Robotic Nerve Surgery: Brachial Plexus

Matthew J. Parham, MS[1,2] Samuel H. Cole, MD[1,2] Nicholas H. Yim, BS[1,2] William C. Pederson, MD[1,2]

[1] Division of Plastic Surgery, Michael E. DeBakey Department of Surgery, Baylor College of Medicine, Houston, Texas
[2] Division of Plastic Surgery, Texas Children's Hospital, Houston, Texas

Address for correspondence William C. Pederson, MD, Division of Plastic Surgery, Baylor College of Medicine, 6701 Fannin St Unit 610.00, Houston, TX 77030 (e-mail: wcpeders@texaschildrens.org).

Semin Plast Surg 2023;37:199–205.

Abstract

Management of closed brachial plexus injuries has traditionally favored conservative approaches with lengthy intervals between initial injury and surgical reconstruction. The complex anatomy of this region often requires large incisions with extensive dissection. Recently, the use of robotic systems in plastic and reconstructive surgery has been increasing, and robot-assisted brachial plexus reconstruction is a novel application that is currently being explored. Current literature describing this application is primarily comprised of feasibility studies using animal and cadaver models, and literature describing use in human subjects is limited. Advantages demonstrated by these early studies include the reduction of physiologic tremor, 3D visualization of anatomical structures, and ergonomic positioning; this allows for increased surgical dexterity and the ability to perform minimally invasive microsurgical procedures within the confined anatomical spaces of the brachial plexus. Limitations revolve around inadequate instrumentation, large learning curves, and increased costs that restrict the ability to perform these complex microsurgical procedures reliably and efficiently. As companies continue to develop instrumentation specific to robot-assisted microsurgery, more extensive longitudinal studies outlining long-term costs, changes in operating time, and functional outcomes will be required before a conclusion about the utility of these systems in brachial plexus surgery can be made.

Keywords
- plastic surgery
- robotic surgery
- brachial plexus

The brachial plexus is a complex network of nerves from the cervical and thoracic spinal cord that provide motor and sensory innervation to the upper extremity. Given the multitude of interwoven connections between the nerves from the root to the nerve level, lesions to nerves in this plexus present with varying degrees of sensory and motor deficits depending on the location and mechanism of injury.[1] Injuries can occur secondary to trauma, compression by adjacent tissues, and inflammation, and can severely affect the patient's quality of life.[2] Treatment of these injuries requires a multidisciplinary approach with cooperation from numerous different medical and surgical specialties.[3]

Management of closed injuries includes observation and serial examinations for 3 to 6 months as current limitations in imaging do not always allow for precise identification of the type and location of the nerve lesion.[1,4] Patients who do not have a resolution of their symptoms require surgical exploration and reconstruction. However, the complex anatomy often makes reconstruction extremely difficult, requiring the surgeon to pinpoint the origin of the injured nerve and match it to its appropriate target in a relatively confined anatomical space.[1] These operations traditionally require wide exposure via large incisions and extensive dissection to establish the correct anatomical pathways, posing some risk of damage to surrounding structures. While scarring from these procedures makes reoperation extremely difficult, delays to surgical intervention also result in extensive scar formation at the nerve lesion, which may necessitate nerve grafting.

One potential solution to these problems has been attempted through the use of minimally invasive techniques

article published online
September 18, 2023

Issue Theme New and Updated Applications for Robotic Surgery in Plastic Surgery; Guest Editors: Jessie Z. Yu, MD, and Jesse C. Selber, MD

DOI https://doi.org/10.1055/s-0043-1772847.
ISSN 1535-2188.

and endoscopic approaches.[5,6] Although an endoscopic approach would seemingly obviate the need to wait for surgical exploration and reduce the extensive scarring associated with open surgery, it does not allow for fine motor capabilities and magnification required for microsurgical nerve repairs.[7] More recently, robot-assisted brachial plexus surgery has surfaced as another proposed solution to combine the minimally invasive techniques of endoscopic approaches with the potential microsurgical capabilities offered by robotics.[8,9]

Despite a substantial increase in the use of robotics in other surgical subspecialties, application in plastic and reconstructive surgery has been relatively slow, gradually increasing over the last decade.[10] Use of robotic systems within the field of brachial plexus surgery has not had the same emphasis as other areas of plastic and reconstructive surgery.[11] However, to appreciate the rationale behind this slow uptake and to recognize the potential of future applications of robot-assisted brachial plexus surgery, it is important to understand the complex evolution of brachial plexus surgery.

Historical Perspective

Some of the oldest diagnoses and treatments of brachial plexus injuries can be dated back to the second century AD.[12] One of the earliest was from the Roman physician Galen, who attributed sensory deficits in a Persian sophist's hand to spinal cord inflammation from a traumatic shoulder injury, a diagnosis for which he recommended conservative management and immobilization.[12,13] Despite this early characterization by Galen, true advances in the anatomical characterization of the brachial plexus injuries did not occur until the second half of the 19th century.[12] During this time, physicians such as Duchene, Klumpke, and Erb, among others, began to describe and isolate the specific nerve lesions associated with various palsies of the upper extremity.[12,14–16] These advancements coincided with other groundbreaking strides in nerve surgery: Nelaton and Laugier performing the first successful nerve sutures in 1863 and 1864, respectively, Phillipeaux and Vulpan's experimental use of nerve grafts in 1870, and Eduard Albert's publication of the first successful clinical nerve graft in 1885.[12,17–20] These surgeons ushered in a new era for the exploration of brachial plexus reconstruction.

Ultimately, the first published description of surgical exploration and repair of a brachial plexus injury can be attributed to William Thorburn in 1900 with his case description of a surgical resection of a neuroma involving the entire plexus, and subsequent direct nerve repair.[21] Although the patient improved minimally, this publication, and the emergence of more novel techniques for nerve repair, resulted in an expanse of studies exploring both adult and obstetrical brachial palsies.[12,22–25] While surgical repair of obstetrical palsies was met with extremely promising results and interest continued to bloom, surgical repair of adult brachial palsies was still widely regarded as hopeless and interest in this area stagnated.

Although the First World War spurred a slight interest in this subject, it was not until the Second World War that interest in the surgical repair of adult brachial plexus injuries would renew with the same fervor that it had initially.[12] Particularly, the large number of penetrating and traumatic brachial plexus injuries combined with novel advancements in diagnostic technology, such as the electromyogram and recording of nerve action potentials through skin, provided ample opportunity to study and to try to correct these injuries once again.[26,27] Results of these studies yielded discouraging results, and surgical recommendations were limited to the most severe cases of brachial plexus palsies.[28,29]

Fortunately, major advancements came with the evolution of microsurgery in the 1960s.[12] The development of the operating microscope and microsurgical suture materials once again peaked interest in brachial plexus surgery. Techniques pioneered by Millesi and Narakas were adopted by surgeons worldwide, this time with substantially more favorable results.[12,30–32] Yet, even with the progress that has been made, brachial plexus repair still presents as a complex reconstructive challenge, particularly in the cases with root avulsion, and nonsurgical treatment is often still strikingly similar to that which was recommended by the Roman physician, Galen, in the second century.[7,33] Although the exploration of surgical reconstructive options has been limited, reconstructive techniques and diagnostic technology have continued to evolve, leaving the field of brachial plexus surgery primed for a new era of growth.

Anatomical Considerations

The brachial plexus is classically divided into five segments as it follows its anatomical course from the nerve root to the terminal branches.[2] The roots are formed from the ventral rami of the lower four cervical spinal nerves and the first thoracic spinal nerve (C5–T1). They travel from the posterior triangle of the neck and pass between the anterior and middle scalene muscles to form the upper (C5–C6), middle (C7), and lower (C8–T1) trunks. After the trunks pass beneath the clavicle, they divide into anterior and posterior divisions. The anterior divisions of the upper and middle trunks then re-form as the lateral cord; anterior divisions from the lower trunk re-form as the medial cord and all three posterior divisions as the posterior cord. Of note, the cords are named for their positions relative to the axillary artery in the infraclavicular region. The terminal branches then extend from the cords and into the distal upper extremity. The ulnar nerve (C8–T1) is a terminal branch of the medial cord; the median nerve (C6–T1) is formed from the medial root of the medial cord and the lateral root of the lateral cord; the axillary nerve (C5–C6) and radial nerve (C5–T1) are terminal branches of the posterior cord; and the musculocutaneous nerve (C5–C7) is a terminal branch of the lateral cord.[34]

Although this simplified description does not account for the various nerves branching from earlier divisions of the plexus, they must also be taken into account when considering the etiologies of brachial plexus injuries. ►**Table 1** provides a functional overview of commonly involved nerves and their associated functions.

Etiology

Injury to the brachial plexus results in loss of motor function and sensation to the areas innervated by the damaged nerves. However, injuries to the plexus often involve multiple nervous structures and make localization of the lesion substantially more difficult.[2] Thus, the mechanism of injury may provide unique insight into the etiology of brachial plexus injuries. In traction injuries, traction in the cephalad direction often results in damage to the lower plexus, while downward traction often results in damage to the upper root and trunks. High-energy trauma resulting in fractures of the humerus or dislocations are more likely to cause root avulsions, while milder trauma to these regions may cause a temporary palsy.[2,4,35] Additional mechanisms of injury include crushing injuries, compression by adjacent tissues, and inflammation of the nervous structures.[2,7]

These injuries can occur independently or in conjunction with one another, resulting in a myriad of presentations and localizing symptoms. A thorough history and physical and neurologic examination are critical in determining the etiology and location of the lesion, and imaging with X-ray, computed tomography (CT), or magnetic resonance imaging (MRI) may offer additional information about the nerve lesions and extent of damage to the surrounding tissues.[2,4] Two to 3 weeks after initial injury, electromyographic studies can be used to measure the progression of nerve recovery. Unfortunately,

Table 1 Functional overview of nerve branches frequently involved in brachial plexus injuries

Nerve branch	Muscle innervation	Motor and sensory functions
Dorsal scapular nerve (C5)	Levator scapulae, and major and minor rhomboids	• Retraction and elevation of the scapula
Long thoracic nerve (C5–C7)	Serratus anterior	• Protraction and elevation of the scapula
Suprascapular nerve (C5–C6)	Supraspinatus and infraspinatus	• External rotation of the shoulder • Abduction of the arm
Lateral pectoral nerve (C5–C7)	Pectoralis major	• Flexion, adduction, and medial rotation of the humerus
Upper and lower subscapular nerve (C5–C6)	Subscapular (both) and teres major (lower)	• Internal rotation of the shoulder and humerus • Depression and abduction of the scapula
Thoracodorsal nerve (C6–C8)	Latissimus dorsi	• Adduction, internal rotation, and extension of the shoulder
Musculocutaneous nerve (C5–C7)	Brachialis, coracobrachialis, and biceps brachii	• Flexion of the elbow • Adduction of the shoulder • Supination of the forearm • Sensation to the lateral forearm
Median nerve (C5–T1)	Pronator teres, flexor carpi radialis, palmaris longus, flexor digitorum superficialis, flexor digitorum profundus (I and II), first and second lumbricals, opponens pollicis, abductor pollicis brevis, superficial head of the flexor pollicis brevis	• Flexion of the digits • Flexion, abduction, opposition, and extension of the thumb • Sensation to the palmar side and dorsal tips of the lateral three and half digits, thenar eminence, and lateral palmar side of the hand
Axillary nerve (C5–C6)	Deltoid and teres minor	• Abduction, flexion, extension, and external rotation of the shoulder • Sensation to the upper arm
Radial nerve (C5–T1)	Triceps brachii, anconeus, brachioradialis, extensor carpi radialis longus and brevis, supinator, extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, extensor pollicis longus and brevis, extensor indicis, and abductor pollicis longus	• Extension of the forearm, wrist, and digits • Sensation to the lateral and posterior forearm, lateral dorsum of the hand, and lateral three and half digits
Ulnar nerve (C8–T1)	Flexor carpi ulnaris, flexor digitorum profundus (III and IV), opponens digiti minimi, abductor digiti minimi, flexor digiti minimi brevis, adductor pollicis, third and fourth lumbricals, dorsal and palmar interossei, palmaris brevis, and deep head of the flexor pollicis brevis	• Flexion of the wrist • Sensation to the medial dorsal and palmar hand, and medial one-half digits

many patients do not improve over time and ultimately require surgical repair of their brachial plexus injuries.[3,4,33]

Surgical Repair

Current indications for surgical repair of brachial plexus injuries and reconstruction options are outlined in ►**Fig. 1**.[7] As previously described, traditional surgical repair requires large incisions and extensive dissection of the regions surrounding the brachial plexus to allow for microsurgical repairs of the damaged nervous structures. Although attempts have been made to conduct these surgeries endoscopically, the decreased dexterity and visualization makes successful minimally invasive nerve surgery extremely difficult.[6,7]

In recent years, robot-assisted surgical techniques commonly utilized for pelvic and abdominal procedures have seen increased utility in plastic and reconstructive surgery.[36,37] Although the minimal utilization of endoscopic procedures in this field has resulted in slower adoption than other fields, the potential advantages these systems can provide to reconstructive procedures have led to the exploration of their utility in transoral surgery, muscle flap harvesting, microsurgery, limb reconstruction, and peripheral nerve surgery.[11,38,39] Although, the adoption of robot-assisted brachial plexus surgery has progressed even more slowly than many other fields of plastic and reconstructive surgery, various surgeons have begun to publish their respective experiences with this technology.

Feasibility Studies

Some of the earliest studies describing the feasibility of the da Vinci Surgical Robotic System (Intuitive Surgical, Sunnyvale, CA) in brachial plexus surgery were published by Drs. Phillipe Livernoux, Stacy Berner, and Gustavo Mantovani between 2009 and 2011. As previously stated by Facca et al,

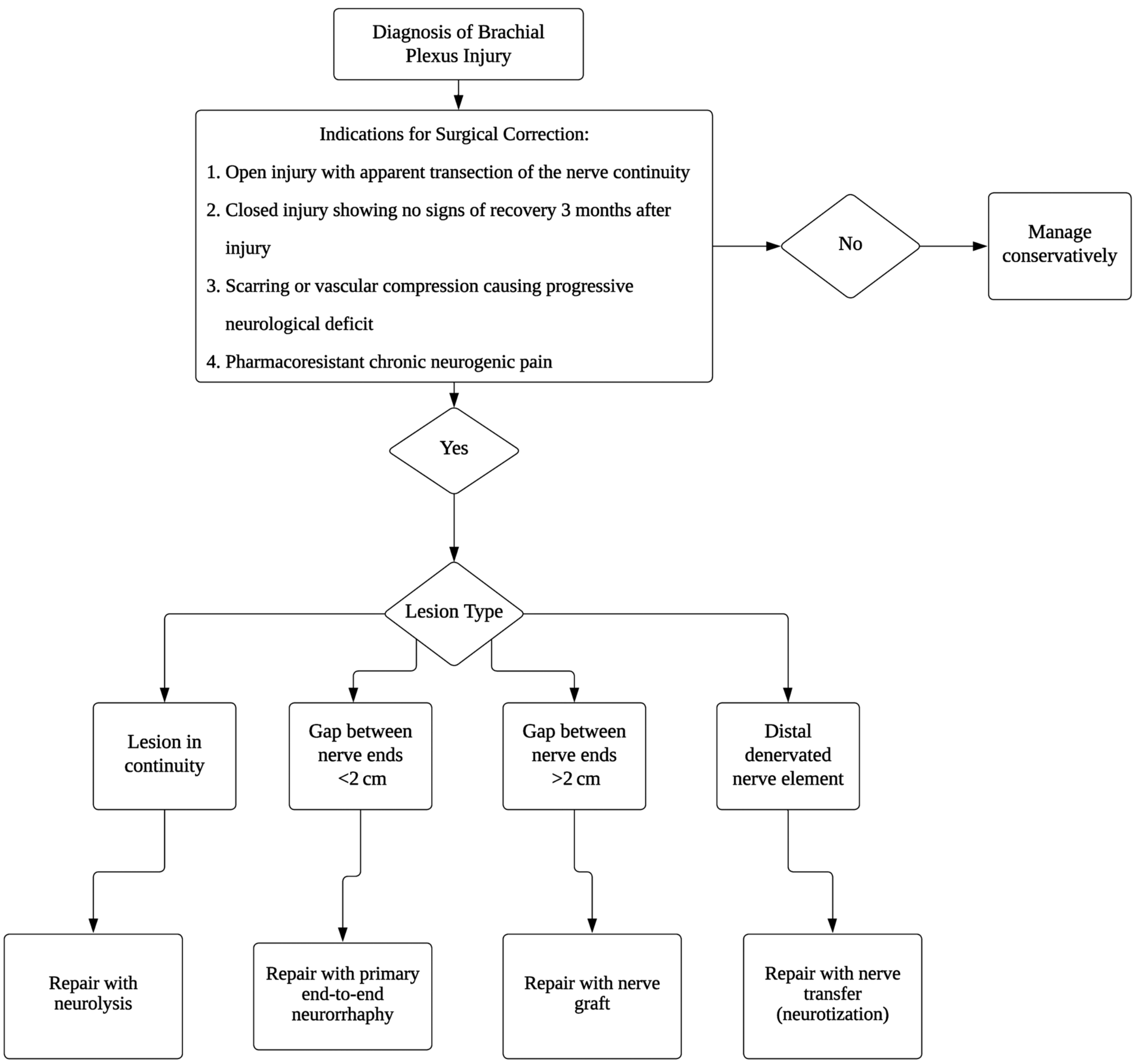

Fig. 1 Indications for surgical repair of brachial plexus injuries with options for reconstruction

robotic-assisted surgery of the brachial plexus has evolved inversely to endoscopy, by initially focusing on peripheral nerve reconstruction and extending into minimally invasive approaches.[1] Several of these early studies used animal models to demonstrate the feasibility of the epineural and neurotrophic repairs, and nerve harvesting techniques for use in brachial plexus repair.[8,40,41] ►**Table 2** outlines the current published literature focusing on robot-assisted brachial plexus repair in human cadavers and subjects.

One of the earliest cadaver studies, published by Manatovi et al in 2011, demonstrated the feasibility of the exclusive use of the da Vinci robot for both endoscopic dissection and microsurgical nerve repair, providing the framework for further attempts in human populations. These later studies, published between 2012 and 2014, attempted either open incisions with robot-assisted dissection and microsurgical repair of the brachial plexus or robot-assisted endoscopic dissection and repair of the brachial plexus, often practicing initial technique on a human cadaver before transitioning to human subjects.[9,42,43] The cadaver studies published by Tetik and Uzun[44] and Jiang et al[45] in 2014 and 2016, respectively, demonstrated the feasibility of alternative uses of the robotic systems with infraclavicular and paravertebral approaches to brachial plexus repair. Although sparse, these studies demonstrated many of the key advantages of robot-assisted brachial plexus surgery and

Table 2 Current publications of robot-assisted brachial plexus surgery

Study	Study type	Procedures	Key findings
Manatovi et al	Human cadaver	Robot-assisted endoscopic dissection and exploration of supraclavicular brachial plexus with nerve graft repair of artificial lesion to the upper trunk	Endoscopic repair of supraclavicular brachial plexus is feasible with exclusive use of the robot. No macroscopic evidence of damage to nerves or surrounding structures
Lequint et al.[43]	Case report ($N=1$)	Minimally invasive robot-assisted biopsy of intraneural perineurioma in the right superior trunk of the brachial plexus	The patient had better cosmesis and decreased scarring without sensory or motor deficits postoperatively. Lack of sensory feedback was not a problem, but nerve biopsy was unable to be confirmed without electrical stimulation
Garcia et al[9]	Human cadaver and case series ($n=3$)	Open dissection of the brachial plexus and robot-assisted microsurgical repair of the brachial plexus in cadaver and then in human subjects	Tremor filtration, motion scaling, and ergonomic positioning allowed for successful repair in all subjects; however, lack of adequate instrumentation was noted
Berner et al[42]	Case series ($N=12$)	Minimally invasive robot-assisted dissection and repair of the brachial plexus	Microsurgical repair of nerves achieved; however, it needed to be converted to open in 9 of 12 cases. Reasons for conversion included inability to maintain insufflation of resection cavity, unsuited instrumentation, blurring of stereoscopic vision, and difficulties with visual identification of anatomical landmarks
Facca et al[1]	Human cadaver and case series ($n=8$)	Open incision with robot-assisted microsurgical dissection and repair of the brachial plexus in cadavers and then in human subjects (repair of two complete brachial plexus palsies, three partial C5–C6, two continuous axillary nerve lesions, and one axillary and musculocutaneous nerve lesion	Confirmed the ability to perform dissection and microneural repair robotically, but inadequate instrumentation prevented minimally invasive and microsurgical techniques
Tetik et al[44]	Human cadaver	Open incision and initial blunt dissection of the infraclavicular space with robot-assisted dissection of the lower trunk of the brachial plexus	Easier exposure and more ergonomic positioning with wider range of motion for robotic arms than the traditional supraclavicular approach
Jiang et al[45]	Human cadaver	Endoscopic dissection of the paravertebral C7 nerve root and contralateral nerve transfer using minimally invasive, robot-assisted technique	This technique allowed for use of smaller incision and nerve graft compared with the traditional open surgery

addressed many of the current limitations preventing their widespread adoption.

Advantages

Many of the advantages demonstrated in these studies are the basis for the widespread adoption in numerous other surgical specialties; however, these advantages also provide specific benefit to brachial plexus surgery and microsurgical nerve repair. Specifically, the reduction of physiologic tremor, 3D visualization of anatomical structures, and ergonomic positioning allow for increased surgical dexterity within the confined anatomical spaces of the brachial plexus.[1] The ability to perform minimally invasive microsurgical procedures exclusively with robotic systems, as demonstrated by Lequint et al and Berner et al, results in decreased scar formation, which is a primary motivation for implementing minimally invasive brachial plexus repair.[5,6,42,43] Although long-term outcomes have not been demonstrated in the current literature, the authors of these early studies posit that the potential benefits of these novel techniques allow for earlier exploration, diagnosis, and intervention compared with the traditional approaches.[9,39,42]

Limitations and Future Directions

Currently, robot-assisted brachial plexus surgery is not without significant limitations. The above-mentioned studies demonstrate the same constraints that have continued to limit the expansion of robotic-assisted surgery into the field of plastic and reconstructive surgery. Specifically, inadequate instrumentation has been consistently cited as the major restricting factor.[7,9,10,42,44] To date, there is no comprehensive set of microsurgical instruments designed for use in the da Vinci systems. The authors consistently noted that the instruments were too large to manipulate the delicate tissue and nerves in the brachial plexus and that the optics of the robot-systems did not allow for proper visualization and identification of anatomical structures.[1,10,42] Additionally, Lequint et al noted that the lack of a nerve stimulator compatible with these robotic systems makes confirming the identity of structures within the brachial plexus significantly more difficult.[43]

The continued evolution of robot-assisted brachial plexus surgery is largely dependent on the development of instrumentation specific to microsurgery and nerve surgery. Although there is currently no comprehensive set of microsurgical instruments for the da Vinci robot, the increased utilization of these systems for microsurgery has led to the development of novel microsurgical software and tools adapted to the robotic console.[11] These include the addition of enhanced optics, confocal microscopy, CO_2 laser dissection, and various other tools designed to facilitate complex microsurgical procedures.[46] These advancements provide new and promising methods to optimize the use of robotic systems in brachial plexus surgery. Continued refinement of procedural steps and adaption of additional microsurgical tools will allow for novel approaches to procedures that previously were limited by this lack of instrumentation.[1,44]

There are various additional limitations to consider that are less significant to the feasibility of robot-assisted brachial plexus surgery. Some authors noted technical difficulties such as fogging of camera lenses, inability to maintain insufflation, and small working spaces making navigation difficult.[1,42] As demonstrated within the case series conducted by Berner,[42] many of the technical difficulties experienced by these surgeons during the endoscopic approach do not require substantial technological advancements. Instead, they require increased case volume to overcome the learning curve associated with robotic systems and optimize their technique with this approach.

Although the feasibility of these procedures has been demonstrated by these initial studies, there are limited data available concerning the hospital costs, length of operation, and outcomes associated with long-term utilization of robot-assisted systems in larger cohorts of patients. While cost and operating time have also been voiced as initial concerns, longitudinal studies are necessary to see if the same benefits that have led to the widespread adoption of robot-assisted surgery in other specialties remain applicable to brachial plexus surgery.[10]

Conclusion

The complex anatomy of the brachial plexus provides a unique challenge to the reconstructive surgeon. Although historical management favored a more conservative approach, the evolution of surgical techniques and diagnostic technology has resulted in renewed interest in surgical correction of these nerve lesions. Recently, the birth of robot-assisted surgery and consequent study in brachial plexus surgery has demonstrated the feasibility of this approach versus the traditional open surgery. Development of instrumentation specific to these endoscopic and microsurgical procedures will potentially allow for more acute intervention without prohibitive scar formation interfering with future surgeries. However, large longitudinal studies outlining long-term costs, changes in operating time, and functional outcomes are required before the decision to use robotic systems in brachial plexus surgery can be made.

Funding
None.

Conflict of Interest
None declared.

References

1 Facca S, Hendriks S, Mantovani G, Selber JC, Liverneaux P. Robot-assisted surgery of the shoulder girdle and brachial plexus. Semin Plast Surg 2014;28(01):39–44

2 Pejkova S, Filipce V, Peev I, et al. Brachial plexus injuries: review of the anatomy and the treatment options. Prilozi (Makedon Akad Nauk Umet Odd Med Nauki) 2021;42(01):91–103

3 Shin AY, Bishop AT, Loosbroch MF, Spinner RJ. A multidisciplinary approach to the management of brachial plexus injuries: experience from the Mayo Clinic over 100 years. J Hand Surg Eur Vol 2022;47(11):1103–1113
4 Chuang DCC. Adult brachial plexus reconstruction with the level of injury: review and personal experience. Plast Reconstr Surg 2009;124(06):e359–e369
5 Krishnan KG, Pinzer T, Reber F, Schackert G. Endoscopic exploration of the brachial plexus: technique and topographic anatomy: a study in fresh human cadavers. Neurosurgery 2004;54(02):401–408, discussion 408–409
6 Braga-Silva J, Gehlen D, Kuyven CRM. Endoscopic exploration of a brachial plexus injury. J Reconstr Microsurg 2006;22(07): 539–541
7 Rasulic L. Current concept in adult peripheral nerve and brachial plexus surgery. J Brachial Plex Peripher Nerve Inj 2017;12(01): e7–e14
8 Nectoux E, Taleb C, Liverneaux P. Nerve repair in telemicrosurgery: an experimental study. J Reconstr Microsurg 2009;25(04): 261–265
9 Garcia JC Jr, Lebailly F, Mantovani G, Mendonca LA, Garcia J, Liverneaux P. Telerobotic manipulation of the brachial plexus. J Reconstr Microsurg 2012;28(07):491–494
10 Tan YPA, Liverneaux P, Wong JKF. Current limitations of surgical robotics in reconstructive plastic microsurgery. Front Surg 2018; 5:22
11 Dobbs TD, Cundy O, Samarendra H, Khan K, Whitaker IS. A systematic review of the role of robotics in plastic and reconstructive surgery: from inception to the future. Front Surg 2017; 4:66
12 Robotti E, Longhi P, Verna G, Bocchiotti G. Brachial plexus surgery. An historical perspective. Hand Clin 1995;11(04):517–533
13 Galenus C. Omnia Quae Extant Opera in Latinum Conversa, Ed VIII. Venice: Giunta; 1609
14 Injuries of nerves and their consequences. Digital Collections: National Library of Medicine. https://collections.nlm.nih.gov/catalog/nlm:nlmuid-66230920R-bk
15 Gilbert A, Pivato G. Obstetrical palsy: the French contribution. Semin Plast Surg 2005;19(01):5–16
16 Diseases of the Peripheral Nerves 1Cyclopædia of the Practice of Medicine. Edited by Dr. H. von Ziemssen. Vol. xi. Diseases of the Peripheral Cerebro-spinal Nerves. By Professor W. H. Erb. Translated by Mr. Henry Power. A. H. Buck, M.D., Editor of English Translation. London, 1876, 8vo, pp. 623. Br Foreign Med Chir Rev 1877;60(119):23–32
17 Laugier A. Note sur la suture du nerf median. Gazette Hop (Paris) 1864;75:297
18 Houel M. Resection et suture du nerf median par M. Nelaton Gazette Hop (Paris) 1864;75:29677:307
19 Albert E. Einige Operationen an Nerven. Wien Med Presse 1885; 26:1221–1224
20 Schmidt G. Eduard Albert and the beginning of human nerve grafting. Acta Chir Austriaca 1993;25(04):287–288
21 Thorburn W. A clinical lecture on secondary suture of the brachial plexus. BMJ 1900;1(2053):1073–1075
22 Kennedy R. Suture of the brachial plexus in birth paralysis of the upper extremity. Am Med Asso 1903;1(2197):298–301
23 Taylor AS. Results from the surgical treatment of brachial birth palsy. J Am Med Assoc 1907;XLVIII(02):96–104
24 Tuttle HK. Exposure of the brachial plexus with nerve-transplantation. J Am Med Assoc 1913;61(01):15–17
25 Harris W, Low VW. On the importance of accurate muscular analysis in lesions of the brachial plexus; and the treatment of Erb's palsy and infantile paralysis of the upper extremity by cross-union of the nerve roots. BMJ 1903;2(2234):1035–1038
26 Dawson GD, Scott JW. The recording of nerve action potentials through skin in man. J Neurol Neurosurg Psychiatry 1949;12(04): 259–267
27 Hodes R, Larrabee MG, German W. The human electromyogram in response to nerve stimulation and the conduction velocity of motor axons; studies on normal and on injured peripheral nerves. Arch Neurol Psychiatry 1948;60(04):340–365
28 Woodhall B, Beebe GW, eds. Peripheral Nerve Regeneration: A Follow-Up Study of 3,656 World War II Injuries. Washington, DC: National Academies Press; 1957
29 Barnes R. Traction injuries of the brachial plexus in adults. J Bone Joint Surg Br 1949;31B(01):10–16
30 Taleb C, Nectoux E, Awada T, Liverneaux P. The destiny of an ace: Algimantas Otanas Narakas (1927-1993). J Brachial Plex Peripher Nerve Inj 2013;8(01):6
31 Millesi H. Microsurgery of peripheral nerves. World J Surg 1979;3 (01):67–79, 128–129
32 Millesi H. Surgical management of brachial plexus injuries. J Hand Surg Am 1977;2(05):367–378
33 Hill JR, Lanier ST, Rolf L, James AS, Brogan DM, Dy CJ. Trends in brachial plexus surgery: characterizing contemporary practices for exploration of supraclavicular plexus. Hand (N Y) 2023;18 (1_suppl, suppl):14S–21S
34 Brown DL, Borschel GH, Levi B. Michigan Manual of Plastic Surgery. Philadelphia, PA: Lippincott Williams & Wilkins; 2014
35 Luo TD, Levy ML, Li Z. Brachial Plexus Injuries.. Treasure Island, FL: StatPearls Publishing; 2023
36 Bush SH, Apte SM. Robotic-assisted surgery in gynecological oncology. Cancer Contr 2015;22(03):307–313
37 Ballantyne GH. Robotic surgery, telerobotic surgery, telepresence, and telementoring. Review of early clinical results. Surg Endosc 2002;16(10):1389–1402
38 Garcia JC Jr, Mantovani G, Gouzou S, Liveneaux P. Telerobotic anterior translocation of the ulnar nerve. J Robot Surg 2011;5(02): 153–156
39 Liverneaux P, Nectoux E, Taleb C. The future of robotics in hand surgery. Chir Main 2009;28(05):278–285
40 Miyamoto H, Serradori T, Mikami Y, et al. Robotic intercostal nerve harvest: a feasibility study in a pig model. J Neurosurg 2016; 124(01):264–268
41 Porto de Melo P, Miyamoto H, Serradori T, et al. Robotic phrenic nerve harvest: a feasibility study in a pig model. Chir Main 2014; 33(05):356–360
42 Berner S. Nerve repair. In: Liverneaux P, Berner S, Bednar M, Parekattil S, Mantovani RG, Selber J, eds. Telemicrosurgery. Paris: Springer; 2013:119–122
43 Lequint T, Naito K, Chaigne D, Facca S, Liverneaux P. Mini-invasive robot-assisted surgery of the brachial plexus: a case of intraneural perineurioma. J Reconstr Microsurg 2012;28(07):473–476
44 Tetik C, Uzun M. Novel axillary approach for brachial plexus in robotic surgery: a cadaveric experiment. Minim Invasive Surg 2014;2014:927456
45 Jiang S, Ichihara S, Prunières G, et al. Robot-assisted C7 nerve root transfer from the contralateral healthy side: a preliminary cadaver study. Hand Surg Rehabil 2016;35(02):95–99
46 Brahmbhatt JV, Gudeloglu A, Liverneaux P, Parekattil SJ. Robotic microsurgery optimization. Arch Plast Surg 2014;41(03):225–230
47 Mantovani G, Liverneaux P, Garcia JC, Berner SH, Bednar MS, Mohr CJ. Endoscopic exploration and repair of brachial plexus with telerobotic manipulation: a cadaver trial. J Neurosurg 2011;115 (03):659–664