Robotic intercostal nerve harvest: a feasibility study in a pig model

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The aim of this study was to report the feasibility of robotic intercostal nerve harvest in a pig model. A surgical robot, the da Vinci Model S system, was installed after the creation of 3 ports in the pig's left chest. The posterior edges of the fourth, fifth, and sixth intercostal nerves were isolated at the level of the anterior axillary line. The anterior edges of the nerves were transected at the rib cartilage zone. Three intercostal nerve harvesting procedures, requiring an average of 33 minutes, were successfully performed in 3 pigs without major complications.

The advantages of robotic microsurgery for intercostal nerve harvest include elimination of physiological tremor, free movement of joint-equipped robotic arms, and amplification of the surgeon's hand motion by as much as 5 times. Robot-assisted neurolysis may be clinically useful for intercostal nerve harvest for brachial plexus reconstruction.

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INTERCOSTAL nerves are commonly used as donor nerves for brachial plexus reconstruction.³⁰ Harvesting of intercostal nerves by a conventional open approach requires a large surgical exposure, which can lead to perioperative complications.¹⁰ In developing minimally invasive techniques, Mikami et al. have described clinical cases in which video-assisted thoracoscopy with small incisions was used to transfer intercostal nerve segments to the musculocutaneous nerve.^{4,18} Thoracoscopic intercostal nerve harvest, however, still presents difficulties because of the long duration of surgery and also because endoscopic instruments are not capable of sufficiently fine movement and interfere with surgeon precision.

Recently, the development of robotics has allowed a glimpse into new perspectives in microsurgery.^{6,13,16,23,31} Surgical robots have some properties that are well adapted to microsurgery, such as 3D vision magnified up to 25 times, movements of the surgeon enhanced up to 5 times, 7 degrees of wrist articulation, elimination of physiological

tremor, and ergonomic surgical positioning.¹² The microsurgical and endoscopic properties of robotic systems have already demonstrated feasibility in thoracic surgery and have been used to perform sympathectomy,⁵ thymectomy,^{17,29} and esophagectomy³⁶ via a thoracoscopic approach.

The aim of the current study is to report the feasibility of robotic intercostal nerve harvest in a pig model.

Methods

This animal study was approved and conducted according to the French government guidelines on animal care and use. Three domestic female swine (*sus scrofa domestica*), having an average weight of 30 kg, were anesthetized using a ketamine (10 mg/kg)/midazolam (0.1 mg/kg) solution, followed by maintenance on pentothal (10 mg/kg/hr). The pigs were intubated, and double-lung ventilation was maintained. After induction of general anesthesia, the pigs were placed in the right lateral decubitus position.

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We have designed the robotic intercostal nerve harvest procedure in 3 stages: setup of the robot, approaches with 3 ports, and intercostal nerve dissection. The da Vinci surgical robot (Model S, Intuitive Surgical, Inc.) was set up (Fig. 1). We placed 3 ports, each 2 cm in diameter, in the left side of the pig's chest (Fig. 2). The camera allowed 3D vision and progressive magnification up to $\times 25$. The movements of the instruments were multiplied by 5 times (superfine position). After the video camera was introduced into the first port, forceps and scissors were introduced under direct vision (Fig. 3A). The video camera arm was equipped with a carbon dioxide insufflation system at a pressure of 4 mm Hg to maintain the operative field and control bleeding. The posterior edges of the fourth, fifth, and sixth intercostal nerves were isolated by microsurgical forceps, microscissors, and a hydrodissector (Erbejet) to the anterior axillary line (Fig. 3B). Venous bleeding was coagulated (Fig. 3C). The anterior edges of the 3 intercostal nerves were transected using robotic microscissors at the rib cartilage zone (Fig. 3D).

An assistant thoracic surgeon arranged the setting and replacement of robotic arms. All robotic intercostal nerve harvests were performed (Video 1) by the same microsurgeon.

VIDEO 1. Clip showing steps in robotic intercostal nerve harvest in a pig model. Copyright Philippe Liverneaux. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

Results

The time to set up the robot and place the 3 ports averaged 33 minutes (40, 30, and 30 minutes). The surgical time for harvesting the fourth, fifth, and sixth intercostal nerves in the console averaged 40 minutes (45, 35, and 40 minutes). The total time needed for the procedure was 1 hour and 13 minutes. The intercostal nerve harvests were successfully performed under appropriate carbon dioxide insufflation without having to convert the procedures to

FIG. 1. Photograph showing a pig placed in the lateral decubitus position and prepared for robotic intercostal nerve harvest. The robot is placed above the pig's shoulder. The visualization system is in front of the animal and the surgeon console is behind it. Figure is available in color online only.

FIG. 2. Skin is marked to show the location of ports for the robotic arms. The first port was placed in the sixth intercostal space in the midaxillary line for the video camera arm (cannula); the second and third ports were placed 5 cm anterior and posterior to the first port at the level of the seventh intercostal space (stars). These two ports were used for robotic arms. Figure is available in color online only.

the conventional open approach. The ribs and major intrathoracic organs appeared intact. No intercostal nerve was accidentally transected. The total amount of bleeding during the operation averaged less than 20 ml.

Discussion

Refinement of open intercostal nerve transfer procedures and the development of advanced microsurgical techniques for restoration of elbow flexion following brachial plexus injuries have improved the outcomes of nerve transplantation procedures.^{11,15,22,24,34} The drawbacks of the conventional open approach for harvesting intercostal nerves include relatively long skin incisions,³⁴ undesirable pleural damage,¹⁰ wound infection,¹⁰ and thoracic cage deformity.²⁶ Complication rates increase as the number of intercostal nerves harvested increases.¹⁰ Kawabata et al. investigated mild growth retardation of ribs corresponding to the site of donor intercostal nerves, although no thoracic cage deformity was detected clinically.⁹ Leaving the periosteum of the ribs intact during dissection of the intercostal nerves is crucial if thoracic cage deformity is to be avoided.²⁶

To resolve these drawbacks, the intercostal nerve harvesting process has been advanced using video-assisted thoracoscopy.^{2,19,21} In 2006, Mikami et al. successfully performed 12 intercostal nerve neurolysis procedures in 3 mini-pig models.^{11,19} One of 12 nerves was inadvertently transected during neurolysis. The average time for nerve harvesting was 30–60 minutes for each nerve.^{2,19} In 3 clinical cases described by Mikami and colleagues in 2008,²⁰ 4 thoracoscopic ports for harvesting 2 intercostal nerves were used. All patients recovered useful biceps function (Medical Research Council Grade 3+/5). One of these 3 clinical cases had to be converted to a conventional open nerve harvesting procedure due to accidental nerve transection. The total operation time in the first clinical case was 9 hours.²⁰ Video-assisted thoracic surgery was also

FIG. 3. Views of the operative field. The fourth intercostal nerve was identified through the pleura along the caudal margin of the rib (arrowheads). **A:** After the video camera was introduced into the first port, forceps and scissors were introduced under direct vision. **B:** The posterior edge of the intercostal nerve was isolated by microsurgical forceps and then by the water-jetting tool held in a forceps. **C:** Coagulation of venous bleeding using the coagulation wire of the Erbejet. **D:** The 3 harvested intercostal nerves. Figure is available in color online only.

applied to harvesting a full-length phrenic nerve to allow direct nerve transfer to the biceps.³⁷ Although existing endoscopic instruments are available for harvesting intercostal nerves, there are some incompatibilities related to the instruments' size and the restricted maneuverability of the tips of the instruments.²⁰

The most important advantages of robotic microsurgery (telemicrosurgery) for intercostal nerve harvest are motion scaling up to 5 times, elimination of physiologic tremor, and free movement of joint-equipped robotic arms, which can improve manipulation.¹² Several publications have compared surgeon performance using robotic microsurgery to conventional freehand microsurgery. Results were similar in the repair of anastomosis: operative time was shorter with conventional freehand microsurgery,^{8,28} but surgery-related comfort was superior with the telemanipulator. The surgical robot has been applied in 3 different types of procedure: 1) brachial plexus reconstruction using the Oberlin procedure;²³ 2) nerve transfer to the deltoid muscle using the nerve to the long head of the triceps;²⁷ and 3) supraclavicular brachial plexus procedures.¹⁶ As with other reported robot-assisted thoracic surgeries,^{1,14,17} robotic intercostal nerve harvesting may contribute to postoperative pain reduction, shorter hospitalization, earlier return to usual activities, lower complication rates, and better quality of life outcomes. After harvesting by robot-assisted thoracoscopy, intercostal nerves can be directed to the axilla subcutaneously and can be anastomosed to whichever nerve is needed to reanimate a particular muscle (biceps, triceps, etc.). Based on 3 clinical

cases of ours, the length of harvested nerve allows direct repair of the recipient nerve (an interpositional graft is not required).

Potential complications associated with robotic intercostal nerve harvest include pneumothorax, atelectasis due to single-lung ventilation, and iatrogenic intrathoracic injuries. Most of the current literature on postoperative respiratory complications after intercostal nerve harvest showed minimal or no clinical effect on respiratory function.^{3,11,35} Chalidapong et al. reported that objective pulmonary function was reduced for 2 weeks and normalized within 3 months. Single-lung ventilation has usually been suggested for video-assisted thoracoscopic surgery to retain the working field and facilitate the surgery. Some authors have investigated the use of double-lung ventilation in thoracoscopic surgery and found that it was safe and provided appropriate exposure while decreasing cost, operative time, and undesirable complications in comparison with single-lung ventilation.^{7,32,34} Our procedure requires a chest tube, unlike the open technique, which, although taking more time and requiring a larger incision, rarely needs a chest tube. Another disadvantage of robotics, which must be weighed against its benefits, is the cost of acquisition, maintenance, and operation of the system.

In our animal experiment, we were able to establish an adequate surgical view and working field under double-lung ventilation. The absence of sensory feedback has been criticized as a fault of surgical robots.³³ However, sensory feedback is not mandatory in conventional microsurgical procedures.²⁵ We had no difficulty in using the robot to

harvest the intercostals nerves without sensory feedback. For clinical cases, to avoid iatrogenic intrathoracic injuries, the surgeon must perform the robotic-assisted nerve harvest under supervision by an experienced thoracic surgeon and be prepared to convert to the conventional open procedure.

Conclusions

Three intercostal nerve harvests in 3 pigs each were performed using a robot. We conclude that intercostal nerve harvest in an animal model is feasible using the surgical robot. Robot-assisted neurolysis appears to be safe and may be useful for intercostal nerve harvest in clinical cases for brachial plexus reconstruction.

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Author Contributions

Conception and design: Liverneaux, Santelmo. Acquisition of data: Liverneaux, Miyamoto, Serradori, Facca. Analysis and interpretation of data: Liverneaux, Miyamoto, Facca. Drafting the article: Liverneaux, Miyamoto. Critically revising the article:

Liverneaux, Mikami, Selber. Reviewed submitted version of manuscript: Liverneaux. Approved the final version of the manuscript on behalf of all authors: Liverneaux. Statistical analysis: Liverneaux, Miyamoto. Administrative/technical/material support: Liverneaux. Study supervision: Liverneaux.

Supplemental Information

Videos

Video 1, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-603_video_1.asx.

Video 1, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-603_video_1.mov.

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