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Technical Strategies and Learning Curve in Robotic-assisted Peripheral Nerve Surgery

Martin Aman, MD, PhD*†
Felix Struebing, MD*†
Jonathan Weigel*†
Amir K. Bigdeli, MD*†
Emre Gazyakan, MD, MSc*†
Ulrich Kneser, MD*†
Leila Harhaus, MD*†
Arne H. Boecker, MD*†

Background: Robotic-assisted peripheral nerve surgery (RASPN) has emerged as a promising advancement in microsurgery, offering enhanced precision and tremor reduction for nerve coaptations. This study investigated the largest published patient collective in RASPN and provided specific technical aspects, operative setups, and a learning curve.
Methods: Data collection involved creating a prospective database that recorded surgical details such as surgery type, duration, nerve coaptation time, and number of stitches. The experienced surgeon first underwent a 12-hour training program utilizing the Symani robot system in combination with optical magnification tools before using the system clinically.
Results: The study included 19 patients who underwent robot-assisted peripheral nerve reconstruction. The cohort included six men (31.6%) and 13 women (68.4%), with an average age of 53.8 ± 18.4 years. The procedures included nerve transfers, targeted muscle reinnervation, neurotized free flaps, and autologous nerve grafts. Learning curve analysis revealed no significant reduction in time per stitch over the initial nine coaptations (4.9 ± 0.5 min) compared with the last 10 coaptations (5.5 ± 1.5 min).
Conclusions: The learning curve for RASPN was compared with early experiences with other surgical robots, emphasizing the importance of surgical proficiency and assistant training. Obstacles such as instrument grip strength and blood clot formation were highlighted, and suggestions for future advancements were proposed. RASPN presents an exciting opportunity to enhance precision; however, ongoing research and optimization are necessary to fully harness its benefits. *(Plast Reconstr Surg Glob Open 2024; 12:e6221; doi: 10.1097/GOX.0000000000006221; Published online 9 October 2024.)*

INTRODUCTION

Robotic-assisted procedures have been heralded as a future-oriented surgical treatment technique. In contrast to conventional surgical approaches, robotic surgery offers distinct advantages, including minimal invasiveness, resulting in reduced local tissue trauma, augmented surgical field visualization facilitated by magnified three-dimensional (3D) high-definition imaging, intuitive control, elimination of physiological hand tremors, and improved ergonomic design for the surgeon.[1–3] Despite the absence of haptic feedback, the indications for robotic utilization have been unequivocally established. Robotic-assisted surgery is now performed ubiquitously across diverse surgical disciplines, including urology,[4] gynecology,[5] hepatobiliary surgery,[6] and colorectal surgery.[7] Preliminary and clinical studies have begun to explore its potential applications, particularly in microsurgery and microvascular anastomosis, which have attracted significant attention.[1,2,8]

Robotic microsurgery allows precise nerve coaptations, even in anatomically challenging areas, by reducing tremors. Although initial studies have demonstrated the feasibility of lymphovenous anastomosis[9] and nerve coaptation,[10,11] there remains a significant need for optimization in terms of technical implementation. We focus in this work on the technical execution, operative setup, and

*From the *Department of Hand, Plastic and Reconstructive Surgery, Burn Center, B.G. Trauma Center Ludwigshafen, Ludwigshafen, Germany; and †Department of Hand and Plastic Surgery, University of Heidelberg, Heidelberg, Germany.*

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learning curve for robotic-assisted peripheral nerve surgery (RASPN) with, to our knowledge, the largest patient collective published yet.

MATERIALS AND METHODS

Data Collection

We built a prospective database that included all robot-assisted peripheral nerve surgery cases. All patients underwent surgery at an A-level trauma center specializing in peripheral nerve surgery, performed by a single operator. Surgical data were obtained, including the type of peripheral nerve surgery, duration of the surgery, duration of nerve coaptation, and number of stitches. The study protocol adhered to the Declaration of Helsinki, and ethical approval was obtained from the local committee (Medical Commission Rhineland-Palatinate, Mainz, Germany; approval no.: 2023-16997). Between March 2023 and November 2023, the study included all patients who underwent microsurgical procedures such as nerve transfer, targeted muscle reinnervation (TMR), or neurotized free flap procedures in which one or more nerve coaptations were performed using the Symani microsurgical system. Data were extracted from medical records or documented intraoperatively, including patient demographics and comorbidities. We also measured and recorded the duration per stitch and the total time for coaptation using the Symani robotic system.

Surgical Technique

All surgeons must complete 12-hour dry training on the handling and management of complications associated with the Symani surgical system before surgery, as previously described.[12] Nerve coaptation was performed by a single experienced surgeon (Tang level 5 expert) using a Symani robot system in combination with a conventional microscope (Mitaka MM51; Mitaka Kohki Ltd, Tokyo, Japan) or a digital exoscope using 4 K-3D screens (Olympus OrbEye; Olympus K.K., Toyko, Japan) for optical magnification. A 9-0 or 10-0 Ethilon suture was used.

Statistical Analysis

This study analyzed data adhering to a normal distribution using one-way ANOVA for the time per stitch analysis. The comparison of the first nine and the second 10 anastomoses were performed with a Welch t test. No datasets exhibited nonnormal distribution characteristics. Normal distribution was tested with the Shapiro–Wilk test. The results are presented as mean ± standard error. A threshold of a P value of less than 0.05 was established for statistical significance. Comprehensive data analysis was performed using GraphPad Prism Version 9.0.2 for Mac (GraphPad Software, San Diego, Calif.).

RESULTS

Learning Curve and Limitations in RASPN

Patient Collective

Nineteen patients underwent robot-assisted peripheral nerve reconstruction (Table 1). The cohort comprised six men (31.6%) and 13 women (68.4%), with an average age of 53.8 ± 18.4 years. Among these patients, arterial hypertension emerged as the most common perioperative comorbidity, affecting eight of the 19 patients (42.1%). This was followed by one patient with coagulopathy (5.3%). The patient demographics and clinical characteristics are summarized in Figure 1.

We completed 19 robot-assisted peripheral nerve reconstructions, incorporating 25 nerve coaptations using the Symani system. The primary indications for these reconstructions were trauma, infections, and burns, where nerve procedures were one part of the necessary operative steps, as detailed in Figure 1 and Table 2.

Takeaways

Question: Is robot-assisted surgery possible in the field of peripheral nerve surgery?

Findings: Robot-assisted surgery is possible in the field of peripheral nerve surgery and underlies a substantial learning curve.

Meaning: The potential of robot-assisted peripheral nerve surgery is tremendous but needs further technical improvement and specific training of the surgeon.

RASPN—Learning Curve

Nerve transfers and TMR were performed by a single surgeon and surgical assistant also trained on the Symani robot. A total of 25 nerve coaptations were performed with an average nerve coaptation time of 23 ± 12 minutes (Fig. 2A). The mean nerve diameter was 3.4 ± 2.0 mm. A median of five stitches was used for nerve coaptation (interquartile range 3.5). Time per stitch during peripheral nerve reconstruction ranged from 1.7 to 8.8 minutes with an average of 4.5 ± 1.7 minutes (Fig. 2B). Time per stitch did not differ between nerve transfers (5.4 ± 1.6 min) or TMR (5.1 ± 0.5 min), but with neurotized free flaps (2.4 ± 0.8 min) (Fig. 2C).

No significant differences were found in the time per stitch between four and six cases and more than six cases (Fig. 3A), compared with the time per stitch for the first three cases. There was a nonsignificant increase ($P < 0.05$) in the time per stitch when comparing the

Table 1. Baseline Patient Characteristics

Parameter	Cohort (n = 19)
Age, mean y ± SD	53.84 ± 18.4
Male sex	6 (31.6)
ASA classification, median ± IQR	2 ± 2
Comorbidities	
Hypertension	8 (47.4)
Active smoking	3 (15.8)
Diabetes	1 (5.3)
Obesity (BMI ≥ 30 kg/m^2)	3 (15.8)
Coagulopathy	1 (5.3)
Other risk factors	7 (42.1)

Reported as n (%), unless otherwise stated.

ASA, American Society of Anesthesiologists; BMI, body mass index; IQR, interquartile range.

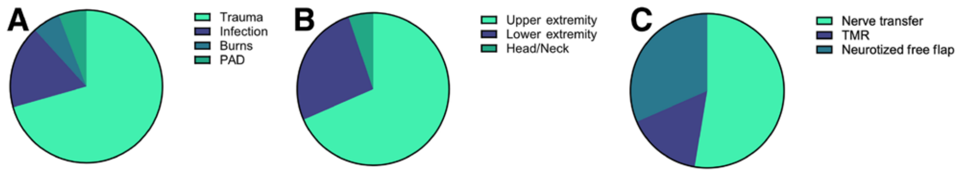

Fig. 1. Etiology of the peripheral nerve lesion treated with RASPN with direct nerve repair, nerve transfers or, for example, burn defects with neurotized free flap reconstruction. RASPN was mainly performed for traumatic injuries (A), with a higher frequency in the upper extremity (B). C, Our team primarily focuses on nerve transfers for peripheral nerve reconstruction. PAD, peripheral artery disease; TMR, targeted muscle reinnervation.

Table 2. Procedure Distribution

Procedure	Cohort (n = 19)
Autologous nerve transfer	9 (47.4)
TMR	4 (21
Neurotized free flap	
ALT	2 (10.5)
Gracilis	2 (10.5)
Latissimus dorsi	1 (5.3)
TMG/TUG	1 (5.3)

Reported as n (%), unless otherwise stated.
ALT, anterior lateral thigh flap; TMG, transverse myocutaneous gracilis flap; TMR, targeted muscle reinnervation; TUG, transverse upper gracilis flap.

first nine nerve coaptations (4.9 ± 0.5 min) with the last 10 coaptations (5.5 ± 1.5 min) (Fig. 3B) and overall cases (Fig. 3C).

Surgical Complications and Limitations

Three postoperative complications were observed in the patient cohort. Of these, two were classified as major: one case involved a hematoma at the recipient site after neurotized free flap reconstruction and the other was a complete loss of a neurotized flap. Additionally, a minor complication was observed in the form of a postoperative wound-healing disorder.

A transition from RASPN to conventional microsurgery was necessitated in two instances. The first case presented major scarring of a peripheral nerve that was impossible to overcome during epineural suturing with the Symani robot. In the second case, nerve transfer involving the anterior interosseous nerve to the deep branch of the ulnar nerve was attempted. The complex trajectory and anatomical findings in this specific patient necessitated nerve coaptation within a 3D space; typically, however, this nerve transfer can be conducted with the coaptation site on a flat plane. Consequently, the surgical approach was altered to conventional microsurgery.

Potential Technical Improvement in RASPN

When improving RASPN, logistics such as placement of the Symani robot in the operating theater, choice of magnification system (exoscope versus microscope), and position of surgeons must be considered. Secondary personal resources, such as the training of the nursing staff and the surgical assistant, must be considered to raise the full potential of RASPN.

Logistics in RASPN

In the limited space of the operating room, it is advisable to ensure that the microsurgical robot remains highly maneuverable. Depending on the optical magnification, two distinct setups are feasible. One option involves using a conventional microscope, typically found in a microsurgical department, for robot-assisted peripheral nerve surgery. Alternatively, an exoscope combined with a 3D display can be used for the same procedure.

The microscope is positioned across the robot directly over the surgical site. The microscope oculars must be aligned as close to the edge of the operating table as possible. Therefore, the surgeon must adeptly navigate between viewing through the microscope's ocular lens and managing the limited space available for controlling the robot via joysticks. Furthermore, this approach requires a larger operating room owing to the inflexibility of the microscope. However, microscopes offer several advantages over exoscopes, including widespread availability in microsurgical units; exceptional contrast and resolution; and instantaneous 1:1 image transmission, avoiding the

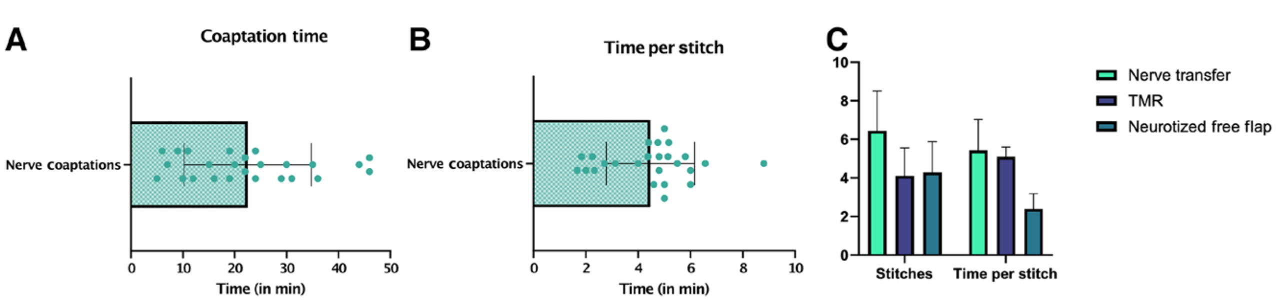

Fig. 2. Learning curve focusing on the needed time and operation. The coaptation of all cases is shown (A), as well as time per stitch in general (B). C, Time per stitch did not differ significantly depending on the applied procedure.

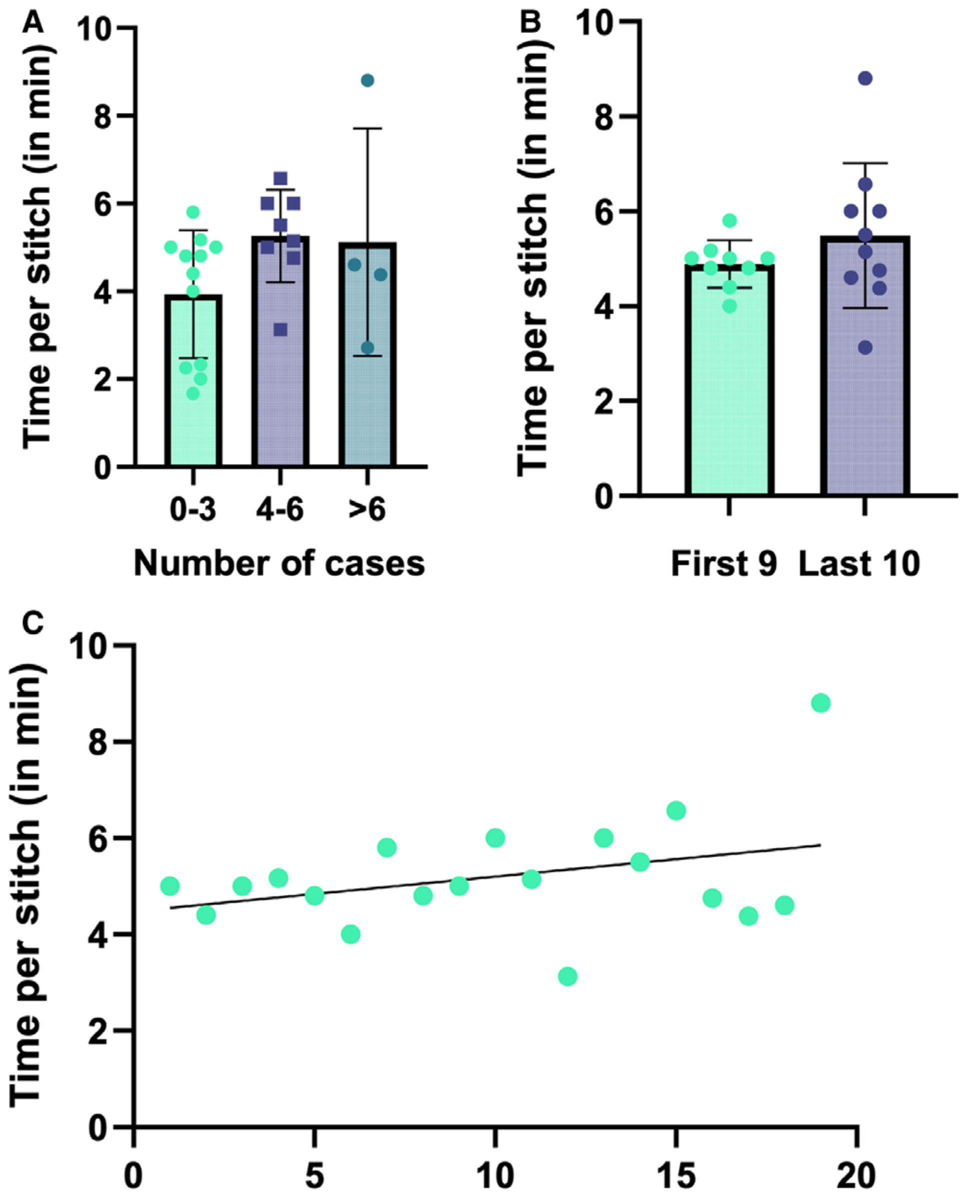

Fig. 3. Learning curve of RASPN. Nerve coaptations of a single surgeon performing nerve transfers. A, Lower learning curve over the amount of nerve coaptations. No significant differences were shown between the first nine nerve coaptations and the second 10 nerve coaptations (B) and overall cases (C).

delay associated with projecting 3D visualization onto a separate screen.

Alternatively, an exoscope can be used as the magnification system. Our department uses the OrbEye system (Olympus K.K.) as an exoscope for magnification. When using this setup, two monitors are usually necessary to ensure that the surgeon and assistant have unrestricted visibility at the surgical site. Compared with conventional microscopes, OrbEye devices are significantly smaller and require less space, especially when using large and bulky surgical robots.

Positioning of the Surgeon

Surgeons' positioning differs depending on the use of the optical magnification system in the peripheral nerve system. With a conventional microscope, it is recommended that the surgeon sit between the arms of the microsurgical robot to have direct visualization and transmission of their movements. The surgeon must sit near the microscope to look through the oculars and have sufficient space to move with the robot's joysticks. The assistant sits opposite to the surgeon and looks through the microscope.

When using the OrbEye exoscope, the assistant is placed in the position of the surgeon and sits between the robot's arms, assisting nerve coaptation. In this setup, the assistant receives optical magnification through a 3D screen in front of the assistant. OrbEye is also positioned opposite, and the camera is rotated to allow direct

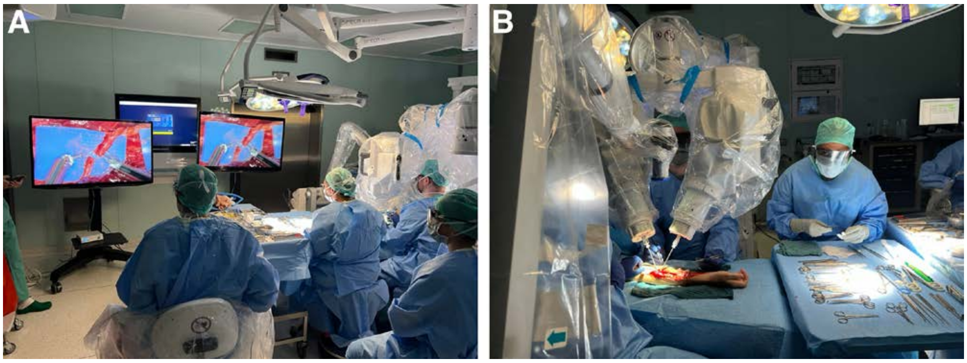

Fig. 4. Surgeon position by robotic peripheral nerve surgery. The surgeon and surgical assistant are sitting towards the 3D screen showing the operative situs. A, The surgical assistant sits between the robotic arms, supporting the surgeon performing the epineural suture. B, The nursing staff sits parallel to the surgical assistant's visualization of the operative situs.

transmission of an unmirrored surgical field (Fig. 4). The compact structure permits clear 3D visualization and magnification without impairing the surgeon's vision. The upper and lower extremities are particularly accessible, and this arrangement can reach anatomically challenging areas, as demonstrated by Aman et al.[13]

Surgical Technique in RASPN

The surgeon can perform sterile and unsterile robot-assisted nerve coaptation. However, if RASPN is performed without sterility, an exoscope is necessary to separate the robotic nerve coaptation from the field of surgery. This study exclusively performed RASPN procedures under sterile conditions. The robotic system enabled precise nerve coaptation and effectively eliminated physiological tremors. This advancement facilitated direct fascicular-to-fascicular nerve coaptation, as demonstrated in the video. [**See Video (online),** which displays needle flipping due to decreased grip strength]. The movements of the robotic arms can be tailored according to the preferences of the peripheral nerve surgeon.

A critical aspect in overcoming the inherent resistance of the peripheral nerve is the accurate positioning of the microsurgical needle. It should be securely fixed to the upper two-thirds of the needle holder to maximize grip strength and prevent needle rotation, which can significantly hinder precise nerve coaptation. Additionally, the use of microsurgical forceps as a counterfort is advisable for suturing the epineural layer and stabilizing the operative field.

The robotic system translates manual movement into robotic action. For surgeons in the initial stages of the learning curve, starting with a lower movement translation is recommended to facilitate acclimatization to the system's mechanics.

Role of the Surgical Assistant

The role of the assistant requires more effort than conventional microsurgical procedures. Being accustomed to positioning between robot arms can be challenging for the assistant. During peripheral nerve surgery, the assistant must appropriately position the nerves and nerve stumps in the surgical field to enable tension-free and precise nerve coaptation. After suturing, the assistant can help pull the suture, which is particularly beneficial in the initial stages when the excursion of the robot arms is limited to a few centimeters. Once the suturing is completed, the assistant or instruments attached to the robot can cut the suture. Furthermore, cleaning the instruments relies more on the surgical assistant than on the nurse because of the static fixation of the microsurgical arms of the robot system and should be focused on when many epineural sutures are needed. In our personal experience, robot-assisted microsurgery is less challenging when the surgical assistant is trained in the robotic system.

DISCUSSION

Robotic-assisted microsurgery, specifically in peripheral nerve surgery, represents a significant advancement, offering enhanced precision in microanastomosis and nerve coaptation by mitigating physiological tremors and allowing movement scaling. This technology enables seamless handling of superfine structures, making the precise coaptation of fascicles in nerve surgery feasible.

In general, experience with RASPN as a subdiscipline of reconstructive surgery is still very limited. Garcia et al[14] gained their first experience with telerobotic brachial plexus reconstruction with sural nerve grafting. Further studies are needed to raise the potential of an endoscopic or minimally invasive approach to transfer peripheral nerves or reconstruct them.[14–16] Others aimed to minimize the side effects of autologous nerve graft harvesting.[17] Given its advantages in tremor elimination and ergonomics, the ideal indications for robot-assisted surgery are yet to be fully ascertained. The indication may not only be influenced by parameters of the operation itself, such as the height of the peripheral nerve injury, nerve diameter, or the patient's general condition. Robotic assistance offers high precision in nerve coaptation for nerves with small diameters and may be advantageous for nerve transfers, autologous nerve transplantation, and TMR compared with conventional microsurgery. In such cases, the peripheral nerves are usually located outside the trauma zone and typically do not undergo extensive fibrotic changes. In main trunk injuries, where the peripheral nerve is thicker, the advantage of tremor reduction is offset by the decreased table strength of the microsurgical instruments, causing insufficient needle fixation. As already seen for the main vessels (Struebing et al), the use of RASPN is still limited. Furthermore, the necessity of investigating the impact of tremor reduction through the adjunctive application of robotic assistance in peripheral nerve surgery—particularly its contribution to the improved placement of sutures during nerve coaptation—must be taken into future investigations. Ultimately, the extent of functional recovery hinges upon the quality of the nerve coaptation.

Relevance of the Magnification System

The dependency of the Symani robotic system on external magnification tools such as exoscopes or microscopes presents operational challenges. Microscopes, offering superior resolution and contrast, may hinder joystick maneuverability owing to spatial constraints. The integration of exoscopes entails a secondary learning curve, as already mentioned by others,[18] where we noted contrast reduction and slight delays in movement visualization compared with microscopes. This makes the simultaneous adoption of the robotic system and exoscope challenging.

In contrast, systems such as da Vinci are designed for comprehensive procedural support, unlike Symani, which is limited to microsurgical applications. Moreover, da Vinci was created to enable precise resection and minimize extensive exploration, without the need for further surgical assistance. Currently, there are no available instruments that provide comprehensive support for microsurgical preparation or resection, which would extend the involvement of the Symani system for further surgical steps besides microsurgery. Nevertheless, the potential to eliminate physiological tremors and to reduce human limitations, a new field in RASPN can be approached and nerve coaptations can be made with the smallest fasciles even possible. In this context, RASPN is not further limited by the human itself, but by the magnification systems and suture materials available. Dealing with the learning curve for RASPN.

Regarding the learning curve of RASPN, parallels can be drawn with the initial experience of the da Vinci robot. In our series of the first 25 nerve coapations with an average time of 23 ± 12 minutes by a nerve diameter mean of 3.4 ± 2.0 mm for one nerve coaptation, there is a tremendous time investment necessary for RASPN. Consequently, the time per stitch also increases, showing results of 3.4 ± 2.0 mm with a greater time investment for nerve transfers and TMR. This may be reflected by the more challenging anatomic circumstances of performing nerve transfers or TMR compared with neurotized free flaps. For experienced microsurgeons, the learning curve in RASPN appeared to be negligible, even after 19 cases. No significant decrease in time per stitch was observed in all cases in general, and by comparing the first nine to the last 10 cases, this is in line with the first experience of the da Vinci robot, which showed flat learning curves across different surgery types, such as prostatectomy and mitral valve repair.[19] Factors such as nerve diameter and fibrotic changes may influence suturing time, as indications were liberated with gaining experience. However, standard procedures in peripheral nerve surgery, such as autologous nerve transplantation, are technically more demanding in RASPN because supporting tools such as the approximator for microanastomosis are not feasible in nerve surgery. The efficacy of RASPN is markedly enhanced by the presence of a skilled surgical assistant, particularly in tasks such as suture management, instrument cleansing, and optimization of the surgical field. Therefore, special training curricula should be established to properly implement robotic microsurgery skills for residents, as was seen for the da Vinci System.[20]

Obstacles to Overcome in RASPN

RASPN faces an obstacle owing to the inferior grip strength of microsurgical instruments. Experience has shown that nerve coaptation often requires more tangential sutures than microvascular anastomosis does. Therefore, secure grasp of the needle is essential. Fibrotic altered nerves or main trunk injuries can hinder robotic nerve coaptation owing to nerve resistance. The needle may flip away in the needle holder of the robot system while attempting to penetrate the epineurium. An additional issue is that instruments tend to become heavily contaminated with blood clots after multiple epineural sutures. In conventional microsurgery, there is a well-established routine for cleaning the instruments at every return; however, this is not possible in RASPN because the instruments are fixed to the robot. Therefore, cleaning instruments relies on a surgical assistant. Future advancements in surgical instruments should include the application of a specialized anticoagulant coating to mitigate blood clotting issues. Furthermore, the technology of RASPN is also limited by the investment cost of the device and the running costs for the instruments. Therefore, RASPN is currently limited to early adopters and first movers in the field of peripheral nerve surgery. To address the issue of cost containment and promote sustainability, next-generation instruments should aim to be sterilizable and reusable, thereby reducing plastic waste and providing ecological benefits.

Future Perspective in the Field of Robot-assisted Peripheral Nerve Surgery

By combining microsurgical robotic systems with high-resolution 3D magnification systems, such as the OrbEye exoscope, the concept of telemedicine surgery becomes possible. It may be feasible to provide complex case management even in regions without a microsurgical center. Furthermore, RASPN provides a chance to utilize the expertise of highly skilled microsurgeons who are otherwise unable to perform due to an increase in physiological tremors in older surgeons.[21] With continued developments and refinements, robotic microsurgery can revolutionize the field, improve surgical outcomes, and expand access to advanced microsurgical techniques.

In conclusion, by reducing tremors and eliminating human errors, this innovative approach enables the precise and seamless treatment of superfine structures, potentially improving nerve surgery outcomes. However, this field is still in its early stages, and there are areas for improvement and ongoing research which have to be addressed, like the high costs of the systems and the containing costs as well as the grip strength of the needle holder, to evolve this field from a pioneer technology to a technology used on a clinical basis in the field of peripheral nerve surgery.

Arne H. Boecker, MD
B.G. Trauma Center Ludwigshafen
Ludwig-Guttmann-Str. 13
67071 Ludwigshafen, Germany
E-mail: arnehendrik.boecker@bgu-ludwigshafen.de

DISCLOSURE

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