EJAIC

Eur J Anaesthesiol Intensive Care Med 2022; **2:**1(e0015)

OPEN

ORIGINAL ARTICLE

Novel co-axial, disposable, low-cost 3D printed videolaryngoscopes for patients with COVID-19: a manikin study

Laura Gorman, Andrew N. Dickson, Myles Monaghan, Frank Vaughan, Brian Murphy, Denis P. Dowling, Conan McCaul and James F.X. Jones

BACKGROUND COVID-19 continues to present challenges to both patient management and the protection of the airway management team involved, in particular in resource-constrained low-income countries. Among the most concerning complications in affected patients is rapid hypoxemic respiratory failure requiring tracheal intubation and mechanical ventilation. Videolaryngoscopy without peri-intubation oxygenation is the recommended approach in COVID-19 patients. However, the absence of peri-intubation oxygenation during intubation attempts can lead to hypoxia, and result in life-threatening complications in already critically ill patients.

OBJECTIVE To develop low-cost disposable 3D printed videolaryngoscope designs with integrated channels for oxygen, suction, WIFI-enabled camera and tracheal tube channels, as well as a flexible transparent barrier anchor to offer optional additional protection to the user and airway management team.

DESIGN A manikin study.

SETTING AND PARTICIPANTS Three experienced consultant anaesthetists in the Mater Misericordiae University Hospital, Dublin, Ireland.

MAIN OUTCOME MEASURES To generate novel co-axial videolaryngoscopes that meet International Standards, ISO7376 : 2020 standards for anaesthetic and respiratory equipment (laryngoscopes for tracheal intubation), and to demonstrate successful tracheal intubation of a manikin trainer in a range of configurations ('easy' to 'difficult') in accordance with the Cormack-Lehane grading of laryngeal view.

RESULTS Final design prototypes met the minimum criteria for strength and rigidity according to ISO7376 : 2020, including blade tip displacement under load (65 N and 150 N). Preliminary validation has demonstrated successful tracheal intubation of a manikin trainer in all configurations including 'difficult' (Cormack-Lehane Grade 3 view).

CONCLUSIONS This low-cost, rapid in-house manufacture could offer a mitigation of supply chain disruptions that can arise during global pandemics. Furthermore, it could offer a low-cost solution in low-income countries where there is an infection risk caused by re-using most current videolaryngoscopes requiring sterilisation before re-use, as well as limitations in the availability of personal protective equipment.

Published online 19 December 2022

KEY POINTS

- The COVID-19 pandemic has highlighted the need for low-cost, rapid in-house solutions such as 3D printing to maintain patient airway management in under-resourced hospitals burdened with supply change disruptions.
- Current guidelines recommend the use of videolaryngoscopy without peri-intubation oxygenation, which risks hypoxaemic respiratory failure.
- No single device currently exists to enable both videolaryngoscopy and peri-intubation oxygenation to support best patient outcome.
- Novel 3D printed co-axial videolaryngoscopes offer a solution towards enabling oxygenation, suction

From the School of Medicine, University College Dublin (LG), I-Form Advanced Manufacturing Research Centre, University College Dublin (AND), Our Lady of Lourdes Hospital, Drogheda, Ireland (MM), I-Form Advanced Manufacturing Research Centre, University College Dublin (FV), The Adelaide and Meath Hospital Dublin, Incorporating the National Children's Hospital (AMNCH) & Rotunda Hospital (BM), I-Form Advanced Manufacturing Research Centre, University College Dublin (DPD), Rotunda Hospital Dublin & Mater Misericordiae University Hospital Dublin (CM), and School of Medicine, University College Dublin, Dublin, Ireland (JFXJ)

Correspondence to Laura Gorman, C335 Health Sciences Building, University College Dublin, Dublin, D04 C7X2, Ireland.
E-mail: laura.gorman@ucdconnect.ie

DOI:10.1097/EA9.0000000000000015

and visualisation of the affected patient airway, while creating additional distance between the airway management team and the patient and the scope for a physical barrier attachment where appropriate.
- Mechanical testing to current ISO guidelines and manikin testing have demonstrated the feasibility of use of these novel, co-axial videolaryngoscopes as both robust and applicable in a variety of configurations according to the Cormack-Lehane grading for laryngoscopic view.

Introduction

Patients who develop respiratory failure due to COVID-19 frequently require tracheal intubation and mechanical ventilation of their lungs. There is conflicting evidence the placement of a tracheal tube during intubation is a risk factor for increasing exposure to aerosolised virus;[1–4] however, it has recently been shown that high-flow nasal oxygenation, which is used concomitantly during laryngoscopy (peri-intubation oxygenation), can significantly increase the risk of aerosolised virus, and this continues to be an area of active research.[2,5–8] Although the national and international guidelines on what constitutes an aerosol-generating exposure (AGE) seem to be constantly shifting,[9] tracheal intubation is still considered to be an event for which there is strong evidence of association with infection.[10–12] To reduce operator risk, videolaryngoscopy is the recommended technique for tracheal intubation,[5] as this facilitates greater distancing from the patient airway, which is not possible with direct laryngoscopy. These devices are relatively costly compared with conventional direct laryngoscopes, and consequently unaffordable in many countries. Although there are a variety of commercial videolaryngoscopes available, and some recently published 3D printed videolaryngoscopes, none offer an all-in-one solution dedicated to maintaining oxygenation, providing suction to the mucus-obstructed airway, and limiting the risk of exposure to aerosolised viral particles.[13–17] Thus, operators continue to be exposed to a virus during a patient's active or passive exhalation, and the COVID-19 patient is also at a greater risk because oxygen delivery must be suspended during tracheal intubation. Moreover, most videolaryngoscopes are not disposable, and as the virus exhibits prolonged survival on metal and plastic surfaces, these instruments can act as fomites.[18–20] At present, plastic sheeting and aerosol containment boxes are being used to minimise escape of secretions during the later stages of airway management.[21–23] As an action to mitigate current and future pandemics, it is prudent to refine medical equipment to address the exigencies of infectious disease.

In response to this, the authors have developed a selection of low-cost, disposable, 3D printed videolaryngoscopes customised for the COVID-19 pandemic. The aim of this project was to design and print mechanically robust multi-channelled novel laryngoscopes suitable for use in patients with respiratory infectious diseases and amenable to healthcare settings in low-income countries. Three-dimensional printing offers a viable, customisable and more easily accessible approach to the generation of medical devices and instruments[14,24–26] in times of demand and supply chain disruption. Our devices incorporate novel features, which are designed to keep the patient well oxygenated via in-built channels for separate oxygen delivery and suction to clear secretions, as well as offering additional protection to the user when coupled with the recommended personal protective equipment by way of an anchor to support a flexible barrier attachment. The introduction of internalised channels is feasible and, in the case of suction, has been previously demonstrated for videolaryngoscope devices. The Inscope® was the first disposable scope with in-built suction.[27] However, this instrument lacks other useful features specific to COVID-19 as described above. Consideration was also given to ergonomics, as tracheal intubation success rates have been correlated with the use of an ergonomic handle.[28]

Materials and methods

Study dates

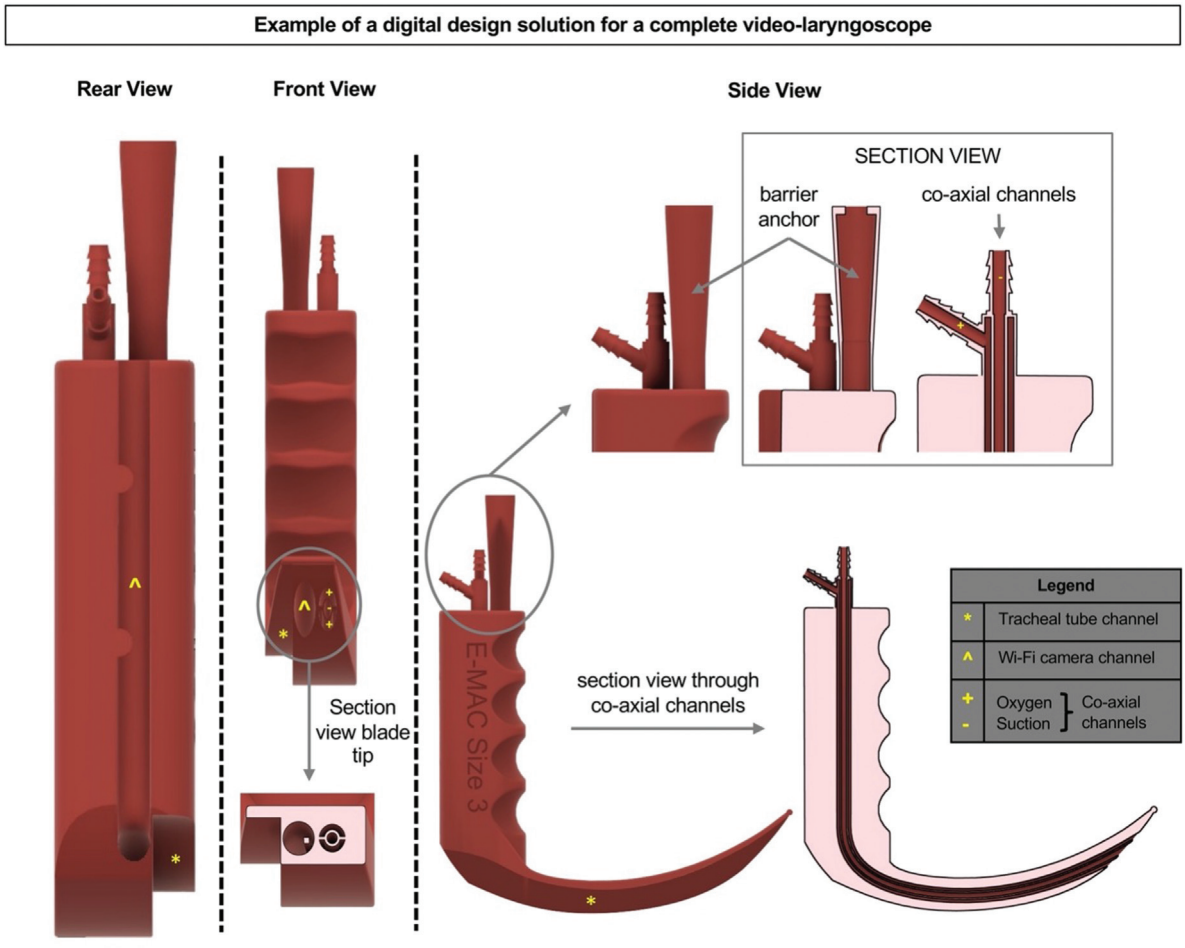
Work pertaining to the development of this project was carried out, from conceptualisation to manikin testing, between August 2020 and July 2021.

Device design

Laryngoscopes were designed using Autodesk® Fusion 360™ (Education License). The software allows for the generation of a design flow based on dimensioned sketches using a variety of techniques such as solid, freeform and mesh modelling, which can be parameterised to create a 3D model, the shape of which can be modified by iterations to its proportions or curvature without the need to reconstruct the model each time. The package contains a simulation workflow, which allows the designer to then verify and virtually test the integrity of the model according to known standards before prototype production and physical testing begins; particularly useful when design iterations occur throughout the design phase. Fusion 360 also creates instructional toolpaths and a means to connect directly to a 3D printer. However, the authors chose to use a separate open-source 3D slicer called Ultimaker Cura (version 4.10.0) to take advantage of additional model refinement capabilities such as infill type and support structures.

Two designs were developed in parallel. The first was based on a standard direct unchanneled English-type Macintosh laryngoscope blade modelled on the Timesco Europa (Timesco Healthcare Ltd., Essex SS14 3WN, UK) blade (sizes 3 and 4). The other was based on a channelled adult videolaryngoscope design, similar to the

Fig. 1 Rear, front (blade tip) and side views of a digital video-laryngoscope design inspired by the English-type Macintosh, E-MAC (size 3) in Fusion 360™. REAR VIEW; rear routed WIFI camera cable channel^ and tracheal tube guide*. FRONT VIEW: blade tip featuring (from left to right) a tracheal tube guide*, WIFI camera channel^ with a flexible clip to pin the camera in place once inserted and a co-axial oxygen+ and suction- channel. SIDE VIEW: magnified view of the co-axial oxygen+ and suction- channel ports and an anchor point for an optional barrier envelope (push down to fit).



AirTraq SP Regular (Prodol Meditec S.A., Spain). An English-type Macintosh blade was chosen, as it performed best in standard and unpredicted difficult tracheal intubation scenarios.[29–31] Timesco Europa blade sizes 3 and 4 were chosen as template sizes, as these blades are generalisable across the adult patient population (designated for medium and large adults) and the blades favoured in Irish clinical settings at the time of writing. A channelled blade design was also chosen based on its performance and utility in a difficult airway scenario, for example cervical spine injury and limited mouth opening.[32,33]

To recreate the general shape of the chosen instruments in Fusion 360™, images were captured and imported into the software workspace as a *canvas* or template. Using the *sketch* design functions, an outline was created to overlay the images, which were then refined according to physical measurements taken using a digital callipers, protractor and ruler, and given volume. Once the framework of the digital videolaryngoscopes was established within the workspace, a tracheal tube guide for the unchanneled **E**nglish **Mac**intosh-inspired videolaryngoscope (dubbed **E-MAC**) was created by trimming a section of the blade using the *sketch*, *extrude* and *cut* function. A tracheal tube guide for the channelled, hyper-angulated **a**dult **v**ideo**l**aryngoscope (dubbed **AVL**) was designed using the *line* and *fit point spline* functions to follow the straight and curved geometry of the blade. Using the *pipe* function to add volume to the sketch and subsequently the *combine* and *cut* functions, a Boolean subtraction of the mesh was achieved to create a space to accommodate a tracheal tube. A central camera channel was designed into each videolaryngoscope using the same principles as per the AVL tracheal tube guide.

A co-axial tube with two separate channels and two separate openings was then designed with separate connectivity to both oxygen and suction ports (Fig. 1). The

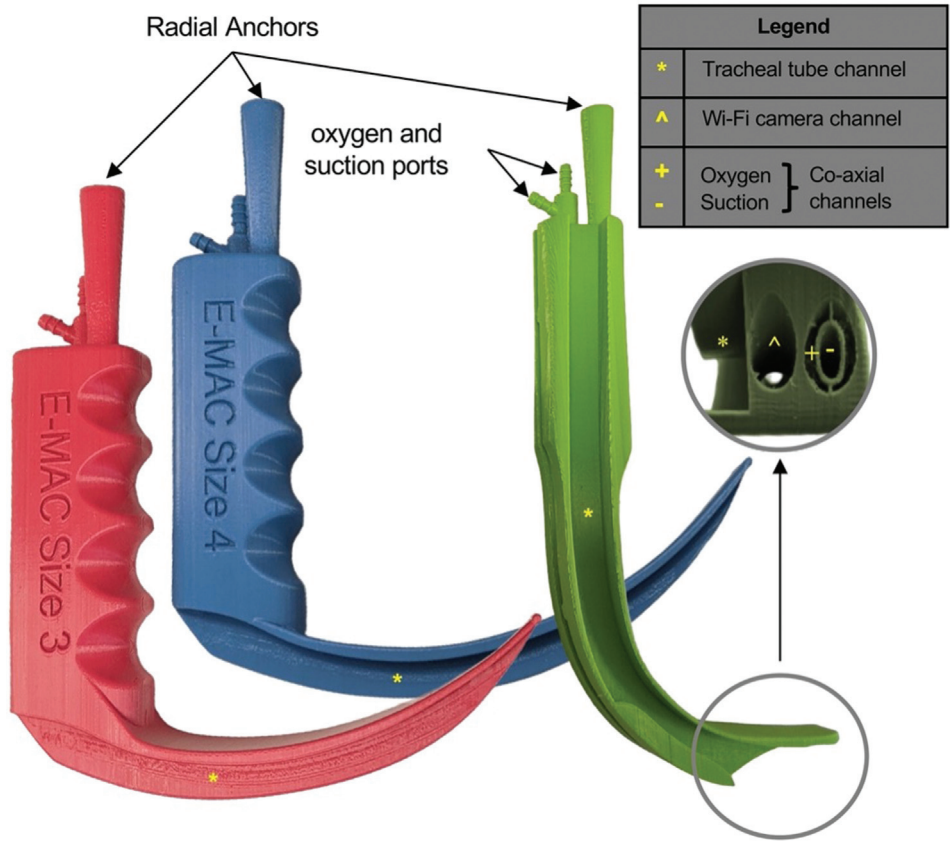
line and *fit point spline* functions were utilised to follow the straight and curved geometry of the blade. The *pipe* function was used while selecting *hollow* and *section thickness* measurements. This achieved a hollow channel with a defined thickness, into which was designed a smaller hollow channel using the same software functions. The smaller diameter channel (inner channel) was connected and stabilised within the larger (outer) channel through radial anchors positioned between the inner wall of the outer channel and the outer wall of the inner channel. To create a functional 'double-lumen' (co-axial) system, a barbed luer fitting, to accommodate hospital tubing, was imported from the McMaster-Carr component library within Fusion 360™ and attached to the superior aspect of the enclosed (inner) channel, and another at an angle to the posterior aspect of the outer wall of the outer channel. This resulted in two fully independent channels occupying minimal volume, with access ports located on the superior aspect of the handle in each case, thus enabling connectivity to standard flexible tubing. Additional refinements of the designs were made using the *fillet* function to create more rounded edges, thus avoiding damage to tissues and increasing comfort during use. A partial enclosure was added to the AVL design at the tip of the blade to prevent lateral deviation of the tracheal tube during intubation prior to testing.

To further adapt the above designs, a low-cost WIFI-enabled endoscopic camera/light source (3.9 mm lens diameter) was purchased (https://www.lightinthebox.com) to use with both videolaryngoscope designs at a cost of €39·48. This WIFI-enabled endoscopic camera/light source is capable of remote connection to a mobile phone interface. To assist further restriction of particle aerosolisation, a detachable transparent sheet was anchored in a push-fit manner via a captive fastener designed into the handle, thus partitioning patient from intubating team. Finger grips were incorporated into the E-MAC designs to improve overall comfort and control (Fig. 2).

In-silico finite element analysis

In-silico analysis was performed on the preliminary designs to identify areas of stress concentration, or structural weakness. The Static Stress Simulation

Fig. 2 Final printed designs featuring ergonomic grip (E-MAC sizes 3 and 4), tracheal tube channel*, central WIFI camera channel^ to accommodate a maximum 3.9 mm lens diameter and co-axial tube enabling separate suction- and oxygen+ delivery. The AVL (in green) features a tracheal tube channel* measuring 13.5 mm in width and accommodates a tracheal tube size up to 7.0 mm internal diameter. Circled is a magnified view of the channel openings at the distal (blade tip) end of the AVL.



workflow in Fusion 360™ was utilised to model the linear response to a single load case when applied to a fixed point (the centre of the superior aspect of the blade tip), using the laryngoscope handle as a constraint (Fig. 3). Three materials were chosen for in-silico analysis. These were acrylonitrile butadiene styrene (ABS), a material known for its high flexural strength and elongation before breaking; antimicrobial polylactic acid (PLACTIVE AN[1], www.copper3d.com), a biomaterial used frequently in medical implants and cheaply sourced (€70–€100 per kg); and Nylon 6 (ONYX™, Markforged, Massachusetts, USA), a nylon and carbon-fibre polymer mix purported to have high strength, and dimensional accuracy (€200–€220 per 800 cm^3). Data pertaining to ABS and ONYX material mechanical properties were sourced from Fusion 360™ materials index, while properties for PLACTIVE AN[1] were acquired from the manufacturer's website and incorporated into the Fusion 360™ materials index.

To avoid the risk of cross-contamination in the event of limited or absent sterile processing capabilities, our 3D printed videolaryngoscopes are intended as single-use devices. Notwithstanding this ideal, it is possible to sterilise ABS, PLA and Nylon 6, albeit not by a conventional steam sterilisation method. PLACTIVE AN[1] and ABS have a glass transition temperature between 55°C–60°C and 90°C–102°C, respectively, while ONYX™ is 145°C, according to manufacturers' specifications. Consequently, the risk of deformation would be too high at standard steam sterilisation temperatures of 134°C, less so for ONYX™. Sterilisation with hydrogen peroxide gas plasma and gamma radiation[34,35] is considered suitable for these materials, which however, are cost and resource-intensive modalities.

Printing of videolaryngoscopes

On the basis of the results of the in-silico testing, two materials were chosen for fabricating the first prototype laryngoscopes, PLACTIVE AN[1] and ONYX™. Mechanical properties of both materials are summarised in Table 1 and printing parameters in Appendix 1, http://links.lww.com/EJAIC/A4.

Fig. 3 Finite element analysis (FEA) of each laryngoscope blade – English-type Macintosh (E-MAC) and channelled adult videolaryngoscope (AVL) incorporating internal oxygen, suction and camera channels – to assess structural performance under a static 150 N load.

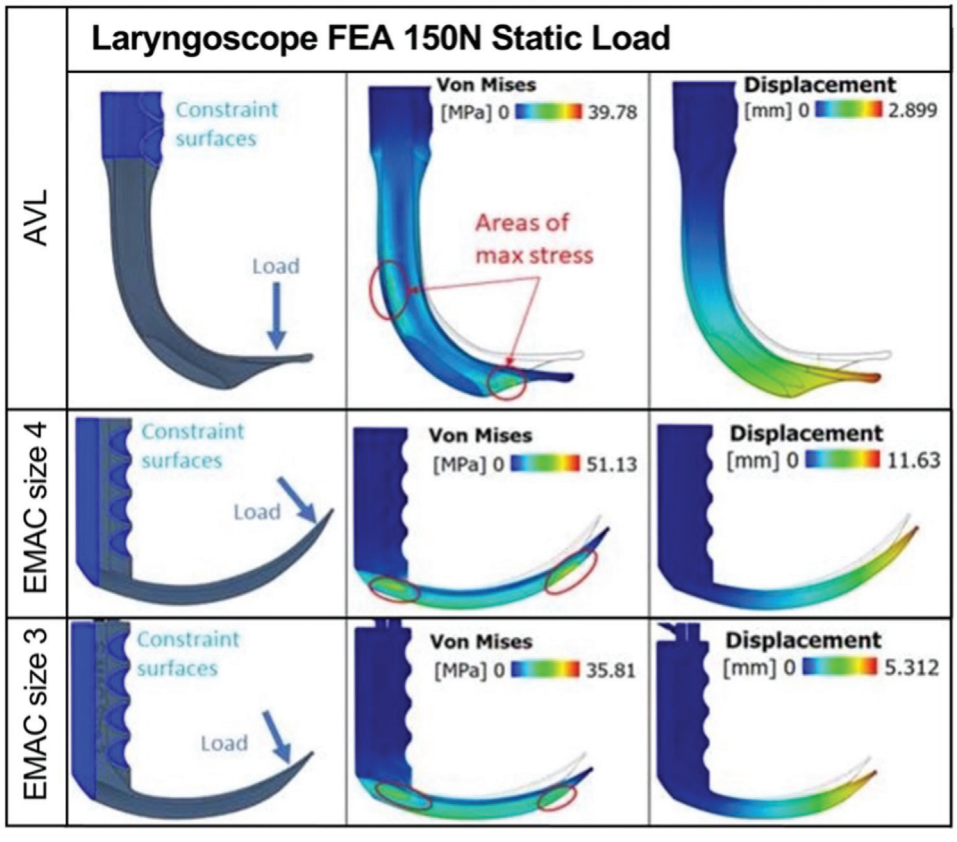


Table 1 Material Properties of PLA, Nylon/CF and ABS Filaments

Material properties Material	Tensile strength (MPa)	Youngs modulus (MPa)	Tensile yield (%)	Flexural strength (MPa)	Flexural modulus (MPa)
PLA (PLACTIVE AN[1])	60	3600	6	83	3800
Nylon/CF (ONYX™)	36	1400	58	81	2900
ABS	30	2240	7	70	2000

Materials data for PLACTIVE AN[1], ONYX™ and ABS materials. Data sourced from www.copper3D.com, www.markforged.com (materials manufacturer) and Autodesk materials index, respectively.

Mechanical testing setup (ISO7376:2020)

The videolaryngoscopes were tested for conformity to International Standards, ISO7376 : 2020: Laryngoscopes for tracheal intubation. With reference to ISO7376 : 2020 sections 7.2.2 (Rigidity) and 7.2.3 (Strength), the test laryngoscopes were subjected to a load of 65 N to calculate stiffness, and to a load of 150 N to test for mechanical failure. A fixation device was designed and fabricated from high tensile steel for mounting the scopes at various angles (Fig. 4). Details on the mounting of samples to this device can be found in Appendix 2, http://links.lww.com/EJAIC/A5.

A WIFI endoscopic camera with light source was inserted into a central internal channel in the scope and secured in place near the tip of the blade. To measure the displacement of the blade tip under loading conditions, the camera was aimed towards a calibrated grid mounted on an aluminium plate, and a 65 N tensile force was applied to the tip of laryngoscope blade. Movement of the camera/light source under loaded conditions was tracked and the extent of displacement of the spot of light during loading measured. The deformation of the blade tip under load was also plotted. A larger load of 150 N was then applied at a rate of 2 mm min^{-1} to assess blade or handle deformation and test for failure.

Manikin testing of 3D printed videolaryngoscopes

Preliminary testing was carried out by three consultant anaesthetists (experience ranging from 7 to 28 years) on a manikin (AirSim Advance X; TruCorp, Lurgan, N. Ireland) in varying levels of difficulty (Fig. 5). The glottic view obtained was documented using the Cormack-Lehane classification for laryngoscopic view. A 'difficult airway' was created by hyper-flexing the neck of the manikin and assessed via a conventional direct laryngoscope. Tracheal intubation of the manikin was performed first without, then with the protective barrier in place. Tracheal intubation was deemed successful with visual confirmation of the tracheal tube passing through the glottic aperture.

Results

Finite element analysis

Results from in-silico finite element analysis (FEA) showed that ABS was unsuitable for building our videolaryngoscopes due to its lower strength and stiffness (mechanical properties for this material are summarised

Fig. 4 Test setup schematic (left) and final laboratory setup (right). Each video laryngoscope was secured to the test instrument (Lloyd LR30K Plus Materials Testing Machine) via a steel mounting pin, and rotational movement prevented via a steel pin.

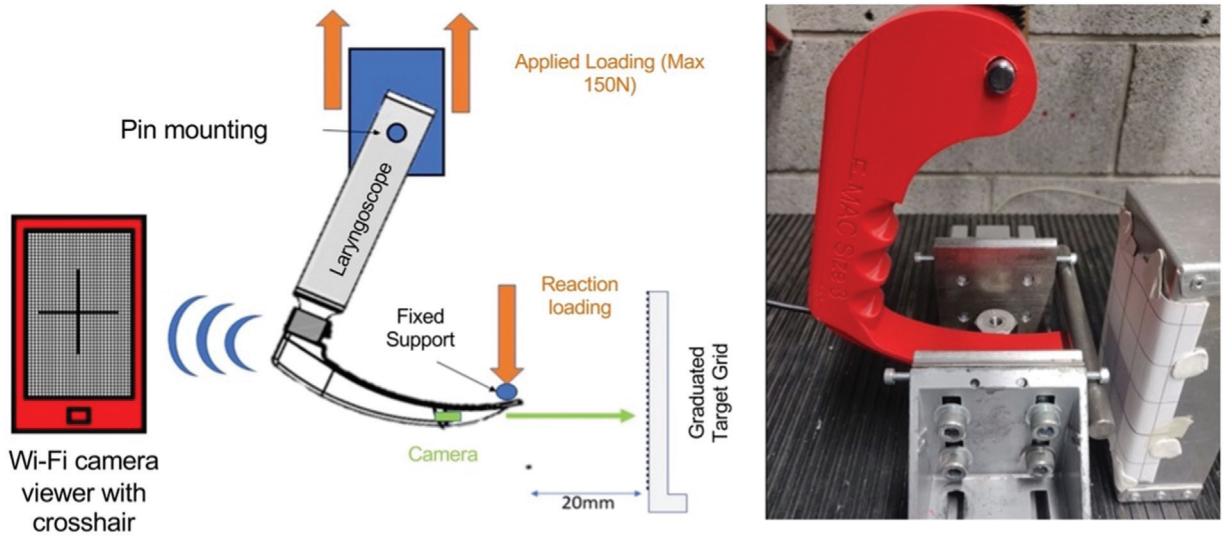


Fig. 5 (a) Intubation and visualisation of the vocal cords of a manikin using the E-MAC size 4 and a WIFI camera connected to the operator's mobile phone. (b) An example of the AVL in use without the optional protective barrier sheet in place. (c) Intubation of a manikin with the protective barrier sheet attached to the barrier anchor point built into the videolaryngoscope handle. (d) View of the passage of a size 6.0 mm tracheal tube beyond the vocal cords during manikin testing with a protective barrier sheet in place.

in Table 1). Under a load of 150 N, ONYX™ and PLACTIVE AN[1] exhibited tip displacements of 8 and 10 mm and a minimum safety factor of 2.2, and 1.6, respectively. Under the same load, ABS exhibited tip displacement of 10.5 mm (a maximum displacement of 10 mm is allowed at 65 N), however, a safety factor of 0.395 was recorded, suggesting some form of permanent deformation [max stress (von Mises) of 50.7 MPa]. The safety factor measures the material strength relative to the maximum stress of the test item when load is applied. When stress becomes superior to the overall strength of the material at a particular location as measured, the safety factor drops below one, which is indicative of failure.

Mechanical testing results

The prototype videolaryngoscopes were ultimately printed in PLACTIVE AN[1], and ONYX™ materials, which were chosen based upon their performance in FEA, their biocompatibility, cost, ease of printing and market availability. According to ISO7376 : 2020, there are two conditions that must be passed to certify that the laryngoscope is suitable for use. First, the laryngoscope must withstand a 65 N force whilst retaining the camera/illumination within 10 mm of its unloaded position. All prototype videolaryngoscopes passed these criteria (Appendix 2, http://links.lww.com/EJAIC/A5).

The second stage of testing involved application of a larger 150 N load to the blade to test for mechanical failure (Appendix 2, http://links.lww.com/EJAIC/A5). All prototypes reached 150 N with no visible damage occurring.

Manikin testing of 3D printed videolaryngoscopes

All three videolaryngoscope blade configurations were successful in intubating an anatomic manikin in both 'easy' (Cormack-Lehane Grade 1) and 'difficult' (Cormack-Lehane Grade 3) configurations. Success in this instance was defined by visualisation of the vocal cords and passing of an endotracheal tube via the glottic opening within three attempts of intubation, in all configurations, by three experienced consultant anaesthetists. Time to completion was not recorded in this instance. Tracheal intubation was also performed successfully with the assistance of a Frova intubation catheter. Laboratory testing of the co-axial lumen for oxygen, and suction using a basic anaesthetic machine produced flow rates of 12 l min^{-1} in both channels. Calculations were performed to determine a maximum deliverable volume flow rate for oxygen of 8.9 l min^{-1} (AVL), and 5.7 l min^{-1} (E-MAC both sizes) is achievable (Appendix 3, http://links.lww.com/EJAIC/A6). A method of containment of aerosolised particles was accomplished through the integration of an anchor point to secure a detachable transparent sheet, reducing aerosolisation by 75 and 66%, respectively, in the E-MAC and AVL designs (Appendix 4, http://links.lww.com/EJAIC/A7).

Discussion

We describe two novel, low-cost disposable 3D printed videolaryngoscope designs with integrated channels for oxygen, suction, WIFI-enabled camera and tracheal tube. On the basis of materials testing and in accordance with ISO7376 : 2020, PLACTIVE AN[1], an antimicrobial PLA material, performed the best and was selected for final design production. Resulting 3D printed videolaryngoscopes were subject to manikin testing by three trained consultant anaesthetists with 7–28 years' experience in the area of anaesthesia. Our 3D printed videolaryngoscopes performed successfully in both 'easy' and 'difficult' configurations using an intubation catheter. Our novel co-axial suction/oxygen channels passed initial laboratory flow testing using a rotameter (12 l min^{-1}), and calculations show that a maximum deliverable volume flow rate for oxygen of 8.9 l min^{-1} (AVL) and 5.7 l min^{-1} (E-MAC both sizes) is achievable before flow becomes turbulent as opposed to laminar (Appendix 3, http://links.lww.com/EJAIC/A6). This could support low-flow oxygenation, as well as suction, during tracheal intubation. The optional barrier device was also shown to reduce artificially generated aerosol exposure (Appendix 4, http://links.lww.com/EJAIC/A7), but the clinical significance of this is unknown and efficacy unproven. Although barrier devices are not shown to be appropriate in all settings, their use should be dictated by situational patient-provider activities and interactions.[36]

Multiple representative associations advocate videolaryngoscopy as the default recommended technique for tracheal intubation in COVID-19 cases.[11] Low-flow oxygenation is recommended during tracheal intubation as an alternative to high-flow nasal oxygen, whose efficacy at intubation is well demonstrated but is in limited supply, and its expense, and high oxygen requirements may put it beyond the reach of many providers.[11,37] High-flow nasal oxygen may also increase the risk of disease transmission compared with other devices, as it is aerosol generating.[38,39] The addition of multiple working channels typically adds to the weight of conventional laryngoscope blades and limits use in patients with poor mouth opening. This has been partially overcome by the novel, co-axial design of the working channel.

There have been several other 3D printed laryngoscopes described. Lambert *et al.*[15] recently evaluated a Tansen videolaryngoscope in a manikin model. The device incorporates a channelled, hyper-angulated blade. Success (88·4%) was somewhat lower than the comparator Pentax AWS (97·7%), and better than achieved with the Macintosh (67·4%). Subjective ease of use, however, was inferior to the Pentax device. Although broadly similar in concept to our device, it does not incorporate additional working channels, and its compliance with ISO regulatory standards is unclear. Similarly, Ataman and Altintas[40] compared the open-source AirAngel® (https://www.airangelblade.org), which is also available for purchase from

the website in a prefabricated Nylon filament, to the GlideScope® videolaryngoscope fitted with a Spectrum MAC S3 blade, in a manikin study placed in normal and difficult configurations. The AirAngel® also incorporates a hyper-angulated blade of 'standard adult' size similar to the Tansen videolaryngoscope. The study reported a first-pass success rate of 47% for AirAngel® and 100% for Glidescope® in a normal airway configuration. The AirAngel® performed worse in a difficult configuration, demonstrating a first-pass success rate of 39%, against 87% for the Glidescope®.[40] It is worth noting that this study compared a hyper-angulated videolaryngoscope blade to a videolaryngoscope fitted with a Macintosh blade, thus not a proportionate assessment. In a clinical study of 24 patients, Karripacheril described the use of a USB-connected endoscopic camera externally attached to a conventionally manufactured Macintosh blade.[41] All patients were successfully intubated. Outside of these publications, there is limited literature in this evolving area.

Limitations

The authors acknowledge several limitations in this study. First, the efficacy and clinical significance of the percentage reduction of the aerosols reported here is unknown. Although several reports have been published regarding this question,[42,43] there are limited data supporting their recommendations and large-scale randomised control trials are needed. Although there is no doubt regarding the importance of appropriate level personal protective equipment when working with patients affected by COVID-19, it is important to note that in many areas of the world, supplies are limited, many healthcare workers remain unvaccinated, and patient testing is not universally available to assess risk and need for high-level personal protective equipment. In addition, airway management is not always carried out in operating rooms with active ventilation systems. Therefore, in the absence of these protective environments, it is recommended that maximal interventions to safeguard healthcare workers from cross-infection with SARS-CoV-2 must be maintained until the risk of viral transmission during aerosol-generating procedures is adequately studied.

Second, manikin intubations were carried out both with and without the aid of an intubation catheter (Frova), which facilitates easier passage through the glottis when visualisation of the larynx in suboptimal. Use of a Frova or bougie is not always indicated because incorrect or inappropriate use can damage the patient's airway.

Third, the E-MAC and AVL video laryngoscopes have not yet been tested on humans; this is an area for future work. Prototyping of these designs in a suitable strength biocompatible resin, for example dental resin, may also offer a superior finish to the fused deposition manufacturing method employed here to 3D print the videolaryngoscopes. Resin prints have superior surface and internal channel detail and smoothness, which may reduce shearing of materials and/or possible tissue damage. Use of the appropriate strength resin for manufacturing will also require further mechanical testing to ISO standards.

Conclusion

Driven by the risks of endotracheal intubation to both patients and providers in the context of COVID-19 and similar infections, the present study aimed to design and test novel videolaryngoscopes with additional features that might improve performance, namely oxygen and suction channels, in addition to the usual channels for an endoscopic camera and endotracheal tube. The option to securely attach a flexible barrier to the videolaryngoscopes may offer additional containment where personal protective equipment may be limited. An additional and important feature of these devices is that they demonstrate compliance with regulatory standards for material strength. These features are uncommon in contemporary

Table 2 Economic Analysis of Videolaryngoscopes

Cost analysis - comparator videolaryngoscopes Item	Item cost per use €	Re-useable accessories upfront cost €:	Approximate total cost €:
E-MAC	€5.68–6.12	reusable endoscope @ €39.48[1]	€45.60
AVL	€6.14	reusable endoscope @ €39.48[1]	€45.62
[2]Inscope	€19–24 (20–25$)	video module @ €335 (350$)	€982.00
		tablet/mounting case/charger @ €622 (650$)	
[3]Timesco Europa LED Easy Bright Pre-Loaded Laryngoscope (Mac 3/4)	€9.63 (£8.34)	none (no video module or suction/oxygen)	€9.63
[4]Rüsch Airtraq SP optical disposable laryngoscope	€81.83	none (no video module or suction/oxygen)	€81.83
[5]Rüsch Airtraq Avant optical reusable laryngoscope	€39.40	reusable laryngoscope @ €486	€525.40
[6]Tansen Videolaryngoscope	€13.60	endoscope @ €13.60	€27.20
[7]Pentax-AWS videolaryngoscope	€256–284 (£220–244.44)	reusable laryngoscope @ €5683 (£4889.89)	€5967.00
[8]AirAngel	€106.03–116.48	WIFI Borescope @ €87.95	€204.43
[9]GlideScope Videolaryngoscope	€15 ($16)	reusable laryngoscope @ €14 510 ($15115)	€14 525

Cost-analysis of comparator videolaryngoscopes mentioned. Where a range is given in 'Item Cost per use €' column, the range is indicative of the size range on offer, for example 3 and 4 in blade sizes and are reflective of a single item, for example disposable blade. Prices are correct as of June 2022 and were sourced from the links provided in Appendix 5, http://links.lww.com/EJAIC/A8.

videolaryngoscopes. As these features could potentially weaken the structural integrity of the blades, it was important that they conformed to ISO standards for strength and safety. Although the efficacy of these features requires further evaluation, following planned detailed clinical evaluation, these designs will be made freely available, under CC BY-ND 4.0 license, by a software download. It is anticipated that because of the modest material cost in these models (see Table 2 and Appendix 5, http://links.lww.com/EJAIC/A8 for cost analysis compared with videolaryngoscopes mentioned herein), they will be of interest in any future outbreaks of infectious respiratory disease, and/or particularly in areas of the world with limited financial resources.

Acknowledgements relating to this article

Assistance with the study: the authors would like to thank Dr Kevin Nolan, Assistant Professor/Lecturer at University College Dublin, School of Mechanical & Materials Engineering, for his assistance in our fluid mechanics calculations. The authors gratefully acknowledge the support of Science Foundation Ireland (Three Park Place, Hatch Street Upper, Dublin 2, Ireland) for a research grant (20/COV/0223), which helped defray the expenses associated with this study.

Financial support and sponsorship: none.

Conflicts of interest: the authors declare no competing interests.

Presentation: preliminary data for this study were presented as a poster presentation at the Science Foundation Ireland (SFI) Science Summit 2020, 4 and 5 of November 2020 and the College of Anaesthesiologists of Ireland, Annual Congress 2021, 20 and 21 of May 2021.

This manuscript was handled by Alistair F McNarry.

References

1 Jackson T, Deibert D, Wyatt G, *et al.* Classification of aerosol-generating procedures: a rapid systematic review. *BMJ Open Respir Res* 2020; **7**: e000730.
2 Fink JB, Ehrmann S, Li J, *et al.* Reducing aerosol-related risk of transmission in the era of COVID-19: an interim guidance endorsed by the International Society of Aerosols in Medicine. *J Aerosol Med Pulm Drug Deliv* 2020; **33**:300–304.
3 Brown J, Gregson FKA, Shrimpton A, *et al.* A quantitative evaluation of aerosol generation during tracheal intubation and extubation. *Anaesthesia* 2021; **76**:174–181.
4 Shrimpton A, Brown J, Cook TM, Pickering AE. Airway procedures: the importance of distinguishing between high risk and aerosol generation. *Anaesthesia* 2021; **76 (Suppl 3)**:28–29.
5 Cook TM, El-Boghdadly K, McGuire B, *et al.* Consensus guidelines for managing the airway in patients with COVID-19. *Anaesthesia* 2020; **75**:785–799.
6 Wilson NM, Marks GB, Eckhardt A, *et al.* The effect of respiratory activity, noninvasive respiratory support and facemasks on aerosol generation and its relevance to COVID-19. *Anaesthesia* 2021; **76**:1465–1474.
7 Jermy MC, Spence CJT, Kirton R, *et al.* Assessment of dispersion of airborne particles of oral/nasal fluid by high flow nasal cannula therapy. *PLoS One* 2021; **16**:e0246123.
8 Tran K, Cimon K, Severn M, *et al.* Aerosol generating procedures and risk of transmission of acute respiratory infections to healthcare workers: a systematic review. *PloS one* 2012; **7**:e35797.
9 Klompas M, Baker M, Rhee C. What is an aerosol-generating procedure? *JAMA Surg* 2021; **156**:113–114.
10 Weissman DN, de Perio MA, Radonovich LJ Jr. COVID-19 and risks posed to personnel during endotracheal intubation. *JAMA* 2020; **323**:2027–2028.
11 Cook TM, McGuire B, Mushambi M, *et al.* Airway management guidance for the endemic phase of COVID-19. *Anaesthesia* 2021; **76**:251–260.
12 Wong P, Lim WY. Aligning difficult airway guidelines with the anesthetic COVID-19 guidelines to develop a COVID-19 difficult airway strategy: a narrative review. *J Anesth* 2020; **34**:924–943.
13 Healy DW, Maties O, Hovord D, Kheterpal S. A systematic review of the role of videolaryngoscopy in successful orotracheal intubation. *BMC Anesthesiol* 2012; **12**:32.
14 Huysamen HW, Kinnear WA, Fonternel TE, *et al.* 3D printed laryngoscope for endotracheal intubation. *South Afr J Ind Eng* 2020; **31**:209–217.
15 Lambert CT, John SC, John AV. Development and performance testing of the low-cost, 3D-printed, smartphone-compatible 'Tansen Videolaryngoscope' vs. Pentax-AWS videolaryngoscope vs. direct Macintosh laryngoscope: a manikin study. *Eur J Anaesthesiol* 2020; **37**:992–998.
16 Kumar SS, Binu A, Devan AR, Nath LR. Mucus targeting as a plausible approach to improve lung function in COVID-19 patients. *Med Hypotheses* 2021; **156**:110680.
17 Wei H, Jiang B, Behringer EC, *et al.* Controversies in airway management of COVID-19 patients: updated information and international expert consensus recommendations. *Br J Anaesth* 2021; **126**:361–366.
18 Chin AWH, Chu JTS, Perera MRA, *et al.* Stability of SARS-CoV-2 in different environmental conditions. *Lancet Microbe* 2020; **1**:e10.
19 Liu Y, Li T, Deng Y, *et al.* Stability of SARS-CoV-2 on environmental surfaces and in human excreta. *J Hosp Infect* 2021; **107**:105–107.
20 van Doremalen N, Bushmaker T, Morris DH, *et al.* Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N Engl J Med* 2020; **382**:1564–1567.
21 Brown S, Patrao F, Verma S, *et al.* Barrier system for airway management of COVID-19 patients. *Anesth Analg* 2020; **131**:e34–e35.
22 Yang Y-L, Huang C-H, Luk H-N, Tsai PB. Adaptation to the plastic barrier sheet to facilitate intubation during the COVID-19 pandemic. *Anesth Analg* 2020; **131**:e97–e99.
23 Yadav P, Garg R. The barrier techniques for airway management in covid-19 patients: review of literature. *J Anaesthesiol Clin Pharmacol* 2021; **37**:171.
24 Abbas MZ. Industrial applications of 3D printing to scale-up production of COVID-19-related medical equipment. *J 3D Print Med* 2021; **5**:97–110.
25 Papanaoum M, Triantopoulos OK, Triantopoulos A, *et al.* 'Vamo': introducing a low-cost reusable 3D printed video laryngoscope. *Trends Anaesth Crit Care* 2018; **23**:21–22.
26 Almeida VS, Almeida VS, Campos GO. Challenges of prototyping, developing, and using video laryngoscopes produced by inhouse manufacturing on 3D printers. *Braz J Anesthesiol* 2021; **71**:309–311.
27 Agrawal J. Inscope direct, the first laryngoscope with built-in suction. *Anaesth Pain Intensive Care* 2017; **21**:502.
28 Kim S-H, Kwon J, Kim Y-J, *et al.* Impact of a custom-made 3D printed ergonomic grip for direct laryngoscopy on novice intubation performance in a simulated easy and difficult airway scenario: a manikin study. *PLoS One* 2018; **13**:e0207445.
29 Asai T, Matsumoto S, Fujise K, *et al.* Comparison of two Macintosh laryngoscope blades in 300 patients. *Br J Anaesth* 2003; **90**:457–460.
30 Rassam S, Wilkes AR, Hall JE, Mecklenburgh JS. A comparison of 20 laryngoscope blades using an intubating manikin: visual analogue scores and forces exerted during laryngoscopy*. *Anaesthesia* 2005; **60**:384–394.
31 Twigg SJ, McCormick B, Cook TM. Randomized evaluation of the performance of single-use laryngoscopes in simulated easy and difficult intubation. *Br J Anaesth* 2003; **90**:8–13.
32 McElwain J, Laffey JG. Comparison of the C-MAC®, Airtraq®, and Macintosh laryngoscopes in patients undergoing tracheal intubation with cervical spine immobilization. *Br J Anaesth* 2011; **107**:258–264.
33 Ndoko SK, Amathieu R, Tual L, *et al.* Tracheal intubation of morbidly obese patients: a randomized trial comparing performance of Macintosh and Airtraq™ laryngoscopes. *Br J Anaesth* 2008; **100**:263–268.
34 Oth O, Dauchot C, Orellana M, Glineur R. How to sterilize 3D printed objects for surgical use? An evaluation of the volumetric deformation of 3D-printed genioplasty guide in PLA and PETG after sterilization by low-temperature hydrogen peroxide gas plasma. *Open Dentist J* 2019; **13**:.
35 Pérez Davila S, González Rodríguez L, Chiussi S, *et al.* How to sterilize polylactic acid based medical devices? *Polymers* 2021; **13**:2115.
36 Eykelbosh A. *A rapid review of the use of physical barriers in nonclinical settings and COVID-19 transmission*. Vancouver, BC: National Collaborating Centre for Environmental Health (NCCEH); 2021.
37 Oliveira J, e Silva L, Cabrera D, *et al.* Effectiveness of apneic oxygenation during intubation: a systematic review and meta-analysis. *Ann Emerg Med* 2017; **70**:483–494; e411.

38 Sorbello M, El-Boghdadly K, Di Giacinto I, *et al.* The Italian coronavirus disease 2019 outbreak: recommendations from clinical practice. *Anaesthesia* 2020; **75**:724–732.
39 Crowley C, Murphy B, McCaul C, *et al.* Airborne particle dispersion by high flow nasal oxygen: an experimental and CFD analysis. *PLoS One* 2022; **17**: e0262547.
40 Ataman AK, Altıntas E. Comparison of a commercial 3D fabricated laryngoscope (Airangel ®) with a widely-used video laryngoscope (Glidescope®): randomized controlled cross-over study. *Trends Anaesth Crit Care* 2021; **40**:35–40.
41 Karippacheril JG, Umesh G, Ramkumar V. Inexpensive video-laryngoscopy guided intubation using a personal computer: initial experience of a novel technique. *J Clin Monit Comput* 2014; **28**:261–264.
42 Iwasaki N, Sekino M, Egawa T, *et al.* Use of a plastic barrier curtain to minimize droplet transmission during tracheal extubation in patients with COVID-19. *Acute Med Surg* 2020; **7**:e529.
43 Yadav P, Garg R. The barrier techniques for airway management in covid-19 patients: review of literature. *J Anaesthesiol Clin Pharmacol* 2021; **37**:171–178.