CLINICAL RESEARCH STUDIES

From the Society for Vascular Surgery

Cyber medicine enables remote neuromonitoring during aortic surgery

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Objective: **This study assessed the feasibility and effectiveness of remote neuromonitoring as an adjunct to spinal cord protection during surgical repair of descending thoracic aortic aneurysms and thoracoabdominal aortic aneurysms.**

Methods: **Four aortic centers in three European countries participated in this prospective observational study. A similar surgical protocol was used in all centers, including assessment of spinal cord function by means of monitoring motor-evoked potentials (MEPs). MEP information was evaluated at one central neurophysiologic department in Maastricht, The Netherlands. Transfer of MEP data from all operating rooms to Maastricht was arranged by Internet connections. In all patients, the protective and surgical strategies to prevent paraplegia were based on MEPs. The on-site surgeons reacted in real time to the interpretation and feedback of the neurophysiologist.**

Results: **Between March 2009 and May 2011, 130 patients (85 men) were treated by open surgical repair. Extent of aneurysms was equally distributed among the centers. Neuromonitoring was technically stabile and successful in all patients. The transfer of data from the operating room in the different vascular centers was undisturbed and without any technical problems. By maintaining a mean distal aortic pressure of 60 mm Hg, MEPs were undisturbed in 65 patients (50%). In another 65 patients (50%), significant changes in MEPs prompted the surgical teams to initiate additional protective and surgical strategies to restore spinal cord perfusion. These measures were not effective in five patients (3.8%), and acute paraplegia resulted. Delayed paraplegia occurred in 10 patients (7.7%) but improved in three and recovered completely in another three. No false-negative or false-positive MEP recordings were experienced.**

Conclusions: **Remote neuromonitoring of spinal cord function during open repair of descending thoracic aortic aneurysms and thoracoabdominal aortic aneurysms as a telemedicine technique is feasible and effective. It allows centralization of expertise and saves individual centers from investing in complex technology. The value of monitoring MEPs was confirmed in different aortic centers, resulting in adequate neurologic outcome after extensive aortic surgical procedures.**

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Assessment of spinal cord integrity during descending thoracic aortic aneurysm (DTAA) and thoracoabdominal aortic aneurysm (TAAA) repair by means of motor-evoked potentials (MEPs) requires complex technology that necessitates specific technical equipment and a dedicated neurophysiologic team. Furthermore, the learning curve of spinal cord neuromonitoring is long because measurements depend on many factors, including muscle relaxation, blood pressure, cerebrospinal fluid (CSF) pressure, temperature, electrolytes, and surgical techniques. In our experience, we showed the significant role of MEPs during TAAA repair and the subsequent surgical strategies necessary to maintain or regain spinal cord function, leading to significantly reduced paraplegia rates.[1-4]

Extending this technology and expertise to other centers can be achieved by acquiring the technical equipment and training teams, consisting of surgeons, anesthesiologists, and neurophysiologists. Building up such infrastructure is expensive and time consuming. A practical solution might be offered by new telecommunication technologies that allow remote neuromonitoring where the experienced neurophysiologist is at another location and connected with the local operating room by means of Internet connection. This would only require local investment for a neurostimulator but would avoid the need for a neurophysiologist and the learning curve of interpreting MEPs.

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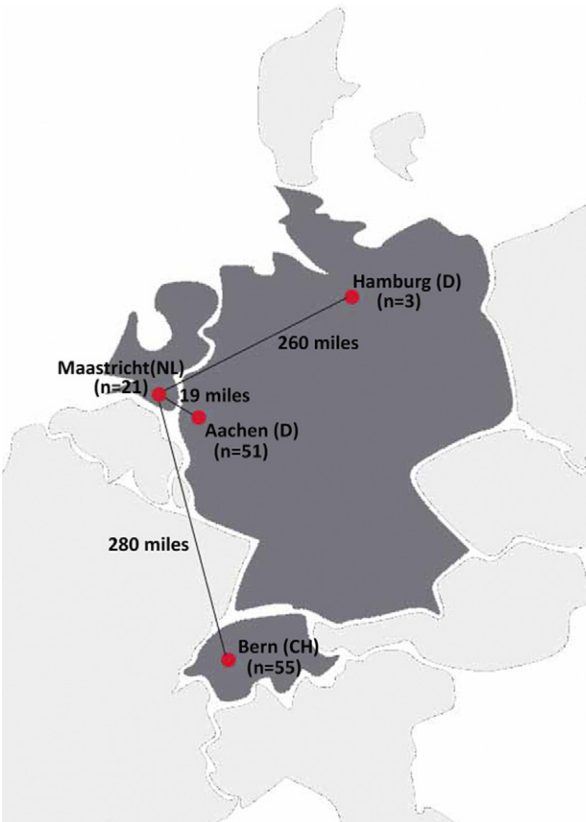

Fig. The participating vascular centers are located in Aachen and Hamburg in Germany (*D*), Bern in Switzerland (*CH*), and Maastricht in The Netherlands (*NL*). The headquarter neurophysiology department is located in Maastricht. The numbers in parentheses indicate the number of aortic procedures that were performed in each center.

The aim of this study was to assess the feasibility and effectiveness of remote neuromonitoring as an adjunct to spinal cord protection during operations on the thoracic and thoracoabdominal aorta. Specifically, this study examined the use of this telemedicine capability at four aortic centers in three European countries connecting to a central neuromonitoring infrastructure.

METHODS

The infrastructure for TAAA surgery and neuromonitoring in the Maastricht University Medical Center (The Netherlands) was built in 2000. An identical set-up was created in the University Hospital, Aachen (Germany) in 2006, but assessment of MEPs was performed in Maastricht by means of Internet data transfer. The University Hospital Bern (Switzerland) and the University Hospital in Hamburg (Germany) followed in March 2009 and September 2010, respectively. The distance between Maastricht and the three participating vascular centers is depicted in the Fig.

The surgical and anesthesia teams were each trained in their own centers, and operations on the first 10 patients were performed with support of the Maastricht neurophysiology team. During surgery, the neurophysiologist was physically present in the data control center of the Department of Neurophysiology in Maastricht and interpreted the MEPs at a distance. All neurophysiologic and clinical data were prospectively assessed in each center and collected for this multi-institutional observational study. This study took place from March 2009 to May 2011.

Principle of neuromonitoring. The same neuromonitoring protocol using MEPs was applied in all centers to monitor the function of the spinal cord intraoperatively. In addition, in surgical procedures involving the aortic arch, changes in brain perfusion were monitored by electroencephalography and transcranial Doppler ultrasound imaging.[4] This study only addresses the applicability of telemedical neuromonitoring of MEPs.

In case of undisturbed function of intact α-motor neurons of the spinal cord's anterior horn, electrical potentials are transmitted through the spinal cord and cause contraction of muscle groups.[2] The principle of MEP neuromonitoring of the spinal cord is based on muscle contraction caused by electrical stimulation of the cerebral cortex as measured by electrode patches. This allows assessment of the integrity of the α-motor neurons during the operation. This technique has been described in detail.[2,5]

In summary, the brain is stimulated electrically (Digitimer D-185; Digitimer Ltd, Herfordshire, UK) with the cathode in the Cz position (just posterior to the vertex). The anode consists of three interconnected electrodes on both mastoids and at Fpz, the center of the forehead. The electrical stimulation consists of a train of five stimuli of 500 V and ~1 to 1.5 A each, with an interstimulus interval of 2 milliseconds. The resulting MEPs are recorded with surface electrodes from the abductor pollicis brevis and the anterior tibial muscle on both sides (filter settings, 3 to 5kHz; sweep duration, 100 milliseconds; sensitivity, 2 mV/div), and the amplitude is measured between the maximal negative and positive deflection. The degree of muscle relaxation is adjusted from a measurement of the compound muscle action potential (CMAP) of the abductor digiti quinti muscle after one supramaximal stimulation of the ulnar nerve at the wrist.

During the surgical procedure, we strived to achieve a value (T1%) of about 20% compared with the CMAP before induction of muscle relaxation. We used vecuronium administered through an infusion pump, the velocity of which was adjusted manually according to the CMAP values. All MEP amplitude values, blood pressure data, and the degree of muscle relaxation were transferred into an external database that allowed for graphic displays of trends in time and the calculation of the ratio between the amplitude of each anterior tibial MEP and the mean of both abductor pollicis MEPs. The ratios were the mainstay for qualifying whether amplitude changes of the anterior tibial anterior MEPs were critical.

Surgical protocol. The same protocol was used in all connected centers. Intubation was performed with a double-lumen endotracheal tube or a selective left main bronchus blocker, enabling collapse of the left lung. CSF pressure was assessed with an intrathecal catheter and allowed to drain spontaneously if pressure increased >10 cm H_2O. CSF drainage was continued for 72 hours.

Patients were placed in a right helical position on a vacuum beanbag, allowing thoracotomy or thoracolaparotomy and access to the left femoral vessels. In patients requiring simultaneous arch repair, we use the fifth intercostal space; in DTAA or TAAA only, the sixth intercostal space was used. In TAAA, the anterior diaphragm was only divided over a limited length. After opening of the crus, the diaphragm was encircled with a loop, enabling movement of the diaphragm and exposing the aorta without the necessity of completely transecting the muscle.

The technique of extracorporeal circulation depended on the extent of the procedure. In DTAA or TAAA without arch involvement, left heart bypass was installed by means of the left atrium or pulmonary vein and left femoral artery cannulation, using limited heparinization (0.5 mg/kg; activated coagulation time ~200 seconds). Alternatively, the femoral vein and artery were cannulated using the same heparinized tubing system and centrifugal pump.

The TAAA reconstruction was generally performed from proximal to distal. However, in extensive (chronic) type B aortic dissection involving the iliac arteries, we prefer to reverse the surgical direction because of the unpredictable changes in organ perfusion with retrograde flow through dissected iliac arteries and aorta. This is feasible if the infrarenal aorta can be sequentially cross-clamped.

First, an aortobiiliac or aortic tube graft is anastomosed distally, cross-clamped, and cannulated as the arterial inflow site. After starting extracorporeal circulation, the aortic reconstruction is commenced with the abdominal phase, followed by the thoracic segment. The patient is allowed to cool to 32° to 33°C and actively rewarmed at the end of the procedure. A four-branched tubing system was connected to the left-sided heart bypass, and these catheters, with balloon-inflatable tips, were used for perfusion of the celiac axis, superior mesenteric artery, and both renal arteries. These perfusion catheters are equipped with pressure channels, enabling pressure-controlled selective perfusion. Volume flow was assessed in each catheter with ultrasound scan flowmeters.

If the shape of the thoracic descending aorta allowed sequential cross-clamping, these positions were prepared, enabling step-by-step reconstruction with assessment of spinal cord integrity and subsequent reattachment of intercostal arteries (ICAs), if necessary. In the abdomen, the aorta was approached through the left retrocolic and retrorenal access. After the left kidney was tilted, the left renal artery was dissected and secured with a vessel loop. After proximal cross-clamping, transection of the aorta, and performance of the anastomosis, distal aortic perfusion was maintained at a mean pressure of ≥60 mm Hg. This arterial pressure was increased, if necessary, as determined by urine output (15 mL/15 min) and the amplitude of MEPs.

Principle of telemonitoring. Four centers participated in this cross-border project: Maastricht University Medical Center (The Netherlands), the University Hospital, Aachen (Germany), the Inselspital and University of Bern (Switzerland), and the University Heart Center Hamburg Eppendorf (Germany). The neurophysiology expertise was centralized in Maastricht.

Intraoperative neuromonitoring data, including MEP amplitude values, blood pressure data, and the degree of muscle relaxation, are transferred to a computer in the operating room and connected to the local hospital's network. This computer visualizes the data stream as curve charts of trends in time on a monitor. To enable a remote user of another local network to view those charts nearly without time delay, a virtual private network (VPN) tunneling has to be established. VPN is a system that connects a local area network to another remote local network using the Internet, among other digital data-transfer systems. Data measured in the operating room in Maastricht are transferred via Internet, and not by the local hospital's intranet, to the Department of Clinical Neurophysiology of the University Maastricht using a VPN.

Very high-speed digital subscriber lines of different Internet providers serve to transfer the data between the hospitals. The monitor content of a computer in the operating room in Maastricht, Aachen, Bern, or Hamburg can be viewed by the neurophysiologist in Maastricht with a time delay of <1 millisecond. Data transmitted via VPN tunneling is protected by cryptography. An algorithm transforms the information computationally, and only those possessing the corresponding cryptographic algorithm can decrypt this encrypted information. In theory, these kinds of systems are not unbreakable; however, it is infeasible to do so by any practical means.

Strategies based on changes in MEPs. Sequential cross-clamping of the TAAA allows stepwise exclusion of aortic segments and subsequent assessment of changes in MEP amplitudes. When the proximal clamp is positioned, spinal cord blood supply depends on distal aortic perfusion. We normally strive for a mean distal aortic perfusion pressure of 60 mm Hg; however, in case of MEP decrease, the distal aortic perfusion pressure is elevated until MEPs increase. The measurements are repeated at least three times, and if the average level decreases progressively, this is considered as a sign of spinal cord ischemia. The pressure required to maintain adequate spinal cord perfusion during the operation is considered the minimal mean arterial pressure in the postoperative phase and is also included in the intensive care orders.

Next, the distal clamp is positioned and the MEP amplitudes are observed during a 3-minute period before opening the aorta. A rapid MEP decrease indicates that the aortic segment contains critical ICAs. In this case, we release the cross-clamps and actively cool the patient to 32°C. The aorta is clamped again and opened. Intercostal arteries are reattached and rapidly reperfused. If no patent segmental vessels are visible, endarterectomy is performed and back-bleeding arteries are reperfused by means of a selective polyester graft that is connected to the tube graft. When MEPs remain normal, we still revascularize these

Table I. Type and extent of treated aneurysms

Aneurysm type	*Total* (*N*)	*Maastricht* (*n*)	*Aachen* (*n*)	*Bern* (*n*)	*Hamburg* (*n*)
Descending aorta	7	1	0	6	0
TAAA					
Type I	18	2	8	8	0
Type II	61	6	21	32	2
Type III	31	10	14	6	1
Type IV	7	1	6	0	0
Type V	6	1	2	3	0
Total	130	21	51	55	3

TAAA, Thoracoabdominal aortic aneurysm.

segmental arteries between T8 and L1 because MEPs might deteriorate during the abdominal phase.

RESULTS

Between March 2009 and May 2011, 130 patients (85 men), who were a mean age of 60 ± 13 years, were treated by open repair of DTAA or TAAA using the above-described remote neuromonitoring. The number of procedures per center is indicated in the Fig. Because Hamburg joined recently, their number was limited to three procedures. Atherosclerotic aneurysms were present in 69 patients, postdissection aneurysms in 58, and mycotic aneurysms in three. One aortobronchial and one aortoesophageal fistula were also treated during the aneurysm repair. The extent of aneurysms and distribution among centers is described in Table I.

Neuromonitoring was technically stabile and successful in all patients. The transfer of data from the operating rooms of the different vascular centers to the Department of Clinical Neurophysiology in Maastricht was undisturbed and without any technical problem. Access to the neuromonitoring data and the on-line connection with the local operating team was always possible for the neurophysiologic team.

By maintaining a mean distal aortic pressure of 60 mm Hg, MEPs were undisturbed in 65 of 130 patients (50%; Table II). In the other 65 patients (50%), a significant drop in MEP amplitudes or complete loss of MEP occurred. Significant MEP changes occurred in all centers: Maastricht, nine of 21 (43%); Aachen, 26 of 51 (51%); Bern, 27 of 55 (49%); and Hamburg, three of three (100%). MEPs were restored in 14 patients: by clamp removal in nine, adjustment of the extracorporeal circulation (restart) in three, antegrade perfusion of the left subclavian artery in one, and rewarming in one. Increasing distal aortic pressure restored MEP amplitudes in five patients and failed in one patient, who developed acute paraplegia.

In 41 patients, aggressive surgical strategies as described above (reattachment of lumbar artery in five, occlusion of back-bleeding ICAs in two) and reattachment of ICAs in 39 restored MEPs in all except in four patients (Table II). Reattachment of ICAs did not lead to restored MEPs in these four patients, and despite increased mean arterial pressures, immediate paraplegia was encountered. Routine CSF drainage for 3 days could not reverse the neurologic deficit. In one patient, peripheral ischemia of the leg caused persistence of pathologic MEPs. Normalization of the blood flow to the legs avoided neurologic deficit. Another patient, who had a ruptured type II aneurysm, received respirator support until he died 17 days after surgery. An adequate neurologic examination was not possible during this postoperative interval, and therefore, whether an acute or a delayed neurologic deficit occurred in this patient remains unclear.

None of the patients with undisturbed MEPs during the operation, or at least at the end of the operation, developed an acute neurologic deficit. Acute hemiparesis developed in one patient due to an apoplectic insult; thus, an acute neurologic deficit became evident after the procedure in five patients (3.8%). All patients with an acute neurologic deficit due to spinal ischemia had type II aneurysms. The patient who developed an apoplectic insult had undergone a type V repair.

Delayed neurologic deficit occurred in 10 patients (7.7%). Five of these patients had undisturbed MEPs during and at the end of the operation, whereas the others showed significant MEP changes (Table II). Nine had a type II aneurysm, and one was treated for a type III aneurysm. The cause of delayed paraplegia could be identified in all patients: hemodynamic instability in six, consisting of acute bleeding in three and sepsis in three, occlusion of a reattached ICA in two, and insufficient CFS drainage in two.

All centers followed the same management protocol for delayed paraplegia, including raising arterial blood pressure and repeat CSF drainage. In three of these patients, the neurologic deficit recovered completely during the following 30 days, and three showed a significant neurologic improvement. The combined acute and delayed paraplegia rate in the 130 patients was 11.5% (n = 15).

DISCUSSION

This study shows the technical feasibility of remote neuromonitoring in patients with extensive aortic aneurysms by means of telecommunication networks. Centralized neurophysiologic expertise at a distance can be used to provide information on spinal cord function at connected centers, irrespective of distance. This study also demonstrates the effectiveness of remote assessment of spinal cord function: surgical teams at a distance were able to react in real-time to the neurophysiologic information they received, and their actions resulted in excellent rates of cord protection.

We recently reported the use of MEP technology in patients undergoing type I and II TAAA repair performed in 2000 to 2005 in Maastricht. Using the same surgical protocol and neuromonitoring technique, acute neurologic deficit was encountered in 2.7% of patients.[2] The current experience in the other centers using the remote technique of neuromonitoring demonstrates similar neurologic outcome, with a comparable acute

Table II. Incidence and management of motor-evoked potential (*MEP*) changes and neurologic outcome

			Paraplegia/paraparesis	
Variable	*No.*	*Normalization of MEPs*	*Immediate*	*Delayed*
MEP change			0/65	5/65
No	65			
Yes	65		5/65	5/65
MEP management				
Clamp removal	9	9	0	0
Restart extracorporal circulation	3	3	0	0
Antegrade perfusion of left subclavian artery	1	1	0	0
Rewarming	1	1	0	0
Reattachment of lumbar artery	5	5	0	1
Occlusion of back-bleeding ICA	2	2	0	0
Raise blood pressure	6	5	1	0
Reattachment to ICA	39	35	4	4
Total			5/130	10/130

ICA, Intercostal artery.

paraplegia rate of 3.8%. The high incidence of significant MEP changes and subsequent surgical strategies to restore evoked potentials illustrates the valuable contribution of neuromonitoring to these favorable results. The surgeons in the different hospitals confirm the drive to re-establish blood flow to the spinal cord the moment they hear from the neurophysiologist that spinal cord function is in danger.

Delayed paraplegia remains a challenging problem in open as well as in endovascular DTAA and TAAA repair. In the present experience, we encountered this complication in 7.7% of patients. Nine had a type II aneurysm, and one patient was treated for a type III aneurysm. MEPs were undisturbed in five patients during the operation, and significant MEP changes occurred in five. In all patients, the causing mechanism could be identified, including hemodynamic instability, occlusion of reattached intercostal arteries, or insufficient CSF drainage. Increasing arterial blood pressure and repeat CSF drainage improved the neurologic deficit in three patients and completely reversed paraplegia in another three.

In our experience, patients with MEP changes during the procedure are at a higher risk to develop delayed spinal cord ischemia.[2,6] During the procedure, their spinal cord was temporarily endangered but obviously restored, as proven by improved MEPs and absence of paraplegia in the acute postoperative phase. However, arterial hypotension can be the reason for fatal infarction of this vulnerable spinal cord, leading to delayed paraplegia. We therefore emphasize even more the recommendation for adequate postoperative management to maintain spinal cord perfusion in patients who have had MEP changes during surgery.

The successful use of neuromonitoring in telemedicine depends on the following essential factors: expertise, reliable technique, cooperativeness and readiness to communicate, and learning. The surgeons and anesthesiologists in all centers welcomed the intensive training, and local technicians were instructed on how to connect the electrodes to the skull and extremities and set up the VPN transfer. In addition, they were taught to communicate with the anesthesiologist on the level of muscle relaxant therapy and with the neurophysiologist in Maastricht. The Maastricht team was present in the participating center during 10 procedures to ensure a robust set-up and reliable connection.

The increasing digitalization of health care enables outsourcing of medical services, thereby reducing investment and operational costs.[7] Indeed, medical outsourcing nowadays serves a variety of specialties, including pathology, dermatology, ophthalmology, and radiology. In the United States, >300 hospitals nationwide and about two-thirds of radiology practices frequently participate in some form of teleradiologic infrastructure.[8-10]

A reliable Internet connection is crucial for the remote technique we describe, and therefore, close cooperation with the information technology department is essential. However, should the connection fail, the highly trained technician who is in the operating room will be able to describe the status of the MEPs to the neurophysiologist by using a telephone connection.

We believe that open repair for TAAA is a typical procedure that should be centralized in high-volume and experienced aortic centers. The incidence of TAAA is relatively low, and the number of centers performing open repair is limited. That clinical outcome is better in high-volume centers with surgeons performing these procedures routinely has been well documented.[11,12] Furthermore, the ideal local infrastructure offers all adjunctive measures, such as extracorporeal circulation, neuromonitoring, intensive care medicine, and a dedicated team. Finally, an aortic center can take care of patients with failed endovascular repair requiring conversion to open surgery. Endovascular repair of TAAA is a very promising technique and is already successful in front-running centers[13,14]; however, technical or disease-related complications can occur, requiring conversion to open repair in a subgroup of patients.[15]

CONCLUSIONS

This study describes the first experience in remote neuromonitoring during open surgical repair of DTAA and TAAA. The telemedicine technique has been shown to be feasible, reliable, and effective, allowing assessment of spinal cord function at a distance by means of an Internet connection, leading to excellent clinical outcomes with respect to ischemic spinal cord complications. This technique can contribute to centralization of expertise and saves individual centers the need to invest in complex technology and manpower.

AUTHOR CONTRIBUTIONS

Conception and design: AG, WM, JS, ED, MJ
Analysis and interpretation: AG, WM, JS, ED, JG, MJ
Data collection: JG, JS, ED, MJ, WM
Writing the article: AG, JG, MJ
Critical revision of the article: AG, WM, ED, JG, MJ
Final approval of the article: AG, WM, JS, ED, JG, MJ
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DISCUSSION

Dr Richard Cambria (*Boston, Mass*). Was there a uniform surgical protocol for how to react to changes in motor-evoked potential monitoring across the four centers?

Dr Michael Jacobs. Indeed, all surgeons from the different centers came to us and we agreed on the protocol, including cerebrospinal fluid (CSF) drainage and distal aortic perfusion, but also the strategic interventions when evoked potentials would disappear. The first logical step is to increase mean arterial and distal aortic pressure. The second step includes reattachment of intercostal arteries. Extremely important is that the anesthesiologists are well trained and well informed, because the equilibrium between anesthesia and evoked potentials is extremely sensitive. For example, if the patient receives too much muscle relaxant, evoked potentials are unreliable.

Dr Cambria. And a follow-up question. Your overall rate of positivity in motor-evoked potential range was in the 50% range. And you quoted no false-positives and no false-negatives. Critics of this technique generally invoke false-positives and false-negatives as the Achilles' heel of it. So will you comment on that?

Dr Jacobs. That is true. Others are using the technique as well and might encounter false-positives and false-negatives. However, we believe that this is purely a technical matter, in which attention to neurophysiological principles and to anesthesiological details play major roles. If that is not working in perfect harmony, you might end up with false-positive and false-negative readings.

Dr Mark Fillinger (*Lebanon, NH*). You mentioned delayed paraplegia, and I wondered if you could comment on how you manage your CSF pressure. Do you have volume limits? What volume do you drain to? And do you treat the patients who get intraoperative deficits differently postop than you do the patients who don't get deficits?

Dr Jacobs. That is a very important question. It is difficult to assess the reasons for the delayed paraplegia in the other centers. However, I know from our own experience that the patients who developed delayed paraplegia either had very low evoked potentials at the end of the procedure or went through a phase of hypotension, sepsis, or any kind of blood pressure drop causing spinal cord damage. We know from some patients that management of spinal cord drainage appeared to be a very important issue: the drain can be blocked and drainage not functioning, causing unnoticed, delayed paraplegia. We keep the pressure between 0 and 10 cm/H_2O and drain as much as is needed to keep these pressures.

Dr Linda Harris (*Buffalo, NY*). I have more of an operational question. Since obviously the patients are remote, how was the neurophysiologist compensated for his or her time?

Dr Jacobs. Yes, absolutely. There is a contract between the different centers and our neurophysiology department: they are paid per procedure. The obvious advantage at the different centers, being either in Beijing, São Paulo, or Chicago, is that they don't have to organize the neurophysiology set-up on site. The only thing you have to do is buy a machine, which is like $70,000, and train a technician to put the electrodes on and make the connection with the central site.

Dr Peter Gloviczki (*Rochester, Minn*). Could you comment on the role of distal ischemia on the effect of evoked potential measurements? Do you need distal perfusion or a BioMedicus pump in all of these patients to get good results?

Dr Jacobs. This is indeed extremely important. We addressed this issue many years ago by stopping distal perfusion for some minutes. In most patients, evoked potential would vanish within minutes. So distal aortic perfusion plays an important role in spinal cord protection by perfusing lumbar and hypogastric arteries during cross-clamping.

Dr Gloviczki. And could you comment on your current technique of intercostal reimplantation, whether it is a simple reimplantation or a bypass, or what do you think works the best? And do you have a number of patency of intercostal reimplantations?

Dr Jacobs. No, we do not have information on intercostal artery patency. However, our strategy is based on the evoked potentials. If we have normal 100% evoked potentials, we oversew the intercostals, except for those in the critical area between T8 and L1, where we reimplant available intercostals, because we know the lower we come in the direction of the iliac vessels during the procedure, the higher the risk will be that you will still lose the evoked potentials. This acts as a sort of a backup system. If we lose the evoked potentials completely, it is very silent in the operating room because we know that if we don't do anything about it, the patient will be paraplegic. We will perform either a bypass or reattachment of segmental vessels. Alternatively, if no intercostals are seen, we rapidly do an endarterectomy of the aortic wall, showing some back-bleeding intercostals, which will subsequently be treated with a selective graft.

Dr Roy Greenberg (*Cleveland, Ohio*). One quick question. We are used to saying that it is the thoracoabdominal aneurysm surgeon that is rare; is the neurophysiologist interpreting the motor-evoked potentials (MEPs) equally rare? How much of the interpretation is art vs science? Is it possible to look forward to computer algorithms that may help us analyze these results, thus minimizing the need for a neurophysiologist to do this? Or is this very much of an art in medicine where the level of complexity and subtlety mixed with patient idiosyncrasies precludes this development?

Dr Jacobs. Well, Roy, I will take that question with me back home and ask the neurophysiologist. It is important to realize that the neurophysiologist is not only reading the signals. If evoked potential disappears, they follow a decision tree, assessing what can cause the trouble. Is it an electrode problem? Is it anesthesia? Is it low blood pressure? Is it calcium? Is it magnesium? They go through that algorithm very quickly, which is very important since they have to assure us whether it is a technical issue or indeed a real spinal cord problem.

Dr Greenberg. There is a lot of communication going back and forth all the time.

Dr Jacobs. Absolutely.

Dr Cambria. And I'll offer a comment too. We have become very fond of this technique, and I agree with Michael that the technique is highly dependent on having an expert neurophysiology team to be sure that you have an adequate technical accomplishment of the monitoring.

INVITED COMMENTARY

Manju Kalra, MBBS, *Rochester, Minn*

Dr Jacobs and his colleagues are to be commended for this first of a kind enterprise using cyber medicine to provide remote neuromonitoring of motor evoked potentials during open thoracoabdominal aortic aneurysm repair. The authors have previously reported extensively on the use of motor evoked potentials as an adjunct for spinal cord protection during these procedures. The complexity, learning curve, and cost have limited the use of this mode of monitoring to a few tertiary centers around the world. With this study, the authors have demonstrated not only the feasibility of a central core center providing this mode of real-time neuromonitoring remotely but also its effectiveness by having achieved similar low rates of spinal cord ischemic complications in the peripheral centers as their own.

The fact that all 130 procedures were successfully performed with complete data transfer to the neurophysiologist at the central institution without time delay is incredible. A Virtual Private Network was set up to enable this, but the fact that this worked flawlessly for several hours at a time during these long procedures is almost unbelievable. Although a backup plan for direct communication with the neurophysiologist through telephone was in place in case of technical problems with the transmission, I wonder if that would have been adequate to pick up subtle changes and troubleshoot satisfactorily.

Whether this technology transfer can be duplicated in other parts of the world remains to be seen. In addition to working out the technical details of remotely providing the service, other aspects would need to be addressed. How would the providing institution be reimbursed for providing the service? Contractual agreements between the participating institutions would have to be fairly complex, given the sensitive nature of the continuous data transfer and the need for immediate action based upon changes, which were not infrequent in this study. Which institution would be liable in case of complications arising from a breakdown of data transfer? These issues would be particularly relevant in the United States with the existing model of health care delivery. They were obviously not significant deterrents to this study, as the authors do not provide any insight into them apart from pointing out the cost savings of not reduplicating the neuromonitoring capability in multiple centers. Regardless, I would like to congratulate the authors for this elegant collaborative study that is very appropriate in the current age of widespread Internet technology.