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Original Research Article

Development of a dynamically adjustable video-laryngoscope for endotracheal intubation (DAVE)

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Abstract: Endotracheal intubation is a routine yet safety-critical procedure in anaesthesiology and emergency medicine. Although video-laryngoscopes have substantially improved airway management, established systems are still based on fixed blade geometries that do not allow patient-specific adjustment during use. This work describes the development and prototypical implementation of a dynamically adjustable video-laryngoscope for endotracheal intubation (DAVE). The device was developed through an interdisciplinary product development process based on VDI 2221, integrating engineering and clinical expertise. Based on clinical and technical requirements, a concept featuring an articulated blade with two mechanically coupled movable segments, a cable-driven actuation mechanism, and an integrated camera system was developed and iteratively refined over fourteen prototype versions. The final prototype was manufactured using multi-material additive manufacturing based on polylactide and thermoplastic polyurethane and enables controlled adjustment of the articulated blade geometry while preserving sufficient rigidity for tissue retraction and lifting. Within the iterative development process, qualitative tests were used to assess distal blade angulation, camera-view angle, and passive camera alignment through movement of the middle segment. The resulting observations were used for prototype refinement and to assess the basic functionality of the adjustment mechanism. These observations indicate that the developed concept is technically capable of dynamically adapting blade curvature and camera orientation during manikin testing. The effect of these adjustments on glottic visualisation and clinical performance was not systematically quantified in the present work. The present work demonstrates the fundamental technical feasibility of a dynamically adjustable video-laryngoscope.

I. Introduction

Endotracheal intubation is a routinely performed yet safety-critical procedure in anaesthesiology, intensive care and emergency medicine [1,2]. Endotracheal intubation requires adequate visualisation of the glottis to allow controlled advancement of the endotracheal tube through the laryngeal inlet into the trachea. Restricted glottis visualisation can complicate tracheal intubation leading to multiple intubation attempts, tissue trauma, oesophageal intubation, hypoxaemia, and further complications [1,2]. Although such airway-related adverse events are rare, they are of high clinical relevance [1,2].

Video-laryngoscopy is a key technique in modern airway management which enables indirect visualisation of the glottis through an integrated camera system [3]. Video-laryngoscopy often provides better visualisation than direct laryngoscopy and is associated with improved first-attempt intubation success rates [4–6]. Commercial video-laryngoscopes are generally based on rigid blades with fixed geometries, such as Macintosh-type and hyper-angulated blade shapes [4,6,7]. Video-laryngoscope performance depends on the blade geometry, which must be appropriately aligned with patient-specific and procedural demands [6,8,9]. Hyper-angulated blades often provide a superior glottic view compared with less-angulated blades; while on the other hand, they can be more technically demanding and typically require additional adjuncts, specific manoeuvres, and distinct hand-eye coordination, which in turn may make tracheal tube advancement more challenging [5,8,10].

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Flexible adjustment of blade geometry may overcome the inherent limitations of individual fixed-geometry video-laryngoscope designs by integrating their complementary and synergistic advantages. Second generation video-laryngoscopes with real-time, adjustable blade geometry and camera alignment have not yet been introduced into clinical practice. Here we present a novel approach.

Given the considerable anatomical variability, an articulated video-laryngoscope blade with adjustable middle and distal segments appears to be a promising approach to dynamically adapt blade curvature and camera alignment during use. Such an approach may support adaptation of blade curvature and camera alignment to patient-specific anatomical conditions and could thereby optimise glottic exposure and the laryngoscopic view. The aim of the present work is the development and prototype evaluation of a dynamically adjustable video-laryngoscope for endotracheal intubation (DAVE).

II. Development and manufacturing of DAVE

The development of DAVE was carried out as an interdisciplinary product development process based on VDI Guideline 2221 [11], integrating engineering and clinical expertise. At the beginning of the development process, the relevant clinical and technical requirements were identified.

The key requirements included, in particular, a dynamically adjustable blade angulation, preservation of sufficient blade rigidity to allow tissue retraction and generation of the required lifting force during laryngoscopy, adjustment of the camera-view angle, a continuous view of the blade tip, and a one-handed mechanism for adjusting the blade angulation. Based on these requirements and the derived functional structures, suitable solution principles were identified and combined into different design concepts. As part of a technical and economic evaluation of these concepts, a cable-driven concept was identified as the preferred solution (see Figure 1).

The final concept provides an articulated blade with two kinematically coupled movable segments controlled by a cable-driven actuation mechanism. The middle segment contributes to the overall blade curvature and to the alignment of the view angle of the integrated camera, whereas the distal segment primarily provides the local deflection to promote indirect epiglottis lifting by engaging the midline vallecular fold with the blade tip [6].

Actuation is achieved by means of a ratchet wheel and pawl integrated into the laryngoscope handle. This enables controlled and seamless adjustment of the articulated blade geometry while preserving sufficient rigidity for tissue retraction and lifting.

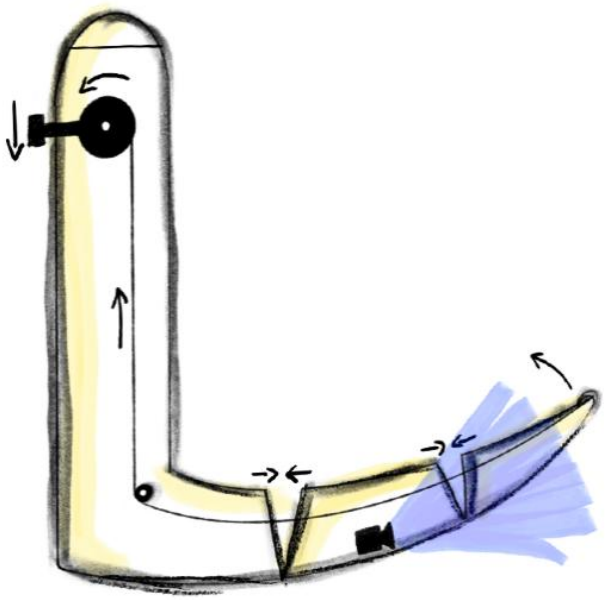

Figure 1: Functional schematic of the cable-driven adjustment mechanism for dynamic adaptation of blade angulation.

The integrated camera is located in the middle segment of the blade and therefore follows its movement during angulation. Image transmission is realised via a cable connection to an external monitor. Because the actuation cable transmits tensile but not compressive forces, the blade can only be actively deflected in the direction of hyperangulation. When cable tension is released, the blade tends to return towards its neutral position due to the elastic restoring forces of the compliant joints, assisted by the counterpressure of the surrounding airway tissues and forces applied by the user during manipulation of the device.

Following concept development, the geometric design was implemented in the 3D CAD software SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France). The subsequent development process followed an iterative approach and comprised a total of fourteen prototype versions. Across these iterations, the prototype was continuously refined on the basis of functional tests, mechanical tests, and feedback from experienced anaesthesiologists.

The development of the hinge joints proved particularly challenging, given the limited installation space within patient's oral cavity, the comparatively high mechanical loads, and the unfavourable geometry for transmitting the required lifting forces. Early versions were based on a pin joint design, which, however, was found to be too delicate for the intended application. The final prototype (see Figure 2a) was constructed by multimaterial additive manufacturing using polylactide (PLA) and thermoplastic polyurethane (TPU). Flexible joints were directly printed as compliant mechanisms, which reduced the number of

components and simplified assembly. Gray PLA (DAS FILAMENT, Emskirchen, Germany) was used for rigid components, whereas the flexible joint regions were manufactured from white TPU 95A (UltiMaker B.V., Utrecht, Netherlands).

The internal anchoring of the flexible TPU within the rigid PLA structure is shown in Figure 2b. The final prototype had an overall blade length of approximately 125 mm, a maximum blade width of 20 mm, and a handle length of approximately 145 mm. The elastic properties of the TPU joints provide an integrated restoring force that returns the blade to its neutral position. CAD-based investigations were used to optimise the camera position on the articulated middle segments relative to the adjustable distal blade tip and the expected line of sight toward the glottis.

Additive manufacturing was a key enabling technology in the development of DAVE, as it allowed both the rapid implementation of iterative design changes and the fabrication of geometrically complex functional components. Process preparation was carried out using the Cura slicer (UltiMaker B.V., Utrecht, Netherlands), while manufacturing was performed on an UltiMaker S5. After comparing different options, a stainless-steel cable (Carl Stahl GmbH, Süßen, Germany) with a diameter of 0.6 mm was selected for force transmission within the adjustment mechanism. For prototypical imaging, an endoscopic camera (model EZ-EN39L-RT-PL, Shenzhen Ezon Electronic, Shenzhen, China) with a diameter of 3.9 mm, integrated LED illumination, and a field of view of 100° was used.

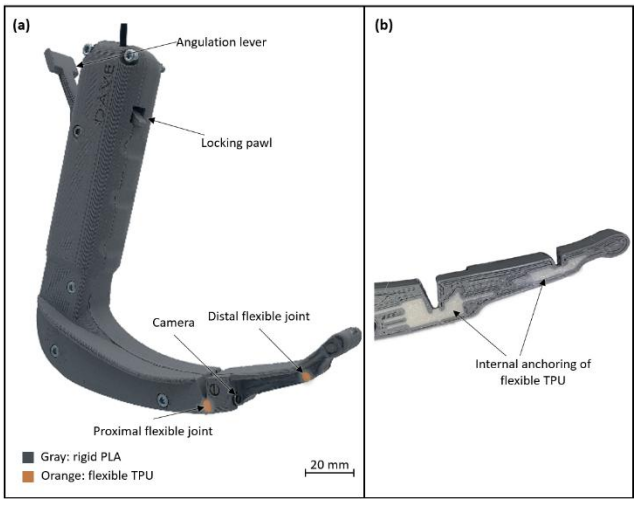

Figure 2: Final prototype and material allocation of the dynamically adjustable video-laryngoscope DAVE. (a) Final prototype, including the angulation lever, locking pawl, integrated camera, proximal flexible joint, and distal flexible joint. Rigid PLA components are shown in grey, while flexible TPU regions used for the compliant joints are highlighted in orange. Approximate scale bar: 20 mm. (b) Detail view of the distal blade segment illustrating the internal anchoring of the flexible TPU within the rigid PLA structure.

III. Results and discussion

All prototypes, and particularly the final prototype, were subjected to iterative functional testing in a commercial airway manikin (AirSim Advanced Bronchi X, TruCorp Ltd., United Kingdom) during development. Figure 3 illustrates the functional testing of the final prototype, including the blade adjustment and the corresponding laryngoscopic views before and after actuation.

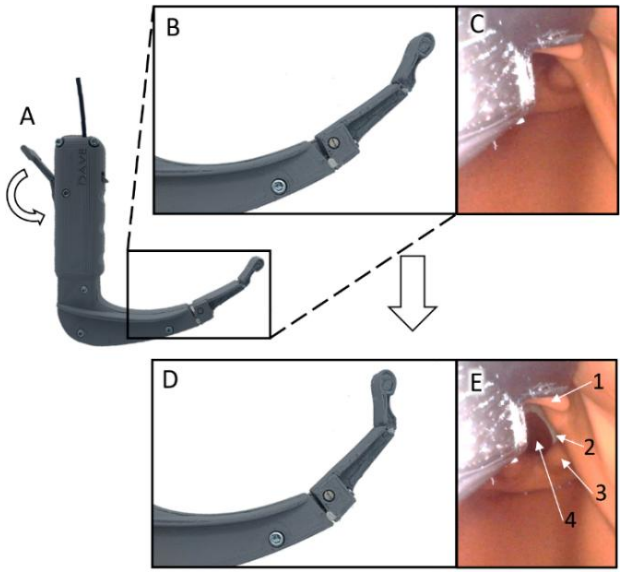

Figure 3: Functional illustration of the DAVE video-laryngoscope and corresponding laryngoscopic views during manikin testing before and after actuation of the adjustment mechanism. (A) DAVE prototype with indicated direction of actuation. (B, C) Blade shape and corresponding laryngoscopic view before actuation. (D, E) Blade configuration and corresponding laryngoscopic view after actuation. (1) Epiglottis, (2) right vocal cord, (3) right arytenoid, (4) rima glottidis.

Within the iterative development process, tests were used to qualitatively assess distal blade angulation, camera-view angle, and passive camera realignment through middle segment movement. The resulting observations were used for prototype refinement and to evaluate their potential influence on the laryngoscopic view.

The observations obtained during these tests indicate that the developed concept is technically capable of dynamically adapting blade curvature and camera orientation to facilitate tracheal intubation in manikin testing. In this context, the concept addresses two basic mechanisms that may influence the laryngoscopic view: (i) indirect epiglottis lifting by increased angulation of the distal blade segment to engage the midline vallecular fold and (ii) adaptation of the camera-view angle by the movable blade-camera arrangement (middle segment). However, the effect of these adjustments on the quality of glottis visualisation was not systematically quantified in the present work. Within the scope of the present work, the fundamental technical feasibility of a dynamically

adjustable video-laryngoscope could thus be demonstrated. Typical manufacturing characteristics associated with fused filament fabrication (FFF) were observed, including visible layer lines, surface roughness, support interface marks, and minor dimensional deviations in narrow openings, cable-guiding regions, and joint-adjacent structures.

Therefore, manual post-processing was required, particularly support removal, light deburring, and inspection of the cable path and locking mechanism to ensure unobstructed actuation. During qualitative functional testing of the final prototype, no gross material failure preventing functional demonstration was observed in the flexible TPU joint regions. However, systematic cyclic testing, fatigue assessment, quantitative load testing, and failure-mode analysis were not performed in the present work.

The present work relies on prototype development and exemplary manikin testing, enabling direct technical improvement through rapid, iterative optimisation cycles and the translation of clinical requirements into technical solutions. Currently no data exist regarding clinical performance and possible benefits, user acceptance, or possible advantages over conventional non-adjustable video-laryngoscopes. These questions are currently being investigated in a controlled manikin study.

The presented PLA/TPU device represents a functional proof-of-concept prototype and is not intended for clinical use at its current stage of development. Future translation towards clinical application requires the selection and validation of suitable medical-grade, reprocessing concepts, manufacturing processes, as well as mechanical safety testing, biocompatibility assessment, and regulatory evaluation. For series production, conventional manufacturing routes such as multi-component injection molding may be more suitable than additive manufacturing.

IV. Conclusion

With DAVE, a functional prototype of a dynamically adjustable video-laryngoscope was successfully developed and manufactured. This work demonstrates that the combination of an articulated blade with two kinematically coupled movable segments, a cable-driven actuation mechanism, and an integrated camera system is technically feasible.

Iterative manikin testing indicated that the concept enables controlled adjustment of blade geometry and camera orientation under qualitative test conditions.

However, based on the currently available data, no conclusions can yet be drawn regarding clinical benefit, improved glottic visualisation, intubation performance, mechanical safety, or superiority over established video-laryngoscopes. These aspects will need to be investigated in controlled studies.

Acknowledgments

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Author's statement

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