Robot-Assisted Surgery of the Shoulder Girdle and Brachial Plexus

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Abstract

New developments in the surgery of the brachial plexus include the use of less invasive surgical approaches and more precise techniques. The theoretical advantages of the use of robotics versus endoscopy are the disappearance of physiological tremor, three-dimensional vision, high definition, magnification, and superior ergonomics. On a fresh cadaver, a dissection space was created and maintained by insufflation of CO₂. The supraclavicular brachial plexus was dissected using the da Vinci robot (Intuitive Surgical, Sunnyvale, CA). A segment of the C5 nerve root was grafted robotically. A series of eight clinical cases of nerve damage around the shoulder girdle were operated on using the da Vinci robot. The ability to perform successful microneural repair was confirmed in both the authors' clinical and experimental studies, but the entire potential of robotically assisted microneural surgery was not realized during these initial cases because an open incision was still required.

Keywords

- brachial plexus
- da Vinci robot
- telemicrosurgery
- shoulder girdle

Robotic-assisted surgery of the shoulder girdle and brachial plexus is still in its early stages. It would be ideal to have even finer and more suitable instruments to apply fibrin glue or electrostimulation in nerve surgery. Nevertheless, the prospects of minimally invasive techniques would allow acute and subacute surgical approach of traumatic brachial plexus palsy safely, without significant and cicatricial morbidity.

Surgery of the shoulder girdle and brachial plexus has undergone several stages of development that use less invasive surgical approaches and techniques that are more precise.

Originally, since the advent of modern anesthesia until the mid-20th century, a proliferation of so-called open surgical approaches has been described. Each had a specific goal to attain access to deep tissue to perform repair of a given lesion while preserving essential structures; however, at this time, the surgeon did not pay much attention to the size of the incision or with the extent of subcutaneous tissue dissection. It was the reign of the adage "big surgeon, big incision." Today,

surgery has lost some of this bravado and some of the massive surgical approaches with it. Despite the publication of the first cadaveric studies about glenohumeral arthroscopy in the 1950s through the 1980s, open surgery has remained the only approach to address the shoulder girdle.^{1,2} The purpose of arthroscopy is to attain access to deep tissue to perform the repair of various types of lesions, with very limited associated iatrogenic injury. But it was only in the 1990s that glenohumeral arthroscopy became popular in clinical practice.^{3–5} Subsequently, arthroscopy of the shoulder girdle itself evolved through several stages of development.⁶ In a first stage, it became a revolutionary diagnostic tool without

significant interventional utility in the clinical setting. The second step was to develop surgical techniques that were equivalent to conventional open surgery⁷ (repair of glenohumeral ligaments, acromioplasty, acromioclavicular resection, suture of the rotator cuff). The third step was to provide new surgical techniques (SLAP lesion chondroplasties, washing, partial debridement, shrinkages, mini-open repair for rotator cuff). The fourth step was to go beyond the glenohumeral joint to reach other joints such as the acromioclavicular,^{8–11} the sternoclavicular,¹² or the scapulothoracic joint.¹³ The fifth stage, still under development, is to extend endoscopy to the peripheral nervous tissue. The liberation of the supraclavicular nerve has already been the subject of a few publications^{14–16}; recent work suggests endoscopic approach of the brachial plexus^{17,18} and even its repair.¹⁹ This is the stage at which robotic-assisted microneural surgery will have its greatest application.

Modern concepts in peripheral nerve repair were described in the late 19th century. It was recognized early on that meticulous handling of the nerves, careful suturing, and matching of the internal fascicles is associated with reliable clinical results whether grafting or performing primary repair. Technical limitations certainly affect the results of nerve repair and these pertain particularly to imprecision at the anastomotic level. These principles are important and can be applied to any peripheral nerve repair; however, there are specific anatomic sites that are anatomically less accessible and where open access has distinct disadvantages.

The brachial plexus is one such environment, where an intricate web-like array of nerves emerges from C4 to T1 at the vertebral level. There are multiple interwoven connections between cervical, supraclavicular, and infraclavicular regions. The complex anatomy of the brachial plexus presents challenges for the surgeon. In addition to precise identification of the origin of the injured nerve, matching it to appropriate target is critical. Establishing these anatomic pathways can be very difficult, and often nerve grafts or conduits are necessary. Access to the brachial plexus traditionally requires a long incision, with significant dissection, resulting in cicatricial morbidity. For this reason, the typical approach has been to treat closed injuries by watchful waiting and serial physical examinations. Serial examination is useful in determining candidacy for surgical intervention. However, this approach can be accompanied by a delay in exploration of 3 to 6 months postinjury. This adds a critical degree of difficulty to the surgery, as exposure and exploration of the plexus and its components requires dissection through scar tissue around and within the neural structures. Unfortunately, physical examination, imaging, and electromyography cannot distinguish between neurotmesis, axonotmesis, or neurapraxia. Many patients will ultimately require exploration if symptoms do not resolve, delaying appropriate treatment by up to 6 months, and potentially compromising results.

Although endoscopic approaches could mitigate the cost of early exploration by reducing incisional morbidity, the technique does not allow for the finely tuned microneural repairs

Fig. 1 Telemicrosurgical workstation with the da Vinci S robot (Intuitive Surgical, Sunnyvale, CA). To the left of the figure is the main console that allows the operator to control the articulated arms of the movable carriage which is in the middle arm of figure. Video column to the right of the figure (provided courtesy of Intuitive Surgical, Sunnyvale, CA).

that are required once the lesion has been identified. In this context, we believe it possible to go one step further than endoscopic approaches to the brachial plexus by developing robot-assisted surgical approaches to the shoulder girdle and brachial plexus. The theoretical advantages of robotics versus endoscopy are the disappearance of physiological tremor, three-dimensional (3D) vision, high definition, magnification, and superior ergonomics.²⁰ These advantages could theoretically allow not only early diagnosis through minimally invasive access, but also early repair without the open incision. First, we will present our experimental work before reporting our preliminary clinical experience.

Experimental Surgery

Under the surgical treatment of paralysis of the shoulder girdle, the recent development of neurotizations and distal nerve transfers should not cause us to forget that direct lesion exploration retains some indications, especially in total brachial plexus palsy. Admittedly, the surgical approach of the supraclavicular plexus, usually performed more than 3 months past the trauma, is made difficult by significant soft tissue fibrosis and cicatrix. For this reason, the development of a minimally invasive technique could allow earlier exploration and possible repair within 8 days of the trauma. The aim would be to make an assessment and repair of graftable roots without burning bridges to secondary, complementary neurotizations.

The following study was conducted at the laboratory of experimental robotic surgery at Intuitive Surgical in Sunnyvale, California. On a fresh cadaver, we prepared three surgical routes of 8 mm facing the lateral half of the right clavicle, spaced ~6 cm apart, origination from the lateral extremity of the clavicle more than 9 cm from the cervical region. We then set up a da Vinci S robot (Intuitive Surgical) (►Fig. 1) next to the right shoulder. Two robotic arms carrying suitable surgical instruments were introduced through the most lateral and the most medial cutaneous tunnels. A dual endoscopic 3D vision high-definition camera was introduced through the two remaining skin incisions. A dissection space was created using forceps and bipolar scissors and maintained by insufflation of CO₂ at a pressure of 4 mm Hg (►Fig. 2).

The supraclavicular brachial plexus and adjacent anatomical structures were dissected robotically: jugular vein, omohyoid muscle, phrenic nerve, scalene muscles, and nerve roots from C4 to C7 (►Fig. 3). Hemostasis was achieved by electrocoagulation and the placement of hemoclips. A complete dissection and full exposure of the supraclavicular portion of the brachial plexus was successfully achieved in this experiment. An artificial lesion was created by resecting a 2 cm segment of the C5 nerve root. The nerve segment was then grafted back into the nerve gap robotically by performing separate epi- and perineural suturing with a 10/0 nylon introduced through an instrumental port.

Our results showed that endoscopic treatment of supraclavicular brachial plexus palsy is feasible. Insufflation of CO₂ at low pressure maintained a comfortable work space and there was no subcutaneous emphysema from gas diffusion

into the tissue planes. The use of the surgical robot enabled easy dissection and allowed microsurgical suturing under good conditions. The improvement of natural range of motion and precision of the surgeon's movements, allowed the investigator to perform an epineural suture with nerve graft in the small cavity space created by the gas insufflation.

Fig. 2 Preparation of a robot-assisted endoscopic repair of the right supraclavicular brachial plexus. (A) Introduction of a finger through one of the instrumental routes and subcutaneous detachment to prepare the workspace. (B) Three trocars in place. (C) Robot in place ready to operate. Note that the stand of the robot is at the head of the opposite side.

Fig. 3 Endoscopic view from the main console of a robot-assisted repair of the right supraclavicular brachial plexus. (A) View of the workspace, gradually enlarged by instrumental dissection. Note the bipolar “Maryland” clamps on either side of the operative field. (B) View of the workspace. Note the omohyoid muscle (*black star*). (C) View of the workspace. Note the jugular vein (*black star*). (D) View of the workspace. Note hemostasis done by clip placement on a branch of the jugular vein (*black arrow*). (E) View of the workspace. Note the phrenic nerve (*black star*). (F) View of the workspace. Note the roots of the supraclavicular brachial plexus: C5 (*white star*), C6 (*black star*), C7 (*black arrow*). (G) View of the workspace. The C5 root was cut 2 cm to form a transplant model (*black star*). The black arrow shows the loss of nerve substance. (H) View of the workspace. Introduction of a 10/0 nylon carried through one of the two instrumental trocars. The needle is seized by a Black Diamond forceps. (I) View of the workspace. Note the passage of the needle through the proximal stump of the root C5. The *black star* shows the transplant model. (J) View of workspace. Note the first point of clamping of the proximal suture. The *black star* shows the transplant model. (K) View of workspace. View of the final graft. The *white star* shows the C5 portion upstream of the graft. The *white star* shows the C5 portion downstream of the graft.

Clinical Experiences

Since the 1990s, telesurgery has commonly been used in urologic, cardiac, gynecologic, and gastrointestinal surgery. It has brought significant advances to these fields, including reduction of operative time, safety, precision of gesture, lowering of bleeding time, and comfort of the surgeon. For all these reasons, we developed the concept of telemicrosurgery²¹ and have used it for certain limited surgical indications within peripheral nerve surgery.²² We

report a series of eight cases of nerve damage around the shoulder girdle, operated using a da Vinci S robot since 2009.

All patients underwent surgery at Strasbourg University Hospital (► **Table 1**). Our series included eight patients, all male with a mean age of 27 years (20–35 yr). There were two complete brachial plexus palsies, three partial C5–C6 brachial plexus palsies, two continuous lesions of the axillary nerve, and one paralysis associated with axillary and musculocutaneous nerve damage.

Table 1 Clinical series of eight paralyses of the shoulder girdle

Patient	Gender	Age	Side (L, R)	Lesion	Intervention	Follow-Up (mo)	BMRC quotation (1–5)
1	M	35	L	Total brachial plexus palsy	C5-musculo-cutaneous graft	16	0
2	M	23	R	Total brachial plexus palsy	XI-musculo-cutaneous graft	0	0
3	M	33	L	Axillary nerve palsy	Neurolysis	12	5
4	M	20	L	Axillary nerve palsy	Neurolysis	10	5
5	M	22	R	C5–C6 roots palsy	Oberlin procedure	8	3
6	M	31	L	C5–C6 roots palsy	Oberlin procedure	7	4
7	M	24	R	C5–C6 roots palsy	Oberlin procedure	4	0
8	M	26	L	Axillary nerve palsy Musculo-cutaneous nerve palsy	Somsak procedure Oberlin procedure	3	0 0

Abbreviations: L, left; R, right; BMRC, quotation of muscle strength by the British Medical Research Council.

All patients were operated on using telemicrosurgery with a da Vinci S robot. The robot was equipped with three arms, one of which was armed with a Pott scissors and the others with two Black Diamond microsurgical needle drivers. All suturing was performed robotically with 10/0 or 9/0 nylon and reinforced with biological glue.

Two complete brachial plexus palsies were treated with a sural nerve graft between the C5 root or the spinal nerve and the musculocutaneous nerve. These procedures were performed after open skin undermining of the supraclavicular region to the cervical region. Three 8-mm incisions were converted to open surgery in both cases due to difficulties of dissection. C5–C6 avulsions of the brachial plexus were treated by neurotization of the fascicle of the ulnar nerve onto the motor branch of the musculocutaneous nerve (Oberlin). In both cases, the axillary nerve exploration using the robot had to be converted to open exposure due to the inability to access operative area with robotic instrumentation.

In case of associated paralysis of the axillary and musculocutaneous nerve, axillary nerve neurotization by the long portion of the triceps (Somsak) and a neurotization of the fascicle of the ulnar nerve onto the motor branch of the musculocutaneous (Oberlin) were performed.

It follows from this short series with still very short follow-up that the prospects of using the telemicrosurgery in peripheral nerve surgery vary depending on the level of injury.

Discussion

Clinical use of the robotic telemanipulation was introduced to perform nerve repair by Philippe Liverneux in France in 2009, by Stacey Berner in the United States in 2010, and by Gustavo Mantovani in Brazil in 2011. Initially, the robot was used in place of the conventional microscope after a traditional open dissection technique. When the surgery reached the point of neural repair, instead of installing the microscope, the robot was brought into the operating field and the surgeon performed the anastomosis from the surgeon's console. This technique was successfully utilized to perform

brachial plexus repair and to treat other peripheral nerve injuries of the upper and lower limbs.

An initial barrier to acceptance of the robot as a useful device for assisting in microsurgery was the concern held by some surgeons regarding the lack of haptic feedback from the telemanipulator systems available. The initial experimental experience suggested that there was no difficulty manipulating fine suture material with the robot, suggesting that haptic sensation was not necessary. This was further confirmed by an interesting and simple study showing that most experienced microsurgeons are not able to feel the haptic feedback when performing conventional microsurgery.²³

The ability to perform successful microneural repair was confirmed in both our clinical and experimental studies, but the entire potential of robotically assisted microneural surgery was not realized during these initial cases because exposure was not performed robotically—an open incision was still required.

A challenge in performing minimally invasive procedures is providing necessary space to see and manipulate the structures. This is easily obtained in the natural anatomical cavities of human body, such as the abdominal and thoracic cavity, but is a barrier when dealing with the extremities (upper and lower limbs). The brachial plexus has some unique anatomical relationships that render minimally invasive procedures possible. The supraclavicular fossa acts as a cavity, and gas insufflation with low pressure is adequate to elevate the subcutaneous and skin away from deeper structures.

As a result of these features, a minimally invasive approach followed by microneural repair was possible in our experimental model of brachial plexus repair. Unfortunately, technical barriers did not allow us to complete the minimally invasive approach in our small clinical series of robotic brachial plexus repairs. However, after seeing some of the robotic subcutaneous exposures created by Dr. Selber and the large optical spaces developed for harvesting the latissimus dorsi muscle, we feel that future attempts have a high likelihood of success.²⁴

In addition to technical refinements in approach, there is vast potential for the future development of refined robotic technology, including more appropriate forceps, graspers, welding techniques, fibrin glue-injection techniques, and improvement in the magnification. Ultimately, this may create the conditions to perform nerve super-microsurgery. The ability to utilize ultrahigh magnification to manipulate individual fascicles inside the nerves would result in highly precise connections.

Conclusion

Robotic-assisted surgery of the shoulder girdle and brachial plexus is still in its infancy.²⁵ Its development has followed the reverse path of endoscopy, which was focused on minimally invasive access, and has slowly begun to explore peripheral nerve structures. Robotic surgery on the other hand, has started with peripheral nerve work, and is extending into minimally invasive approaches to that work. For further refinement of the technique in clinical practice, it would be ideal to have even finer and more suitable instruments for nerve surgery to be able to apply fibrin glue or electrostimulation. Nevertheless, the prospects of minimally invasive techniques would allow acute and subacute surgical approaches to traumatic brachial plexus palsy safely, without significant and cicatricial morbidity.

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