Nerve Repair in Telemicrosurgery: An Experimental Study

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ABSTRACT

Since the development of microsurgery in the 1960s, the prognosis of peripheral nerve lesions has greatly improved. However this new technique's evolution has remained limited by human factors, in particular by physiological tremor. Telesurgery, a technique used in other surgical fields, was developed in the 1990s. This study assesses the feasibility of peripheral nerve repair using telemicrosurgery. Anatomical material from three subjects of different species (rat, pig, and human) was used. The telesurgical step of the procedure was performed with a Da Vinci S robot (Intuitive Surgical, Inc., Sunnyvale, CA). Four anatomical epiperineural repairs were performed. Another neurotrophic repair was performed with a nerve regrowth guide. Regardless of the type of repair performed, the telemanipulator removed the physiological tremor factor. The suture needle was distorted when held by two clamps at a time. Repairs were all performed without any damaging twisting movements of both nerve ends. Our results demonstrated that telesurgery allows very safe and precise peripheral nerve repairs by counteracting physiological tremor and by improving the overview of the surgical field, either with an anatomical or a neurotrophic technique.

KEYWORDS: Anastomosis, microsurgery, nerve, robot, telesurgery

The prognosis of peripheral nerve lesions has improved significantly since the development of microsurgery in the 1960s, a concept that has allowed us to perform very precise repairs. Within this concept, two different peripheral nerve lesion repairing techniques oppose each other: on the one hand, the anatomical repair by epiperineural suturing,[1] on the other, neurotrophic repair with a regeneration chamber.[2] Despite undeniable improvements in the field of instrumentation as well as in optical magnification, microsurgery has undergone no significant developments over the past 10 years. In both anatomical and neurotrophic techniques, the main limit in microsurgery development is not technical but human. For example, to date no interface can filter physiological tremor between surgeons' hands and their microsurgical instrument. Moreover, movements are limited by the physiological articular amplitude of their wrists.

Several decades after the advent of microsurgery, telesurgery was developed in the 1990s. It was defined as any robot-assisted surgical intervention.[3] The first telesurgical operation was a transatlantic laparoscopic cholecystectomy performed in 2001.[4] Telesurgery with a surgeon-controlled telemanipulation has two theoretical advantages: first, the possibility to carry out any surgical procedure with a remote teleoperating system, and second, the improvement of overall surgical movement accuracy. The latter is the only advantage acknowledged

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Figure 1 Telesurgical work station. The left-hand side of the photograph shows the terminal from which the operator can control the articulated arms of the mobile cart shown on the right. A rat is placed on the mobile cart. The operator sits in front of the terminal with his head resting between two infrared sensors on a supporting frame into which he can look into a binocular viewing system giving him a three-dimensional sight of the operating field. The operator's hands control the arm's movements by the means of joysticks connected to the surgical instruments by electronic circuits transmitted by servomotors. On the far right is a monitor displaying the operator's view so the telemanipulator staff can watch and follow the operation.

today in elective procedures in many specialities such as cardiac, urological, gynecological, or even digestive surgery.[5–7] No peripheral nerve repair with telemicrosurgery has yet been reported to our knowledge.

In this context, the aim of this study was to assess peripheral nerve repair feasibility in regard to a new concept: telemicrosurgery. Our hypothesis was that the use of a telemanipulator could not only improve the microsurgeon's movements but could also address all the inconveniences related to physiological tremor. This hypothesis has already been validated in vascular microsurgery in recent studies on anastomoses of rat tail vessels.[8] The experimental paradigm of this study consisted of performing peripheral nerve repairs on various nerve specimens with increasing nerve diameters by telemicrosurgery, either with an anatomical technique or a neurotrophic technique.

MATERIAL AND METHODS

The material consisted of three subjects belonging to different species (Wistar rat, large white pig, and fresh Caucasian human anatomical material), a standard set of surgical instruments, and a telemanipulator.

The telemicrosurgical step was performed with a Da Vinci S telemanipulator (Intuitive Surgical, Inc., Sunnyvale, CA) made up of three main units: a mobile cart holding four robotic articulated arms, an imaging cart, and a remote terminal enabling the surgeon to control the telemanipulator's arms (Fig. 1).

The mobile cart was made up of four articulated arms. Three arms were equipped with surgical instruments, and the fourth arm supported the optical device. Each arm featured several joints, enabling a tridimensional handling of both the surgical instruments and the optical device. The three arms holding the instruments were equipped with an extra inner joint that allowed 360 degrees of circumduction movements. The surgical instruments consisted of dissecting forceps and straight scissors. The fourth arm held the optical device.

The imaging cart included a video unit similar to those used in conventional arthroscopy: two light sources and two cameras providing a tridimensional image with an up to $\times 25$ progressive magnifying power. The remote-control terminal was equipped with a viewing system, two control handles, and a pedal device. The viewing system, called a "stereo viewer," provided a tridimensional view of the operating field and displayed real-time text and icon messages related to the system status. The two handles allowed remote control of the four articulated arms, although they could only control two arms at a time. A pedal-clutch control enabled the surgeon to switch easily from an arm to another during the operation. The pedal system also controlled focus and image sharpness to keep an optimal position for the instruments on the stereo viewer screen.

The surgical technique was not different from any other conventional microsurgical technique except for the use of the remote-controlled instruments.

The fresh anatomical subjects were prepared in accordance with the current medical guidelines. Each

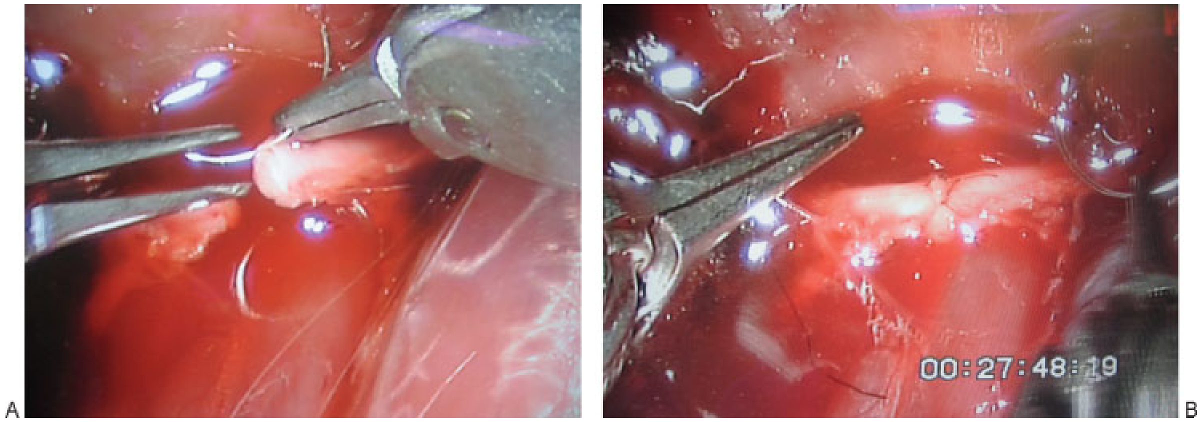

Figure 2 Telemicrosurgical operating field. Anatomical peripheral nervous reparation of a rat sciatic nerve. (A) Epiperineural passing of the 10–0 needle. The right forceps holds the needle passing through a superficial nervous fascicle. The left forceps gets ready to catch the needle. (B) Result of an anatomical peripheral nervous repair. Two epiperineural 10–0 stitches can be seen. Two other stitches are located on the hidden side of the nerve.

nerve (rat thigh sciatic nerve, pig upper limb median nerve, and human wrist median nerve, human wrist ulnar nerve, and human finger collateral nerve) was approached by means of conventional surgical instrumentation.

The following operative steps were all performed by telemicrosurgery. The first operative step involved the performance of an extrafascicular neurolysis freeing the epineurium from its fascicle insertions with dissecting forceps and straight scissors. The second step consisted of cutting the nerve with straight scissors. The third step consisted of repairing the peripheral nerve with two dissecting forceps and straight scissors. The quality of the stitching was assessed according to the coaptation of the fascicles and the matching of the epiperineural vessels on each side of the cross section.

In four cases (rat thigh sciatic nerve, pig upper limb median nerve, and human wrist ulnar nerve and human finger collateral nerve) anatomical repairs with epiperineural interrupted stitches were performed with 10–0 nylon sutures (Fig. 2A). In the human wrist median nerve, neurotrophic repair was performed with a nerve regrowth guide (Neurolac; Polyganics BV, Groningen[Q1], The Netherlands) (Fig. 3A) using Q1
4–0 and 7–0 nylon sutures.

RESULTS

In both anatomical or neurotrophic techniques, physiological tremor was removed by the telemanipulator. The microsurgical needle was distorted or broken when held by two dissecting forceps while one of the forceps made a move. The results depended on nerve size and the type of repair performed (Table 1).

In every anatomical peripheral nerve repair, sutures were performed without any twisting disruption

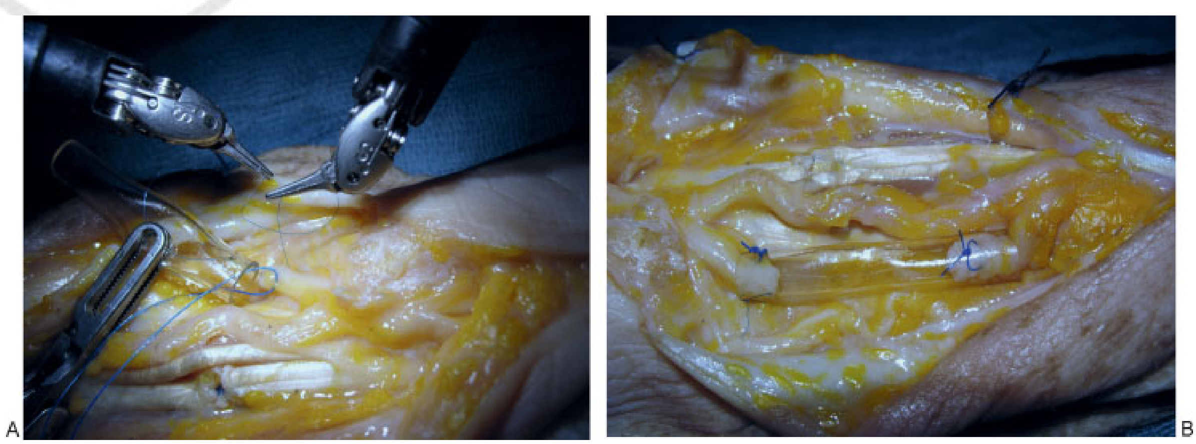

Figure 3 Telemicrosurgical operating field. Neurotrophic peripheral nervous repair of a human anatomical subject median nerve. (A) Passing of the suture in the nerve regrowth guide. We can see a 4–0 nylon suture already passed through the epineurium and a 7–0 suture passing through the regrowth guide. In this case it was necessary to perforate the Neurolac (Polyganics BV, Groningen, The Netherlands) beforehand with a 4–0 needle because it was too thick for the 7–0 needle to go through it directly. (B) Result of a neurotrophic peripheral nervous repair. Note the 15-mm gap between both nervous ends and the distortion of the regrowth guide. Two stitches (4–0 and 7–0 nylon sutures) were performed on each nerve ending.

Table 1 Different Types of Peripheral Nervous Repair Performed

N	Experimental Nerve Model	Nerve Diameter (mm)	Suture Type	Thread Size	No. of Stitches
1	Rat sciatic	1	Epiperineural	10–0	4
1	Human cadaver finger collateral	1.5	Epiperineural	10–0	4
1	Pig ulnar	2	Epiperineural	10–0	6
1	Human cadaver ulnar	3	Epiperineural	8–0	8
1	Human cadaver median	4	Neurolac regrowth guide*	7–0 and 4–0	4

*Polyganics BV, Groningen, The Netherlands.

of the distal end with respect to the proximal end of the nerve. Good alignment of the epiperineural vessels on both sides of the cross section was noticed, consequently confirming the good matching of both nervous segments (Fig. 2B).Thus the orientation of the different nerve fascicles was preserved. The number of stitches depended on the nerve's size (Table 1). There were no complications while performing the anatomical repairs.

As for the human median nerve neurotrophic repair, a 15-mm-long gap was left on purpose (Fig. 3B). From the good alignment of the median central artery, we concluded that the fascicle orientation on both sides of the gap seemed to have been preserved. However we noticed a distortion of the nerve regrowth guide by the forceps stabilizing it.

DISCUSSION

We faced some technical difficulties on the choice and manipulation of the instruments for both anatomical and neurotrophic peripheral nervous repair.

Regarding anatomical repair, the operating procedure was subjected to the Da Vinci S technical features. For example, we encountered, as others have,[9,10] some problems manipulating the thinnest peripheral nerves with the oversized instruments designed for cardiovascular telesurgery. Besides, it has to be kept in mind that the telemanipulator was designed in the first place for laparoscopic surgery in a damp abdominal cavity environment. Performing an open operation caused some adhesion phenomena that resulted from the drying of the needle on the microinstruments. The latter seldom occurs in conventional microsurgery because stitching is always performed in an aqueous medium. Regular intervention of our telemanipulator staff was required to irrigate the operating field and clean the tip of the instruments. Finally, the lack of proprioceptive feedback prevented us from estimating the forces applied on the dissecting forceps. Each time a needle was held between two forceps, either torsion or a breaking of the needle occurred. We addressed this inconvenience by using only one dissecting forceps at a time to handle the needle. However, swapping the needle from one forceps to the other was possible as long as the forceps were not moved during this phase. Furthermore, visual control was necessary during knot tightening to overcome the lack of force proprioception on soft tissues or on the sutures. After a few minutes, visual feedback efficiently replaced the proprioceptive feedback.[11]

In our experience, after three 3-hour-long training sessions, our team, which included a senior attending surgeon and two junior surgeons, could achieve high-quality nervous sutures and permeable arterial and venous anastomoses in a limited period of time.[8] We think both the overall smoothing of the surgical moves that resulted from the absence of physiological tremor and the tridimensional vision of the operating field can explain this dramatic decrease in the length of the learning curve by means of a consequent surgical easing.[12]

As for the neurotrophic repair, the operating procedure was subjected to the nerve regrowth guide's physical properties. For example, its 4-mm diameter made it impossible to use surgical instruments as thin as those we had for the anatomical repair. During the human median nerve repair, 4–0 and 7–0 sutures were used in regard to the regrowth guide thickness, but the thinner forceps couldn't handle the needles properly. Likewise, we needed a strong instrument to perforate the guide's thick surface with the needle to pass the suture. Finally, suturing both nerve endings to the regrowth guide required its stabilization during the entire procedure. This was achieved by adding a third instrument, a stronger forceps, to stabilize the guide. This pressure applied by the forceps on the guide's surface resulted in a crushing distortion, theoretically preventing nerve regrowth through the guide. In vivo at 37°C, the Neurolac effectively regains its initial shape in a few minutes,[13] thus counteracting the distortion.

Altogether, whatever technique of peripheral nervous repair is considered, either anatomical or neurotrophic, substitution of the instrument on the telemanipulator arms required regular interventions from our telemanipulator staff.

Telesurgery and the automation of surgical movements are two different concepts. Unlike robots, telemanipulators do not perform programmed movements without control. They can rather be considered as surgical instruments having the special feature of being remotely controlled by the operator.

In cardiac, urological, gynecological, or even digestive surgery, telesurgery addresses some inconveniences related to conventional laparoscopy. For example, the overview on the operating field is improved, not only because it benefits from three-dimensional stereoscopic vision instead of a classic two-dimensional vision,[14] but also because the view angle can be controlled remotely and single-handedly by the operator. The stereoscopic view enables the operator to have a very clear view of the nervous fascicles and the epiperineural vascularization next to the nerve's cross section. It makes it easier for the surgeon to position the needle at the exact desired spot, resulting in a better approximation of the fascicles and good nervous coaptation.

Moreover, the operator's gestures are improved, not only because physiological tremor[11] is removed, but also because the instruments are designed with 7 degrees of movement like a human wrist but with the additional asset of a 360-degree pronosupination instead of 180 degrees for a conventional operator. Thus telemanipulation transcends the operator's gestures by offering him or her some additional articular sectors and a three-dimensional view of the operating field. It has been demonstrated indeed that upgrading from a bidimensional to a three-dimensional view in combination with larger freedom in the Da Vinci S's arm movements is synergetic.[15] Regarded separately, neither of these two features can explain such a gestural easing.

High-cost equipment for telesurgical systems could be the main limiting factor for this sort of project, although some authors underline a paradoxical health cost reduction when using telemanipulators.[16]It is thought to result from a decrease in operative bleeding and from the improvement of some operating features. Another limiting factor could be the congestion of telesurgery systems, should surgical mindset not change, because telemanipulators clearly highlight the need to reconsider operating room ergonomics in the coming years.

In conclusion, the results of this experimental study confirm our previous impressions regarding our studies on vascular anastomoses. Telemicrosurgery, by removing physiological tremor and benefiting from three-dimensional stereoscopic vision, enables a safe and accurate repair of peripheral nerve lesions with whatever technique is used, either anatomical or neurotrophic.

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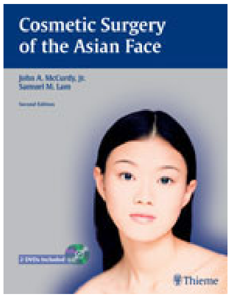

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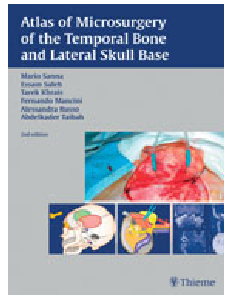

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