An Innovate Robotic Endoscope Guidance System for Transnasal Sinus and Skull Base Surgery: Proof of Concept

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Abstract

Objective Advanced transnasal sinus and skull base surgery remains a challenging discipline for head and neck surgeons. Restricted access and space for instrumentation can impede advanced interventions. Thus, we present the combination of an innovative robotic endoscope guidance system and a specific endoscope with adjustable viewing angle to facilitate transnasal surgery in a human cadaver model.

Materials and Methods The applicability of the robotic endoscope guidance system with custom foot pedal controller was tested for advanced transnasal surgery on a fresh frozen human cadaver head. Visualization was enabled using a commercially available endoscope with adjustable viewing angle (15–90 degrees).

Results Visualization and instrumentation of all paranasal sinuses, including the anterior and middle skull base, were feasible with the presented setup. Controlling the robotic endoscope guidance system was effectively precise, and the adjustable endoscope lens extended the view in the surgical field without the common change of fixed viewing angle endoscopes.

Conclusion The combination of a robotic endoscope guidance system and an advanced endoscope with adjustable viewing angle enables bimanual surgery in transnasal interventions of the paranasal sinuses and the anterior skull base in a human cadaver model. The adjustable lens allows for the abandonment of fixed-angle endoscopes, saving time and resources, without reducing the quality of imaging.

Keywords

- robotic
- surgery
- sinus
- endoscopic
- skull base
- FESS
- RAS

Introduction

Conventionally speaking, transnasal endoscopic surgery is the archetypal approach for surgical treatment of the most common pathologies of the paranasal sinuses. Decisive developments, including Harold H. Hopkins' rod-lens endoscope from 1959 and Karl Storz's subsequent adoption and development of this technique, have led to paradigm changes in the field of endoscopic surgery.¹ The range of possible applications extends from common functional endoscopic sinus surgery (FESS) of rhinosinusitis with or without polypoid² to benign and malignant tumors of the paranasal sinuses and beyond.³ Complex interventions such as the

management of traumatic, spontaneous, and iatrogenic cerebrospinal fluid (CSF) leaks are routinely performed via the transnasal endoscopic approach, while indications for safety and efficiency are reported comprehensively.^{4–6} In the present day, head and neck surgeons, as well as neurosurgeons, are exceeding the anatomic boundaries of the skull base and treating neoplasms of the anterior skull base,⁷ clival region,⁸ odontoid,⁹ and perhaps most commonly, the pituitary gland,¹⁰ either using solely endoscopic methods or in combination with an open approach. For all these applications, difficulties of instrumentation and visualization increase with the skill level of the specific intervention, which is mainly attributable to limited space and applicability of

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instruments. Consequently, some authors promote a four-handed or bimanual instrumentation,^{11,12} especially in advanced applications of transnasal endoscopic surgery.

Robot-assisted surgery (RAS) is also under constant development. Even though conventional surgery remains to be the gold standard in every surgical field, frequency of use, as well as the range of possible indications of RAS are increasing progressively.¹³ Successful adoption of RAS is reported for partial and total laryngectomy,^{14,15} tumors of the parapharyngeal space,¹⁶ thyroidectomy,¹⁷ neck dissection,¹⁸ and other entities, while oropharyngeal tumors remain the main indication.¹⁹

Yet, in attempts to transfer the benefits of RAS onto surgery of the paranasal sinuses and transnasal approaches to the skull base, experiences with the clinically available robotic systems have been ineffective as summarized by Trevillot et al.²⁰ Few contributions to this demand can be found in literature, while improvements are evidently required. Schneider et al presented a concentric tube continuum robot taking advantage of an ultra-small diameter for an endonasal approach of one single instrument.²¹ Wurm et al presented a robot for sinus surgery, which was capable of performing sphenoidotomy and sphenoidectomy.²² The SoloAssist endoscope holder (AKTORMed ROBOTIC Surgery, Barbing, Germany), purposely created for abdominal surgery, was adopted for sinus surgery by Kristin et al.²³ The automated endoscopic system for optimal positioning (AESOP) scope holding system has been equipped with voice-controlled movement enabling bimanual manipulation to optimize workflow and applicability in endoscopic sinus surgery.²⁴ In our department, the Flex system (Medrobotics, Raynham, MA, United States) has been successfully adopted for visualization of the maxillary sinus, sphenoid, and even brain stem via transnasal approach in a cadaver model.²⁵ In summary, none of these systems have yet gained acceptance in clinical routine, thus confirming a demand for new developments in the field of robot-assisted sinus and skull base surgery. In this study, we introduced an innovative pre-market robotic endoscope guidance system for surgery of the paranasal sinuses and the anterior skull base, featuring a hands-free semi-automated endoscope guidance for advanced applications in combination with an adjustable lens endoscope.

Materials and Methods

Robotic Endoscope Guidance System

The robotic guidance system (Medineering, Munich, Germany) consists of an intelligent mechatronic holding arm with four segments and seven degrees of freedom (►Fig. 1). It is manually controlled by the surgeon and can be locked in any possible position. The maximum load capacity is 2 kg. With an overall weight of less than 10 kg, the construction is highly versatile and can be easily attached to the standard side rails of a surgical table in any position as the respective procedure requires. Joints of the holding arm can be released by touchpads on each segment at any time throughout the procedure. The status of the system (locked/released) is indicated by light-emitting diode (LED) lights. On its distal end, a compact robotic hand with five actuated degrees of freedom performs the movement of the endoscope, driven by five brushless DC

Fig. 1 System overview. The robotic guidance system consists of an intelligent mechatronic holding arm with four segments and seven degrees of freedom. Soft touchpads on each segment enable the releasing and alignment of the robotic arm at any time. Light-emitting diode (LED) rings on each joint visualize the status of the system. A robotic hand with five active degrees of freedom is attached to the tip, realizing movement of the endoscope.

motors (►Fig. 2a). Standard 4 mm endoscopes are connected to the robotic hand with a specific clip mechanism (►Fig. 2b). Three-dimensional motion and fine adjustment of the endoscope are controlled by the surgeon through a custom foot pedal with joystick (Steute, Lohne, Germany; ►Fig. 2c). The pedal also has an extra foot button to return the endoscope to its basic position. The surgeon can switch between transitional movement (moving the endoscope forward/backward, left/right, or up/down) and pivot point rotation (to pitch the approach angle) of the endoscope.

Endocameleon Endoscope

The clinical applicability of endocameleon endoscope has previously been published for neurosurgical interventions and lacrimal surgery.^{26,27} It features an adjustable rod-lens endoscope in common 4-mm design with an infinitely variable angle of view from 15 to 90 degrees (Karl Storz, Tuttlingen, Germany; ►Fig. 3a). Adjustment is realized by an inbuilt lever on the hand piece of the endoscope (►Fig. 3b). The endoscope is attached to the robotic guidance system with a universal 4-mm endoscope clip.

Experimental Setup

A fresh frozen human cadaver head was used for preclinical evaluation. Regular anatomy was intact. The head was placed in supine position on a surgical table as regularly set for transnasal surgery and stabilized on a head pod without further fixation by clamp or other means. The robotic endoscope guidance system was mounted onto the respective side rails of the surgical table and positioned alongside the cadaver head. The endoscope was then attached to the system using the system

Fig. 2 System components. (a) Three-dimensional endoscope movement is implemented through the robotic hand. The endoscope is easily attached to the robotic hand by specific connection clip (b), and controlled by a customized foot pedal and joystick (c).

Fig. 3 System application. (a) The rod lens endoscope features an (b) adjustable viewing angle that is infinitely variable from 15 to 90 degrees. (c) After manual insertion of the endoscope, the system allows for hands-free bimanual instrumentation, while (d) visualization of the surgical field is displayed on a high display (HD) video screen.

specific connection clip. After returning the endoscope to its basic position, introduction of the endoscope was performed manually by releasing the system brakes and leading the endoscope to the desired position, always visualized on the imaging screen (►Fig. 3c). From this point, steering and positioning the endoscope are achieved with the customized foot pedal, while hands are free for bimanual instrumentation with a standard range of tools and instruments (►Fig. 3d).

Results

After basic positioning and introduction of the endoscope into the nasal cavity, the robotic endoscope guidance system enabled constant hands-free repositioning of the endoscope, realizing the continuous visualization of every step of the intervention. Following differentiation of major landmarks, the middle turbinate was medialized and uncinectomy was performed (►Fig. 4a). Widening of the maxillary sinus ostium (►Fig. 4b), as well as anterior and posterior ethmoidectomy, was conducted accordingly. In addition, the sphenoid sinus was opened directly over its natural ostium (►Fig. 4c). After visualization, the bony cover of the anterior skull base was removed with suitable instruments and the frontal lobe came into display (►Fig. 4d). The robotic guidance system facilitated manipulation in the surgical situs and allowed full visualization of the face of the anterior skull base (►Fig. 5a–c). Bimanual instrumentation with conventional force was possible without major displacement of the endoscope, while the

endoscope position was held steadily throughout the procedure without relevant deviation. The adjustable endoscope lens enabled visualization of the complete anterior skull base without the need to change or reposition the endoscope. A postprocessed stitching image provided a panoramic image of the anterior skull base (►Fig. 5d). All described landmarks and structures were displayed in adequate quality. During the whole procedure, the endoscope was returned to home position and removed manually four to five times, either for cleaning or major repositioning of the system. At the end of the procedure, once more, the endoscope was returned to basic position and removed manually, which as mentioned in the introduction, takes only few seconds (see also ►Video 1).

Video 1

Demonstration of an innovate robotic endoscope guidance system for transnasal surgery. The endoscope is easily introduced into the specimen. Robotic guidance allows for bimanual instrumentation in advanced sinus and skull base surgery. The endoscope with adjustable viewing angle enables visualization of the situs without the common change. Online content including video sequences viewable at: www.thieme-connect.com/ejournals/html/doi/10.1055/s-0037-1603974 of fixed viewing angle endoscopes.

Fig. 4 Two-handed surgery. The usage of an endoscope holder allows for two-handed surgery at different stages of the procedure. (a) Resection of the right infundibulum using a Freer dissector and straight suction device. (b) Opening of the maxillary sinus. The middle turbinate is medialized by the upper instrument (#). The ostium of the maxillary sinus (*) is entered by the suction device. (c) For access to the sphenoid sinus with the suction device (#), the middle turbinate is lateralized by a second instrument (*). (d) The frontal lobe (#) is manipulated by two instruments following resection of the bony anterior skull base (*).

Fig. 5 Endoscopic view. The skull base in the medial tunnel is displayed in its whole extension using the endoscope with adjustable viewing angle (15–90 degrees) reaching (a) from the axilla of the middle turbinate with the (b) frontal recess to the (c) anterior skull base plane. (d) Stitched picture, giving a panoramic view of the skull base. *Ostium of the frontal sinus. #Middle turbinate.

Discussion

Endoscopic surgery is state of the art for most pathologies of the paranasal sinuses.²⁸ Also, it is held in high esteem for a variety of skull base interventions, especially for borderline cases between head and neck surgeons and neurosurgeons or for managing skull base defects following transnasal surgery.^{29–31} The advantages of improved visualization and lower morbidity come with considerable challenges in terms of instrumentation and surgical skill. Furthermore, complex instrumentation in FESS is reported to lead to physical fatigue of the surgeon.³² The recommendation of a four-handed approach

to complex pathologies evidently requires monetary and personnel resources.³³ In this context, the introduction of a reliable, active endoscope guidance is a promising development, which has not yet been described in a market-ready construction. The combination of an intuitively controlled endoscope with both hands-free instrumentation and manipulation allows the perspective of an application in advanced endoscopic surgery of the paranasal sinuses and the anterior and middle skull base. In this concept, an additional surgeon or assistant is rationalized to certain extent. Major restrictions in this pre-market setup include a lack of an irrigation system, necessitating a full removal of the guidance system after staining in the

operative situs. This could be overcome with the implementation of available rinsing system.³⁴ However, feedback mechanisms for movement borders of the endoscope are not being realized in this study, putting the specimen at risk for unintended injury while maneuvering the endoscope.³⁵ The combination of the robotic guidance system with an endoscope with adjustable lens is beneficial, as changing of endoscopes becomes dispensable. An integrated rotation option would be a desirable improvement in the combination to fully utilize the advanced capabilities of this technical attribute. Furthermore, setting and changing the viewing angle is only possible by manual adjustment, diminishing the benefits of the hands-free controlling of the endoscope. Thus, it would be an interesting development to integrate these features into controller foot pedal. Finally, it is significant to note that the potential benefits of robotic endoscope surgery might also interfere with the dynamics of an advanced procedure, in which constant adjustment and repositioning of the endoscope are essential for three-dimensional orientation in complex anatomy.

Conclusion

Our results verify the applicability of the robotic endoscope guidance system in a human cadaver experiment. Advantages and disadvantages in surgery of the paranasal sinuses and the skull base are illustrated and discussed. Combined with an adjustable endoscope lens and hands-free visualization of the surgical area, bimanual instrumentation for advanced transnasal interventions is feasible without the need for additional assistance concerning endoscope guidance. Precision and intuitive steering of the endoscope can be further improved and a reliable rinsing system is an absolute premise. Nonetheless, the market-ready construction is a promising supplement in advanced sinus surgery.

Conflict of Interests

The robotic endoscope guidance system was provided and costs for cadaver experiments were sponsored by Medi-neering, Munich, Germany. The adjustable endoscope was provided by Karl Storz, Tuttlingen, Germany. None of the authors received any financial compensation, and declare no conflict of interests. Permission was obtained from the respective manufacturers for publication of the figures.

Authors' Contributions

D.T.F. and P.J.S. performed experiments and wrote the manuscript. F.S. and J.G. prepared the figures. T.K.H. and M.O.S. analyzed results and revised the manuscript.

Ethical Approval

For this study, a human cadaver was utilized. The specimen used was from a voluntary body donor. All procedures performed in studies involving the human cadaver were in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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