printing is now a cutting-edge technology for airway management. It proposes translating patient-specific imaging data into actual objects, allowing healthcare providers to make informed decisions on complex airway anatomies, resulting in more accurate surgical planning and better patient outcomes. In paediatric otolaryngology, 3D-printed life-size airway models have proved priceless in preoperative planning of highly complex procedures, such as cricotracheal resection and laryngotracheal reconstruction. The model can be used to estimate critical parameters, like lengths of stenotic segments, best locations for incision, and single- vs. double-stage requirements, thereby facilitating optimisation of the surgical plan and possibly reducing operating time [30,31].

Beyond preoperative planning, 3D-printed airway models are more fidelity simulants for operating and anesthesiology personnel. They permit simulation of airway management methods such as intubation and tracheostomy in a simulated environment. This simulation is beneficial in expected difficult airways, where traditional imaging would be too low resolution. Simulation training with anatomically correct replicas enables the clinician to predict challenges better and refine the technique to deliver higher levels of safety to patients. Individualisation of airway devices also comes preoperatively through the application of 3D printing. Preoperative simulation and planning with 3D printing is a worthwhile advance in airway management. Using real anatomical data and the capacity for tailoring surgery and devices, 3D printing makes airway procedures more precise and safe and ultimately results in better patient outcomes [32,33].

Limitations and Challenges

While 3D printing has brought significant advancements in airway management, some inherent limitations and challenges need to be overcome in adopting the technology in a systematic way in clinical practice. One of the major challenges is process variability in 3D printing. Process variability in the printing process, material, and post-processing can result in product variability in the mechanical properties and biocompatibility. This heterogeneity precludes the attainment of tight regulatory targets and guarantees homogeneous quality assurance for medical devices. Inability to have a single, universally applicable design method and validation process for customised 3D printed airway stents, for example, precludes them from being easily certified and embraced significantly [22,34].

Sterilisation of 3D-printed products is also an extensive issue. Conventional sterilisation methods, including autoclaving, utilise high temperatures that warp or degrade certain 3D printing materials, weakening medical devices' structural integrity and safety. Cold sterilisation is generally ineffective and not an option in resource-poor environments [35].

Clinically, 3D-printed airway models cannot match human tissue's dynamic physiological behavior, such as bleeding, elasticity of tissue, and immediate feedback during a procedure. This can decrease the realism and effectiveness of simulation-based training, affecting the practice of health professionals' readiness. Moreover, creating 3D-printed airway devices customised for patients is time-consuming and costly. The process takes high-resolution imaging information, proper design, and proper fabrication, all of which require resources and human beings. Such constraints can make the products produced using 3D printing scarce and scalable, especially for emergent therapy where seconds matter most [36].

Regulatory and ethical aspects are also important considerations in the adoption of emerging technologies for airway management. Regulatory frameworks ensure that innovations such as artificial intelligence systems and 3D-printed airway models meet safety, accuracy, and efficacy standards before being introduced into clinical practice. Ethical principles emphasise patient safety, informed consent, and the protection of personal data, particularly when patient-specific anatomical information is used for modeling or treatment planning. Clinicians must also maintain professional competence when using these technologies and ensure that their application supports, rather than replaces, sound clinical judgment. Attention to these regulatory and ethical dimensions helps promote responsible and safe integration of technology into airway management [29,34].

The long-term biocompatibility and stent durability of 3D-printed airway stents are also parameters that need to be explored. Migration issues of the device, mucosal inflammation, and potential for airway obstruction require that stringent preclinical and clinical trials be performed before such a device is safe for use in routine clinical practice. In general, 3D printing has vast potential to enhance airway management. Still, resolution of these challenges will be paramount if this technology is safely, effectively, and equitably delivered in the clinic [37].

Future Trends and Breakthroughs

The 3D printing technology is developing at a rapid pace, with further transformation of airway management in the years to come, with new uses and greater personalisation. Advances in material science, printing technologies, and computer simulations are shaping tomorrow into a next-generation airway device that is more patient-specific, functional, and biocompatible [38].

One of the biggest frontiers of the future is intelligent airway stents with sensing and drug delivery capabilities. Integrated electronics in 3D-printed scaffolds will allow doctors to monitor real-time airway patency, sense early warning of obstruction or inflammation, and deliver localised therapy within the airway itself. These "smart" implants will enhance patient safety and therapy performance relative to current devices [39].

One of the most promising technologies is bioprinting, which is the construction of living tissue from bioinks that are a mixture of cells and biomaterials. Bioprinting potentially would enable the production of functional airway tissue constructs for transplant or reconstructive surgery, augment therapy for severe airway defects, and reduce the reliance on donor tissue. Although an early experimental technology, bioprinting holds great promise for individualised regenerative airway therapies [40].

Integrating machine learning and AI with 3D printing technology is set to revolutionise the design and optimisation of airway devices. By leveraging vast imaging data, AI algorithms can automatically generate highly accurate models and predict device performance, significantly reducing production time while enhancing customisation precision. This synergy enables personalised treatment planning and minimises the risk of human error, paving the way for safer, more effective airway management solutions [41].

CONCLUSION(S)

The future of 3D printing in airway management offers significant personalisation, improved functionality, and integration with emerging technologies such as artificial intelligence. It enables creating patient-specific models and devices, improving clinical accuracy, speeding up preoperative planning, and enhancing surgical outcomes. Its uses include custom airway stents, anatomical models, and simulation-based training for complex airway scenarios. While there are still challenges with materials, sterility, cost, and regulatory requirements, these limitations continue to be addressed through ongoing research. With continued innovation and collaboration, 3D printing is set to transform airway care and significantly improve patient outcomes.

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