European Journal of Cardio-Thoracic Surgery 2023, 63(6), ezad198
https://doi.org/10.1093/ejcts/ezad198 Advance Access publication 30 May 2023

ORIGINAL ARTICLE

CONVENTIONAL AORTIC SURGERY

Cite this article as: Schachner T, Gottardi R, Schmidli J, Wyss TR, Van Den Berg JC, Tsilimparis N *et al.* Practice of neuromonitoring in open and endovascular thoracoabdominal aortic repair—an international expert-based modified Delphi consensus study. Eur J Cardiothorac Surg 2023; doi:10.1093/ejcts/ezad198.

Practice of neuromonitoring in open and endovascular thoracoabdominal aortic repair—an international expert-based modified Delphi consensus study

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Received 26 October 2022; received in revised form 21 April 2023; accepted 12 May 2023

Key question

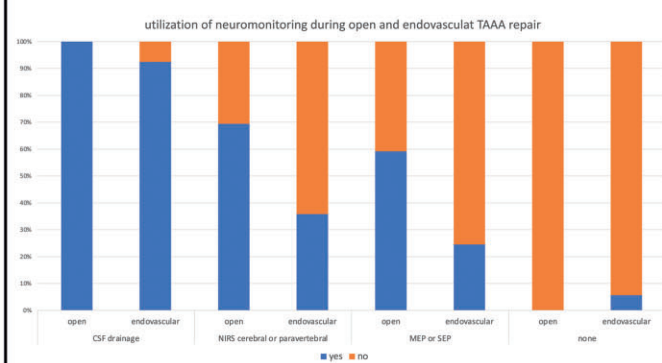
What is current practice in neuroprotection and monitoring in patients undergoing TAAA repair.

Key finding(s)

Use of CSF drainage and neuromonitoring varies depending on the extent of TAAA repair and is more often utilized during open repair.

Take-home message

There is broad consensus on the importance of neuromonitoring and spinal cord protection during open and endovascular TAAA repair.



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Abstract

OBJECTIVES: Spinal cord injury is detrimental for patients undergoing open or endovascular thoracoabdominal aortic aneurysm (TAAA) repair. The aim of this survey and of the modified Delphi consensus was to gather information on current practices and standards in neuroprotection in patients undergoing open and endovascular TAAA.

METHODS: The Aortic Association conducted an international online survey on neuromonitoring in open and endovascular TAAA repair. In a first round an expert panel put together a survey on different aspects of neuromonitoring. Based on the answers from the first round of the survey, 18 Delphi consensus questions were formulated.

RESULTS: A total of 56 physicians completed the survey. Of these, 45 perform open and endovascular TAAA repair, 3 do open TAAA repair and 8 do endovascular TAAA repair. At least 1 neuromonitoring or protection modality is utilized during open TAAA surgery. Cerebrospinal fluid (CSF) drainage was used in 97.9%, near infrared spectroscopy in 70.8% and motor evoked potentials or somatosensory evoked potentials in 60.4%. Three of 53 centres do not utilize any form of neuromonitoring or protection during endovascular TAAA repair: 92.5% use CSF drainage; 35.8%, cerebral or paravertebral near infrared spectroscopy; and 24.5% motor evoked potentials or somatosensory evoked potentials. The utilization of CSF drainage and neuromonitoring varies depending on the extent of the TAAA repair.

CONCLUSIONS: The results of this survey and of the Delphi consensus show that there is broad consensus on the importance of protecting the spinal cord to avoid spinal cord injury in patients undergoing open TAAA repair. Those measures are less frequently utilized in patients undergoing endovascular TAAA repair but should be considered, especially in patients who require extensive coverage of the thoracoabdominal aorta.

ABBREVIATIONS

CSF	cerebrospinal fluid
MEPs	motor evoked potentials
NIRS	near infrared spectroscopy
QD	quartile deviation
SCI	spinal cord injury
SEPs	somatosensory evoked potentials
TAAA	thoracoabdominal aneurysm aortic repair

INTRODUCTION

Open and endovascular thoracoabdominal aortic procedures remain a challenge and carry the risk of significant morbidity and mortality [1]. Neurologic complications, especially spinal cord injury (SCI), are detrimental for the patients. Neuromonitoring-guided aortic repair reduces spinal cord ischaemia [2]. On the other hand, however, adjunct techniques to an already complex procedure may be perceived as an obstacle. The use of the different established neuromonitoring and protection modalities [i.e. cerebrospinal fluid (CSF) drainage, cerebral near infrared spectrometry (NIRS), motor evoked potentials (MEPs), somatosensory evoked potentials (SEPs) and paravertebral NIRS] is not standardized. The aim of this survey and of the modified Delphi consensus was to gather information on current practice and standards in neuroprotection and monitoring in patients undergoing open and endovascular thoracoabdominal aortic aneurysm (TAAA) repair as well as to formulate expert consensus statements on the topic. The purpose of the Delphi technique is to generate a consensus of a group of experts by an iterative process of questionnaire interspersed with controlled feedback. Therefore, the Delphi method can be defined as a structured group communication process in which coarse facts are judged by experts about the uncertain and incomplete knowledge that exists [3]. The term modified Delphi Consensus does not have a standard definition, but in principle, in a modified Delphi Consensus, a steering group facilitates the group communication process [4].

METHODS

The Aortic Association (https://www.aorticassociation.org) conducted an international online survey on neuromonitoring and protection techniques in open and endovascular thoracoabdominal aortic repair surgery. Physicians with experience in the treatment of patients with thoracoabdominal aortic disease were contacted via email containing the link to the online survey.

In the first round, a survey on the different aspects of neuromonitoring and protection as well as other procedural aspects was put together by an expert panel of the Aortic Association (TS, RG, JS, TRW, JVDB, NT, MC). The questions were designed to create an overview of the different procedural aspects of the current practice in open and endovascular aortic repair. In the first round, the survey consisted of 65 closed questions that allowed those surveyed to add a comment or an answer not provided in the preformulated answers. The list of questions in the first round of questions can be found in Supplement 1. Due to the amount of data that was acquired with the first round of the survey, in the Delphi round, the focus was only on different aspects of neuroprotection and monitoring.

Based on the answers from the first round of the survey, 18 Delphi consensus questions were formulated by the Aortic Association expert panel and sent out to the participants of the first round. In the second round, the participants were provided with closed-ended, 5-point Likert scale questions in order to elicit their level of agreement with the statements and their importance. The possible answers on the Likert scale were strongly agree, agree, neither agree nor disagree, disagree and strongly disagree.

ETHICS

The institutional review board of Innsbruck Medical University approved the study (Nr.1160/2021).

STATISTICAL ANALYSIS

The data were analysed using Microsoft Excel for Mac Version 16.59 (Microsoft Corporation, Redmond, WA, USA). Results from the first round of the survey are presented as percentages. Results from the second round are presented as median and quartile deviations. The answers provided in the Likert scale for the Delphi consensus round were given numbers from 5 (strongly agree) to 1 (strongly disagree). The quartile deviation was calculated by dividing the interquartile range by 2 [(Q3-Q1)/2]. A quartile deviation (QD) of 0.5 or less was considered a high level of consensus; a QD of more than 0.5 and equal to or less than 1.0 was defined as moderate consensus; and a QD of more than 1.0 was considered as low or no consensus. A median of 4 and above was defined as a high level of importance, and a median of 3.5 or less, as a low level of importance [5, 6]. For determination of consensus among participants, a standardized Cronbach's alpha was calculated using DATAtab (DATAtable. University of Graz, Graz, Austria).

RESULTS

First-round survey

The first-round survey was sent to 80 physicians, 56 of whom were from 18 countries on 4 continents (Australia, Austria, Belgium, China, Finland, France, Germany, Hungary, Italy, Japan, South Korea, Netherlands, Norway, Poland, Portugal, Switzerland, the United Kingdom and the United States) responded and completed the survey. Of the first-round responders, 27 (48%) were vascular surgeons, 12 (21%) were cardiovascular surgeons, 16 (29%)were cardiac surgeons and 1 (2%) was an interventional cardiologist. Forty-five (80.4%) physicians answered that their centre performs open as well as endovascular TAAA repair; 3 (5.4%) perform only open TAAA repair; and 8 (14.3%), only endovascular TAAA repair.

In the centres of the participating physicians, open TAAA repair is performed in 18.4%, 1–4 times a year; in 36.7%, 5–9; in 18.4% 10–15; and in 26.5%, more than 15 times a year. Endovascular repair is performed in 7.5% 1–4 times per year; in 22.6%, 5–9; in 24.5%, 10–15; and in 45.3%, more than 15 times per year.

TYPES AND FREQUENCY OF NEUROMONITORING AND PROTECTION TECHNIQUES

Open thoracoabdominal aneurysm aortic repair

All physicians used at least 1 neuromonitoring or protection modality during open TAAA surgery. CSF drainage was used by 47/48 (97.9%); cerebral or paravertebral NIRS was used by 34/48 (70.8%); and MEPs or SEPs was used by 29/48 (60.4%) of the centres.

Endovascular thoracoabdominal aneurysm aortic repair

Three of 53 centres do not utilize any form of neuromonitoring or protection during endovascular TAAA repair. Forty-nine (92.5%) use CSF drainage; 19 (35.8%) use cerebral or paravertebral NIRS and 13 (24.5%) use MEPs or SEPs.

Physicians not using neuromonitoring or protection during endovascular TAAA repair further specified that they utilize moderately controlled hypertension during surgery.

CEREBROSPINAL FLUID DRAINAGE

Of the 53 centres utilizing CSF drainage during open or endovascular TAAA repair, 25 (47.2%) answered that prior occlusion of vessels feeding the collateral network would influence their decision to insert a CSF drain. If any of the major branches contributing to the collateral network was already occluded or would be occluded during the TAAA repair, those physicians would more liberally utilize a CSF drain, especially if the left subclavian artery or the internal iliac arteries were occluded or would be occluded during the TAAA repair. When asked if they take measures to precondition the spinal collateral network, 9 (16.1%) answered no; 10 (17.9%) said they use preoperative/preinterventional minimally invasive segmental artery coil embolization (MISACE protocol); 47 (83.9%) said they do a staged interventional repair; 22 (39.3%), a staged open repair; 27 (48.2%) use a sidebranch/fenestration that initially remains open for spinal cord protection in endovascular repair; and 1 (1.8%) employs a hybrid approach with thoracic endovascular aortic repair for the thoracic aorta and an open repair for the abdominal aorta.

Of the 53 physicians utilizing a CSF drain, 26 (49.1%) place the CSF drain the day before the procedure; 24 (45.3%), on the day of the procedure; and 3 (5.7%), only if symptoms of spinal cord ischaemia develop or MEPs change. The CSF drain is placed in 92.5% by the anaesthesiologist, in 5.7% by a neurosurgeon and in 1.9% by the surgeon performing the TAAA repair.

In case of a bloody puncture, 9 (17.0%) respondents would continue with the procedure without a CSF drain; 3 (5.7%) would wait for 4 h and would puncture again. Eleven (20.8%) would discontinue and reschedule the CSF drain insertion for the next day; 26 (49.1%) would discontinue and reschedule the procedure; and 4 (7.5%) would decide if they would reschedule or proceed without a CSF drain depending on the urgency of the procedure.

The upper pressure limits of the CSF drain tolerated intraoperatively are < preoperative values, 10 (18.9%); < 10 mmHg, 15 (28.3%); <15 mmHg, 25 (47.2%); and 3 respondents (5.7%) would make the limit dependent on the procedure, up to 25 mmHg, 12 mmHg or do not measure pressure.

Postoperatively, the pressure limits that are tolerated if no neurologic symptoms are present are < preoperative values in 10 (18.9%); < 10 mmHg in 14 (26.4%); < 15 mmHg in 30 (56.6%); and 4 (7.5%) do not measure pressure or would tolerate pressure up to 25 mmHg or 12 mmHg.

Of the 47 centres that utilize CSF drainage during open TAAA repair, 3 (6.4%) would remove the CSF drain after 24 h if no neurologic deficit is evident. Seventeen (36.2%) would remove it after 48 h; 23, (48.9%) after 72 h. In 2 (4.2%) centres, the drain is left in place up to 5 days. Two (4.2%) institutions would leave the drain in place until the patient is extubated, regardless of how long it takes.

Of the 49 centres that utilize CSF drainage in patients undergoing endovascular TAAA repair, 7 (14.3%) remove the CSF drain after 24 h if no neurologic deficits are evident. Twenty-three (46.9%) remove the drain after 48 h; 15 (30.6%), after 72 h. In 1 institution (2.0%), the drain is left in place for up to 7 days. In another centre (2.0%), the drain is kept in place until the patient is extubated. In only 2 services, a CSF drain is placed postoperatively if symptoms of SCI develop and is left in those patients for 72 h.

If SCI is suspected intraoperatively, 1/53 (1.9%) services would keep the CSF pressure below the preoperative value; 9 (17.0%) <15 mmHg; 29 (54.7%) <10 mmHg; and 8 (15.1%) < 5 mmHg. Six (11.3%) services would keep the pressure either < 12 mmHg, 5–8 mmHg, 8 mmHg, have no other monitoring, do not monitor pressure or would increase the mean arterial pressure in combination with the withdrawal of 10 ml CSF fluid.

In case of the postoperative presence of SCI, the maximum CSF drain withdrawal tolerated is 10 ml/h in 4/53 (7.5%) centres; 15 ml/h in 13 (24.5%); 20 ml/h in 16 (30.2%); 25 ml/h in 2 (3.8%); and 30 ml/h in 1 (1.9%) centre. Fourteen (26.4%) centres prefer open CSF drainage until a headache develops. Finally, 1 centre would tolerate a maximum CSF drainage volume of 400 ml/24 h; another centre would drain as much fluid as needed to maintain a pressure between 5 and 15 mmHg; and 1 centre would make the decision, depending on symptoms and the individual situation.

Utilization of CSF drainage and neuromonitoring varies depending on the extent of TAAA repair: the highest utilization is in type II aortic repair and the lowest, in type IV aortic repair (Figs. 1 and 2).

An automated pressure-controlled CSF drainage system is used regularly in 23 of 53 centres (43.4%); occasionally in 3 (5.7%); and never in 27 (50.9%). If a pressure-controlled CSF drainage system is used, 10 (35.7%) centres would set it to a maximum flow rate of 15 ml/h and 16 (57.1%), to 20 ml/h.

DELPHI CONSENSUS ROUND

Based on the results of the first-round survey, 18 Delphi consensus questions were formulated by the Aortic Association expert panel and sent to the physicians who participated in the first-round survey. Of the initial 56 responders, 48 (85.7%) answered the Delphi consensus questions.

Of the 18 Delphi consensus questions, 13 achieved a high importance and a high consensus. Three questions achieved a high importance but only a moderate consensus. One question had high importance but no consensus, and one question had low importance with moderate consensus (Table 1). The correlations between the answers of the individual respondents, the Cronbach's alpha value, was 0.81. A level of ≥ 0.8 is considered a good consensus among Delphi panel members [7, 8].

DISCUSSION

Open and endovascular treatment of thoracoabdominal aortic disease is performed in experienced centres with different adjuncts of neuromonitoring and protection tools. The use of neuromonitoring devices depends on the planned extent of the

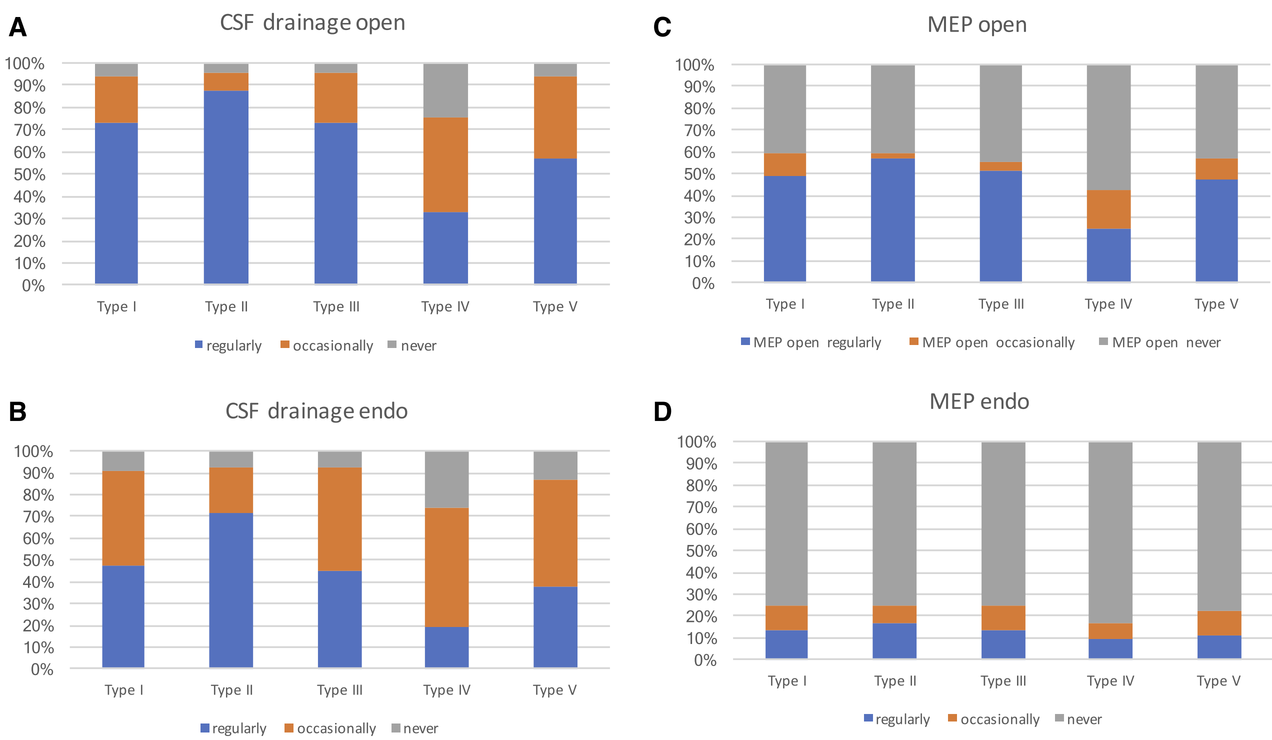

Figure 1: (**A**) Use of CSF drainage depending on type of open TAAA repair. Type I: regularly, 76.6%; occasionally, 21.3%; never, 2.1%; type II: regularly, 91.5%; occasionally, 8.5%; type III: regularly, 76.6%; occasionally, 23.4%; type IV: regularly, 34.0%; occasionally, 44.7%; never, 21.3%; type V: regularly, 59.7%; occasionally, 38.3%; never, 2.1%. (**B**) Use of CSF drainage depending on type of endovascular TAAA repair. Type I: regularly, 51.0%; occasionally, 46.9%; never, 2.1%; type II: regularly, 77.6%; occasionally, 22.4%; type III: regularly, 49.0%; occasionally, 51.0%; type IV: regularly, 20.4%; occasionally, 59.2%; never, 20.4%; type V: regularly, 40.8%; occasionally, 53.1%; never, 6.1%. (**C**) Use of motor evoked potentials depending on type of open TAAA repair. Type I: regularly, 82.8%; occasionally, 17.2%; type II: regularly, 96.5%; occasionally, 3.5%; type III: regularly, 86.2%; occasionally, 6.9%; never, 6.9%; type IV: regularly, 41.4%; occasionally, 31.0%; never, 27.7%; type V: regularly, 79.3%; occasionally, 17.2%; never, 3.5%. (**D**) Use of motor evoked potentials depending on type of endovascular TAAA repair: type I: regularly, 53.8%; occasionally, 46.2%; type II: regularly, 69.2%; occasionally, 30.8%; type III: regularly, 53.8%; occasionally, 46.2%; type IV: regularly, 38.5%; occasionally, 30.8%; never, 30.8%; type V, regularly; 46.1%; occasionally, 46.2%; never, 7.7%. CSF: cerebral spinal fluid; MEP: motor evoked potential; TAAA: thoracoabdominal aortic aneurysm.

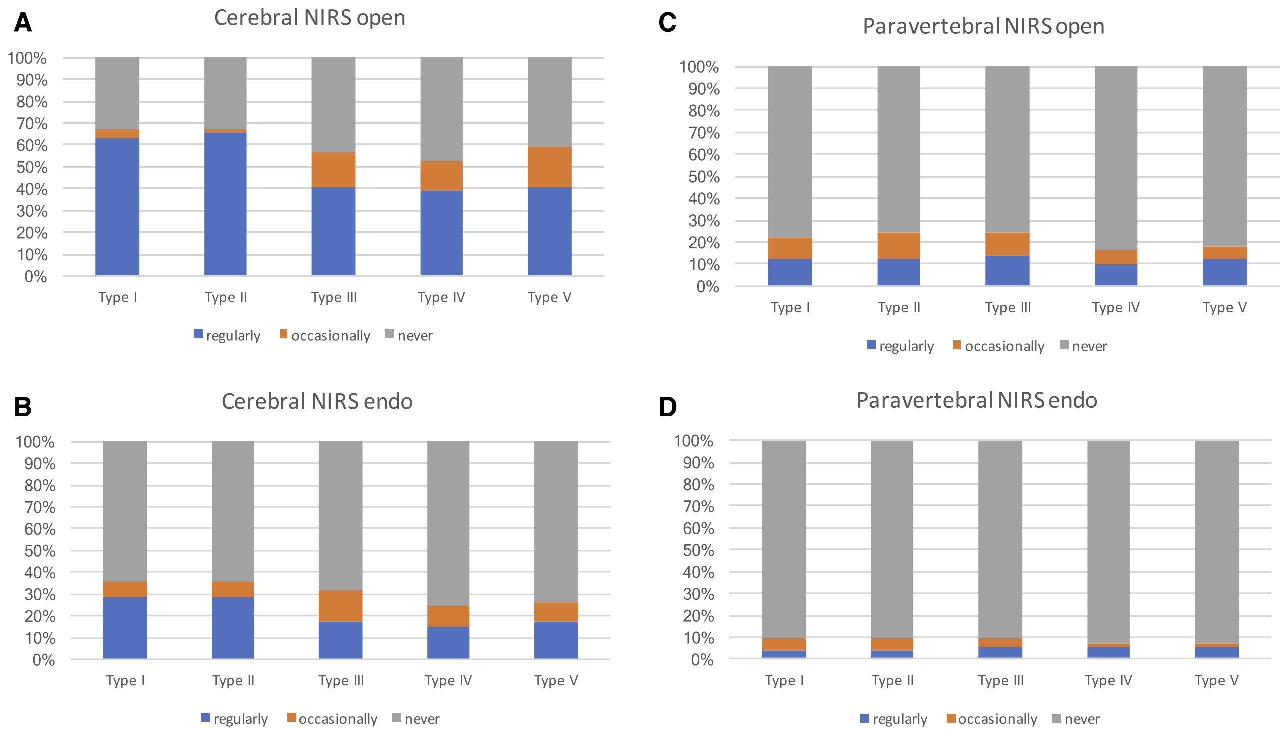

Figure 2: (**A**) Use of cerebral near infrared spectroscopy (NIRS) depending on the type of open TAAA repair. Type I: regularly, 93.9%; occasionally, 6.1%; type II: regularly, 97.0%; occasionally, 3.0%; type III: regularly, 60.6%; occasionally, 24.2%; never, 15.2%; type IV: regularly, 57.6%; occasionally, 21.2%; never, 21.2%; type V: regularly, 60.6%; occasionally, 27.3%; never, 12.1%. (**B**) Use of cerebral NIRS depending on type of endovascular TAAA repair. Type I: regularly, 78.9%; occasionally, 21.1%; type II: regularly, 78.9%; occasionally, 21.1%; type III: regularly, 47.4%; occasionally, 42.1%; never, 10.5%; type IV: regularly, 42.1%; occasionally, 26.3%; never, 31.6%; type V: regularly, 47.4%; occasionally, 6.3%; never, 26.3%. (**C**) Use of paravertebral NIRS depending on type of open TAAA repair. Type I: regularly, 18.2%; occasionally, 15.2%; never, 66.6%; type II: regularly, 18.2%; occasionally, 18.2%; never, 63.6; type III: regularly, 21.2%; occasionally, 15.2%; never, 63.6%; type IV: regularly, 15.2%; occasionally, 9.1%; never ,75.7%; type V: regularly, 18.2%; occasionally, 9.1%; never, 72.7%. (**D**) Use of paravertebral NIRS depending on type of endovascular TAAA repair. Type I: regularly, 10.5%; occasionally, 15.8%; never, 73.7%; type II: regularly, 10.5%; occasionally, 15.8%; never, 73.7%; type III: regularly, 15.8%; occasionally, 10.5%; never, 73.7%; type IV: regularly, 15.8%; occasionally, 5.3%; never, 78.9%; type V: regularly, 15.8%; occasionally, 5.3%; never, 78.9%. NIRS: near infrared spectroscopy; TAAA: thoracoabdominal aortic aneurysm.

TAAA repair. It was found that neuromonitoring was used most frequently in type II, followed by types I and III, followed by type V and was used least often in type IV TAAAs. This result can be explained by the fact that complication rates are grouped similarly within the different types of TAAAs. Coselli *et al.* found cerebral complications most frequently in type II TAAAs (11.6%) and least frequently in type IV TAAAs (4.3%). The same group found any spinal cord deficit in 13.9% of type II and 4% of type IV TAAA [9]. The data from our survey showed that there is a difference in utilization of neuromonitoring and protection techniques. CSF drainage was most frequently used, followed by cerebral NIRS, MEPs, SEPs and paravertebral NIRS. This pattern presented consistently throughout all types of TAAA repair, with more frequent utilization in patients undergoing open aortic repair compared to endovascular aortic repair.

The reason that CSF drainage was at the top of the list of all neuromonitoring options for TAAA surgery is that there is good scientific evidence for its benefits [2]. In addition, CSF drainage is not only a monitoring tool but can also be used to lower CSF pressures, which differentiates it from all other monitoring tools. Safi *et al.* reported in 2005 a significant reduction of neurologic deficits after introduction of CSF drainage (plus distal aortic perfusion) in TAAA surgery [10]. In a randomized trial, CSF drainage was associated with a significant reduction of SCI in types I and II TAAA operations [11]. The pathophysiological background is due to the inverse relationship between spinal perfusion pressure and CSF pressure described by the formula: spinal perfusion pressure = (mean arterial pressure = cerebrospinal fluid pressure). However, potential complications of CSF drainage, such as neuraxial haematoma, intracranial bleeding, drain fracture and meningitis have to be kept in mind [12]. An individual indication for CSF drains is necessary, depending on the type of TAAA and other risk factors. A high consensus was noted for the statement that CSF drainage should be used in all patients undergoing open surgery for types I, II, III and V TAAA and should be considered in patients with type IV TAAA if additional risk factors for symptomatic SCI are present. The use of CSF drainage in patients undergoing endovascular treatment for types I, II, III and V did not reach consensus. Because patients undergoing endovascular TAAA repair seem to have a lower incidence of SCI than patients undergoing open TAAA repair, there is a trend towards not utilizing prophylactic CSF drainage in patients undergoing endovascular TAAA repair but only therapeutic CSF drainage in symptomatic patients [13].

Complications associated with CSF drains are a critical issue. One issue is a bloody puncture while attempting to place the CSF drain, which might put the patient at risk for neuraxial haematoma, which is a severe complication [14–16]. In our study, a high consensus was reached regarding maximum patient safety: In the case of a bloody puncture, the use of the CSF drain should be discontinued, and the operation should be rescheduled with a minimum delay of 24 h.

Table 1: The 18 Delphi consensus questions and the level of importance and level of consensus

Delphi questions: Open and endovascular aortic repair	Median	1st Quartile	3rd Quartile	IQR	QD	
1. CSF drainage should be used in all patients undergoing OPEN types I, II, III and V TAAA repair and should be considered in patients undergoing type IV repair if additional risk factors for symptomatic spinal cord injury are present. (Risk factors would be occlusion of 1 or more vascular territories feeding the collateral network.)	5.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
2. CSF drainage should be used in all patients undergoing ENDOVASCULAR types I, II, III and V repair and may be considered in patients undergoing type IV repair if additional risk factors for symptomatic spinal cord injury are present. (Risk factors would be occlusion of 1 or more vascular territories feeding the collateral network.)	4.00	3.00	5.00	2.00	1.00	**High importance – no consensus**
3. In OPEN types I, II, III and V TAAA repair, despite CSF drainage, at least 1 additional method (MEPs, SEPs or paravertebral NIRS) to monitor spinal cord perfusion should be routinely used.	4.00	3.50	5.00	1.50	0.75	**High importance – moderate consensus**
4. In ENDOVASCULAR types I, II, III and V TAAA repair, despite CSF drainage, at least 1 additional method (MEPs, SEPs or paravertebral NIRS) to monitor spinal cord perfusion should be considered.	3.00	2.00	3.25	1.25	0.63	**Low importance – moderate consensus**
5. Cerebral NIRS should be used in all patients undergoing an OPEN type I or II TAAA repair.	4.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
6. Cerebral NIRS should be considered in patients undergoing an OPEN type III or V TAAA repair	4.00	3.00	4.00	1.00	0.50	**High importance – high consensus**
7. Staged OPEN or hybrid repair (TEVAR + OPEN repair of remaining downstream aortic segments) or preoperative minimally invasive segmental artery coil embolization (MISACE protocol) should be considered if feasible.	4.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
8. Staged ENDOVASCULAR TAAA repair or preinterventional minimally invasive segmental artery coil embolization (MISACE protocol) should be considered, if appropriate, to minimize the risk of symptomatic spinal cord injury.	5.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
9. In ENDOVASCULAR TAAA repair, an “intentional endoleak“ (branch that remains initially open) may be a useful option to prevent symptomatic spinal cord injury.	4.00	3.75	5.00	1.25	0.63	**High importance – moderate consensus**
10. In case of a bloody puncture, the placement of the CSF drain should be discontinued and the operation should be rescheduled.	4.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
11. In case of bloody puncture, delay of rescheduling the procedure and re-puncturing should be at least 24 hours.	4.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
12. When puncturing for CSF drainage, initial puncture pressure should be monitored.	4.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
13. Intraoperatively the CSF pressure should not exceed 10-15 mmHg. However, initial pressures should be used as a reference, and higher values might be accepted if preoperative CSF pressure was higher.	4.00	3.75	5.00	1.25	0.63	**High importance – moderate consensus**
14. Postoperatively, in the absence of symptomatic spinal cord injury, the CSF pressure should be kept to preoperative levels but should not exceed 10–15 mmHg. However, initial pressures should be used as a reference and higher values might be accepted if preoperative CSF pressure was higher.	4.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
15. If spinal cord injury is suspected intraoperatively, CSF pressure should be kept below preoperative CSF pressure.	5.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
16. In the absence of symptomatic spinal cord injury, the CSF drain can be removed 48–72 hours after OPEN TAAA repair.	5.00	4.00	5.00	1.00	0.50	**High importance – high consensus**

Continued

Table 1: Continued

Delphi questions: Open and endovascular aortic repair	Median	1st Quartile	3rd Quartile	IQR	QD	
17. In the absence of symptomatic spinal cord injury, the CSF drain can be removed 24–72 hours after ENDOVASCULAR TAAA repair.	5.00	4.00	5.00	1.00	0.50	**High importance – high consensus**
18. In case of symptomatic spinal cord injury, CSF drainage should be kept at least 2 days beyond when the diagnosis is established, even if CSF pressure has already returned to preoperative levels.	5.00	4.00	5.00	1.00	0.50	**High importance – high consensus**

CSF: cerebrospinal fluid; IQR: interquartile range; MEPs: motor evoked potentials; MISACE: minimally invasive segmental artery coil embolization; NIRS: near infrared spectroscopy; QD: quartile deviation; SEPs: somatosensory evoked potentials; TAAA: thoracoabdominal aortic aneurysm; TEVAR: thoracic endovascular aortic repair.

The upper CSF pressure limits during TAAA surgery in the literature are most commonly described within 10 to 15 mmHg [14]. Coselli said that he maintains the CSF pressure at less than 15 mmHg [11]. In agreement, it was seen that the most frequently used upper CSF pressure limits intraoperatively were 15 mmHg in about half of the centres and 10 mmHg in about one-third of the centres. In addition, similar thresholds were used for the uncomplicated postoperative course. It is usually advised that CSF drainage volume should be limited because excessive CSF drainage carries the risk of tearing the subdural veins and of intracranial haemorrhage [17]. Nevertheless, it has to be noted that there is no high-level evidence available on an upper limit of CFS pressure or drainage volume to prevent or reverse spinal cord malperfusion and subsequent SCI.

About half of the centres in our study used MEPs and to a smaller extent, SEPs. This explains why only moderate consensus was achieved for the Delphi statement that in open surgery for types I, II, III and V TAAA, despite CSF drainage, at least 1 additional method [MEP, somatosensory evoked potential (SEP) or paravertebral NIRS) to monitor spinal cord perfusion should be used routinely. For endovascular TAAA repair, the consensus for the use of an additional method for monitoring the spinal cord function was even less. The use of evoked potentials in TAAA surgery certainly demands additional know-how and manpower to accurately detect and interpret the signals. In addition, it adds time to the perioperative setting. Tanaka *et al.* reported a loss of MEP or SEP signals in 58% of patients ($n = 822$, 62% TAAAs) undergoing descending aortic replacement. Immediate SCI occurred in none of the patients without loss of EPs; in none of the patients with isolated SEP loss (which rarely happened); in 1% of isolated MEP loss; and in 9% of combined MEP and SEP loss [18]. Jacobs *et al.* reported a good experience with the use of MEPs in TAAAs. They saw a decrease of MEPs in 17% of patients after aortic cross-clamping, and all patients with early or delayed paraplegia were in this group [19].

NIRS is the least invasive neuromonitoring method in TAAA surgery. Cerebral NIRS, with sensors placed on the head, are frequently used in cardiac surgery [20]. This procedure is in agreement with our study where two-thirds of the centres use cerebral NIRS in patients with types I and II TAAAs. In addition, high consensus was reached that cerebral NIRS should be used in all patients undergoing surgery for type I or II TAAA, and cerebral NIRS should be considered in patients undergoing surgery for type III or V TAAAs.

In contrast, paravertebral NIRS is less frequently used, and only about one-fifth of centres used paravertebral NIRS regularly or occasionally in TAAA surgery. This might in part be due to lower scientific evidence for its use. However, some promising experimental and clinical data are already available. Etz *et al.* demonstrated an association between paravertebral NIRS (lumbar position) and blood flow in the spinal collateral network during surgery for type II TAAAs. After aortic cross-clamping, NIRS values decreased, and they increased following initiation of distal aortic perfusion. In addition, although it was a small study, they found a more profound drop of the paravertebral NIRS in patients who developed SCI [21]. The same group recently published data from a porcine model. They found that the values of low thoracic and lumbar sensors of paravertebral NIRS show a close correlation with both aortic cross-clamping and releasing the aortic blood flow [22].

The 18 Delphi consensus statements that the Aortic Association expert panel formulated, based on the results from the first-round survey, were sent to 56 physicians experienced in the treatment of open and/or endovascular repair, 45 of whom completed the Delphi consensus statements. The number of experts is considered large because Delphi consensus statements are often formulated with a far lower number of participants [23]. Because the first survey that was sent out had already been provided by the expert panel, whose members formulated the Delphi consensus questions, and had offered much insight into the current practices in neuromonitoring and protection in patients undergoing open and endovascular TAAA repair, only 1 round was required for the Delphi consensus. From the 18 consensus statements, we achieved a high consensus with high importance in 13, which means here was broad consensus on those questions. Three statements were considered of high importance, but yielded only a moderate consensus. Those 3 statements are on the use of neuromonitoring in addition to CSF drainage in patients undergoing open TAAA repair, the use of an intentional endoleak in patients undergoing endovascular TAAA repair for spinal cord protection and the degree of intraoperative CSF pressure tolerated. We did not reach consensus on the statement that CSF drainage should be used in patients undergoing endovascular types I, II, III or V repair. Because there are to date no large, randomized trials available on that topic, there is no clear evidence for the use of CSF drains in those patients but neither is there clear evidence against it. Therefore, the lack of consensus on this statement reflects current practice, and reformulation of this statement might not have led to a different result, which is why we chose to accept that there is no consensus on this topic. The consensus statement on the use of additional monitoring techniques in patients undergoing endovascular types I, II, III or V TAAA repair was of low importance and reached only moderate consensus. There is even less evidence showing the benefit of additional spinal cord monitoring in patients undergoing endovascular TAAA repair compared to the use of CSF drainage. The lack of consensus on this statement also reflects current scientific knowledge and practice.

LIMITATIONS

Although the number of physicians involved in this survey and the Delphi consensus is high, with a high number of physicians who are on the forefront of scientific research in the field of open and endovascular repair, involving physicians from 4 continents, we may have missed important contributors to the topic. Although this survey and the Delphi consensus do not include clinical data, the Delphi consensus statements are expert opinion only. In addition, lack of availability or reimbursement for adjunctive measures for neuromonitoring and protection might have an impact on the utilization in the participating centres and might be a potential hidden bias.

CONCLUSION

The results of this survey and the Delphi consensus show that there is broad consensus on the importance of protecting the spinal cord via monitoring, CSF drainage, preoperative segmental coil embolization or staged procedures to avoid SCI in patients undergoing open TAAA repair. Because the risk of SCI seems to be less pronounced in patients undergoing endovascular TAAA repair, those measures are less frequently used in those patients but should be considered, especially in patients who require extensive coverage of the thoracoabdominal aorta (i.e. type II repair) or major side-branches forming the collateral network.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *EJCTS* online.

ACKNOWLEDGEMENTS

Members of the Aortic Association Study Group are as follows:
Ourania Preventza (Department of Cardiothoracic Surgery, Baylor College of Medicine, Texas Heart Institute, Baylor St Luke's Medical Center, Houston, TX, USA), Hitoshi Matsuda (Department of Cardiovascular Surgery, National Cerebral and Cardiovascular Center, Suita/Osaka, Japan), Michael Jacobs (Department of Vascular Surgery, Maastricht University Medical Center, Maastricht, the Netherlands), Benedikt Reutersberg (Department of Aortic Surgery, University Hospital Zurich, Zurich, Switzerland), Roberto Chiesa (Division of Vascular Surgery, Vita Salute San Raffaele University, IRCCS San Raffaele Scientific Institute Milano, Italy), Chris Probst (Department of Cardiovascular Surgery, University Hospital Mainz, Mainz, Germany), Gabriele Piffaretti (Vascular Surgery, Department of Medicine and Surgery, University of Insubria, School of Medicine, Varese University Hospital, Varese, Italy), Marco Di Eusanio (Lancisi Cardiovascular Center, Ospedali Riuniti, Politechnic University of Marche, Ancona, Italy), Vitaly Sorokin (National University Heart Center, Singapore, National University of Singapore, Singapore, Singapore), Fabio Verzini (Vascular Surgery Unit, Department of Surgical Sciences, University of Turin, Turin, Italy), Zoltan Szeberin (Department of Vascular and Endovascular Surgery, Semmelweis University, Budapest, Hungary), Stephen Wk Cheng (Department of Surgery, The University of Hong Kong, Hong Kong, China), Luca Di Marco (Department of Cardiac Surgery, S. Orsola University Hospital, Bologna, Italia), Yvonne Gosslau (Vascular Surgery, Faculty of Medicine, University of Augsburg, Augsburg, Germany), George Matalanis (Cardiac Surgery, Austin Hospital, Melbourne, Australia), Konstantinos Tsagakis (Department of Thoracic and Cardiovascular Surgery, West German Heart and Vascular Center, University Hospital Essen, Essen, Germany), Gustavo Oderich (Cardiothoracic and Vascular Surgery, The University of Texas Health Science Center at Houston, McGovern Medical School, Houston, TX, USA), Øyvind Jakobsen (Department of Cardiothoracic and Vascular Surgery, University Hospital of North Norway, Tromsø, Norway), Aung Oo (Department of Cardiothoracic Surgery, St Bartholomew's Hospital, London, United Kingdom), Ahmed Koshty (Vascular and Endovascular Surgery, Diakonie Klinikum Jung Stilling, Siegen, Germany), Maximilian Pichlmaier (Department of Cardiac Surgery, Ludwig-Maximilians-University, Munich, Munich, Germany), Maciej Kolowca (Department of Cardiac Surgery, Univeristy Hospital, Rzeszow University, Rzeszow, Poland), Robin H Heijmen (Department of Cardiothoracic Surgery, Radboud UMC, Nijmegen, the Netherlands), Luís Mendes Pedro (Vascular Surgery, Hospital Santa Maria, Lisboa, Portugal), Inge Fourneau (Vascular Surgery, University Hospitals Leuven, Leuven, Belgium), Alexander Zimmermann (Department of Vascular Surgery, University Zurich, Zurich, Switzerland), Kenji Minatoya (Department of Cardiovascular Surgery, Kyoto University, Kyoto, Japan), Stephan Haulon (Division of Vascular Surgery, Aortic Centre, Hôpital Marie Lannelongue, Groupe Hospitalier Paris Saint Joseph, Université Paris-Saclay, Paris, France), Maximilian Luehr (Department of Cardiothoracic Surgery, University of Cologne, Cologne, Germany), Christian Reeps (Department of Vascular and Endovascular Surgery Dresden, Uniklinikum Dresden, Dresden, Germany), Thanos Sioris (Department of Cardiothoracic Surgery, Tampere University Hospital, Tampere, Finland), Christoph Nienaber (Department of Cardiology, Royal Brompton Hospital, London, United Kingdom), Santi Trimarchi (Department of Surgery, Fondazione IRCCS Cà Granda Ospedale Maggiore Policlinico Milan, University of Milan, Milan, Italy), John A Elefteriades (Aortic Institute, Yale University, New Haven, CT, USA, Ernst Weigang (Department for Vascular Surgery, Academic Hospital Hubertus, Berlin, Germany), Toru Kuratani (Minimally Invasive Cardiovascular Medicine, Osaka, University Osaka, Osaka, Japan), Katrin Meisenbacher (Department of Vascular and Endovascular Surgery, University Hospital Heidelberg, Heidelberg, Germany), Arminder Jassar (Division of Cardiac Surgery, Massachusetts General Hospital, Boston, MA, USA), Martin Grabenwoeger (Department of Cardiovascular Surgery, Clinic Floridsdorf, Vienna, Austria), Mario D'Oria (Division of Vascular and Endovascular Surgery, University Hospital of Trieste, Trieste, Italy), Martina Fink (Department of Vascular Surgery, HGZ Bad Bevensen, Bad Bevensen, Germany), Joost van Herwaarden (Department of Vascular Surgery, University Medical Center Utrecht, Utrecht, the Netherlands), Fabrizio Rosati (Department of Cardiac Surgery, Spedali Civili di Brescia–University of Brescia, Brescia, Italy), Eric Verhoeven (Department of Vascular and Endovascular Surgery, General Hospital Nuremberg, Nuremberg,

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Conflict of interest: The authors declare no conflict of interest related to this work.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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