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Robotic assistant systems for surgical procedures of the anterior skull base

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Abstract: Robot-assisted surgery (RAS) has been widely accepted in the clinical routine around the world with a focus on urology, gynecology and general surgery. Even transoral robotic surgery (TORS) is applied on a regular basis in some specialized medical centers. However, the anatomical constraints and the delicate procedures at the anterior skull base prevent the introduction of RAS until today. We have performed an extended literature research on robot-assisted skull base surgery and added our own pre-clinical experiences to the list of publications. The overview includes available systems, pre-clinical and clinical applications, specific limitations, remaining challenges and an outlook into future developments.

Keywords: Robot-assisted surgery, anterior skull base, TORS, assistant

seen in general surgery. The first procedures of transoral robotic surgery (TORS) have been performed in 2005 mainly driven by Weinstein et al. in Philadelphia and consequently also in Germany.^{1,2} But until today, TORS is routinely used only in very specialized centers, which overcome obvious limitations like additional financial burden and limited patient benefit.³

The anterior skull base is a privileged space due to its anatomical constraints and the vulnerability of the bordering organs like the orbit, the olfactory organ and the frontal lobe of the brain. On the one hand, this makes the anterior skull base a suitable candidate for RAS. On the other hand, the needs for adjustments in RAS are especially challenging in this area.

Here, we present an overview of RAS at the anterior skull base including available systems, pre-clinical and clinical applications including our own experiences, specific limitations, remaining challenges and an outlook into future developments.

1. Introduction

Since the introduction of robot-assisted surgery (RAS) a series of robotic systems has been tested in almost all fields of medical surgery. Based on available numbers of performed procedures, it becomes clear that the main focus of RAS has been established in the fields of urology, gynecology and general surgery. The highest increase of RAS cases is currently

2. Material and Methods

An extended literature research was performed with the keywords robot, assistant system, surgery, skull base, endoscope, and TORS. Search platforms included medline, pubmed, google scholar and youtube.

Our research group applied the Flex system and the Cirq endoscope holding system for surgical procedures of the anterior skull base in pre-clinical body donor studies as described below.

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3. Results

Robotic assistant systems can be classified into (I) Master-slave systems, (II) hybrid systems, (III) continuum robots, and (IV) endoscope holding systems (**table 1**).

Master-slave systems. The Da Vinci Robot is the by far most widespread medical robotic system worldwide. It is, therefore, not surprising that most of the available publications dealing with anterior skull base surgery are based on this system (**figure 1**). Chauvet et al. described a series with cystic tumors in the sella turcica in four cases. All patients were treated with a combined transoral robotic and transnasal endoscopic approach.⁴ Henry et al. report on a series with three patients, which presented with large midline chordomas at the clivus. Again, the tumors were resected with a combined transnasal endoscopic and transoral robotic approach including splitting of the palate.⁵ The application of master-slave systems has also been described in pre-clinical studies. Faulkner et al. published on a combined transnasal and transorbital approach using the Versius system in a body donor study.⁶ Similarly, Marinho et al. developed a master-slave system called SmartArm, which enables the surgeon to perform stitching of the dura at the anterior skull base.⁷



Figure 1. The Da Vinci Xi system with one camera arm and three arms for instrumentation (courtesy of Intuitive Surgical).

Hybrid systems. These systems combine a master-slave-controlled element with features with other means of manipulation. E.g. the Flex system contains a computer-controlled flexible endoscope with flexible instruments, which

are manually driven. Our research group has demonstrated the possibility to reach the anterior skull base with the Flex system via midfacial degloving in a body donor experiment.⁸ However, the morbidity of the proposed approach may not be suitable for the usage in clinical cases (**figure 2**). Of note, the company Medrobotics, who invented the Flex system, is now insolvent due to a lost patent law suit.



Figure 2. The Flex system approaching the anterior skull base via a midfacial degloving approach (adapted from [8]).

Continuum robots. These robotic assistants contain a series of concentric pre-curved tubes, and each tube is controlled by a single motor. The tubes rotate and translate inside one another to reach each point in a three-dimensional space. A very active working group for the development of continuum robots is located in Nashville (USA). Although continuum robots are not suitable yet for clinical application, they may be able to improve dexterity, tool motion and end effector capabilities as compared to the currently used straight instruments.⁹ Another subgroup are the so-called tendon-driven continuum robots. These systems have a different construction plan and may have a series of advantages including reduced space requirements.¹⁰

Endoscope holding systems. Like other robot-like assistant systems, the endoscope holders display no autonomous motions. More specifically, they hold the endoscopes and can be controlled by foot paddles or voice commands. A selection of published endoscope holding systems is listed in **table 1**. Zappa et al. have enrolled 21 patients in a prospective study, in which the ‘Endoscope Robot’ was used for surgical skull base procedures. The authors described, that the system was especially advantageous in lengthy interventions through deep and narrow corridors.¹¹ Our own working group described the utilization of the Cirq endoscope holder for endonasal skull base surgery in a body donor study (**figure 3**). In this case the

Cirq model was combined with a rigid endoscope featuring an adjustable viewing angle.¹²



Figure 3. The Cirq endoscopic holding system is used for the visualization of the anterior skull base (adapted from [12]).

Ogiwara et al. developed a holding system called iArmS, which automatically follows the arm of the surgeon and supports it at an adequate position. The use of the system has been demonstrated in 43 patients, which underwent advanced surgery of the anterior skull base with a transsphenoidal approach.¹³ Hintschich et al. described the application of the EndofixExo system in 30 patients including a series of skull base procedures.¹⁴ The robotic science group from the University of Brescia developed an endoscope holding system (BEAR), which can be steered either by joystick or by registered glasses worn by the surgeon.¹⁵ The system was tested in skull base dummies.

Advantages and limitations. In privileged space like the skull base, robotic surgery may be able to improve our surgical skills by many different means. Master-slave systems regularly display high quality 3D vision, which by itself can improve surgical resection results due to improved visualization. Some assistant systems described above may be able to improve dexterity, tool motion and end effector capabilities as compared to the currently used straight instruments. Finally, assistant systems like the iArmS do not directly influence the surgical procedure, but aim to reduce the fatigue of the surgeon by supporting the arm.

On the other side, robotic assistant systems are currently limited by the lack of drilling instruments and the large diameter of the available instruments. In addition, there exists no possibility yet to integrate navigation systems to the available systems, and the lack of haptic feedback in some systems may be dangerous in procedures at the anterior skull base.¹⁶

4. Conclusion

Requirements for robotic skull base surgery are very sophisticated. As the potential number of treated patients is quite limited, the development of these systems is not in the focus of industrial companies and lies more in the hands of academic research groups.

Robotic assistant systems for skull base surgery should be specifically designed for this anatomical area and they have to meet the size requirements in order to avoid interference with other tools or anatomical landmarks. Additional tools like a flexible drilling system have yet to be developed to make robotic skull base surgery beneficial for the patients.

Author Statement

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Table 1. Classification of robotic assistance systems

Classification	Examples*
Master-slave systems	Avatera (Avateramedical), Da Vinci (Intuitive Surgical), Hugo (Medtronic), Ottava (Johnson&Johnson), Senhance (Asensus Surgical), SmartArm (University of Tokio), Versius (CMR Surgical)
Hybrid systems	Flex (Medrobotics), MicroRALP (EU-project FP7 ICT # 288663)
Continuum robots	Vanderbilt University, University of Toronto, and Nanjing University
Endoscope holding systems	EndofixExo (Aktormed), Cirq (Medineering/Brainlab), iArmS (Shinshu University), BEAR (Brescia University)

(*) not including all available systems