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Differential selective hypothermic intercostal artery perfusion: a new method to probe spinal cord perfusion during thoracoabdominal aortic aneurysm repair

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Abstract

Objective To prevent paraplegia in patients undergoing thoracoabdominal aortic aneurysm repair, the importance of preoperative identification of the Adamkiewicz artery and reconstruction of critical intercostal artery have been advocated. Conversely, significance of collateral network for spinal cord perfusion has been recognized. We invented a new system consisting of a direct monitoring of cerebrospinal fluid temperature (CSFT) and differential selective hypothermic intercostal artery perfusion (D-HIAP).

Methods After exposing a critical intercostal artery, a 10-mm prosthetic graft was anastomosed in an end to side fashion. A balloon-tipped catheter was inserted into the graft to perfuse with 15 °C blood. Neighboring intercostal arteries were also perfused in the same fashion. Serial monitoring of CSFT was performed. Between January 2011 and January 2015, D-HIAP was employed in 50 patients with Adamkiewicz artery that located within a reconstructed area.

Results Significant CSFT drop was recorded after initiation of D-HIAP in 42 (84%) patients. Of those, 34 (68%) patients showed significantly lowered CSFT with D-HIAP into a single critical intercostal artery. Perfusion into plural intercostal arteries was necessary for CSFT drop in 2 cases (4%), and plural intercostal artery perfusion further enhanced CSFT drop that had been modestly achieved by single intercostal artery perfusion in 6 cases (12%). Eight (16%) patients did not exhibit a significant drop in CSFT even when D-HIAP was employed for the critical and neighboring intercostal arteries.

Conclusions The detection of a disparity in temperature between the intrathecal space and blood generated by D-HIAP revealed individual variability in CSFT changes, which may imply a complexity in spinal cord perfusion. Intraoperative D-HIAP may help to identify a major blood supply for spinal cord perfusion and underlying collateral network.

Keywords Thoracoabdominal aortic aneurysm · Spinal cord injury · Hypothermic perfusion

Introduction

Paraplegia as a complication of thoracoabdominal aortic aneurysm (TAAA) repair has not been completely resolved and remains a devastating factor exacerbating both early- and long-term outcomes [1–3]. Various methods have been applied to prevent paraplegia during TAAA surgeries. Various mechanisms and concepts involving spinal cord blood flow have also been proposed for a decade; however, 2.7–11.4% of cases continue to suffer spinal cord injury after surgery [4–7].

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To prevent paraplegia in patients undergoing TAAA repair, the importance of preoperative identification of the Adamkiewicz artery (AKA) and reconstruction of critical intercostal artery (ICA) have been advocated [8]. Conversely, significance of collateral network for spinal cord perfusion has been recognized [9, 10]. It is assumed that blood supply to the spinal cord carries an inherent complexity and acquired alterations due to pathophysiological condition in arterial systems.

With regard to intraoperative monitoring of spinal cord perfusion, motor evoked potentials (MEPs) have been reported as a useful means to detect spinal cord ischemia [8, 11]. However, intraoperative monitoring of MEPs is not consistently reliable to indicate a perfusion status of the spinal cord during the TAAA repair and cannot predict all neurologic deficits [12].

With this in mind, we have developed a new system consisting of a direct monitoring of cerebrospinal fluid temperature (CSFT) and differential selective hypothermic intercostal artery perfusion (D-HIAP). Our initial clinical experience with D-HIAP was reviewed in this study.

Materials and methods

Preparation and procedures for D-HIAP

This system consists of a direct monitoring of CSFT using a cerebrospinal fluid drainage catheter incorporated with a temperature sensor [13] and selective intercostal artery perfusion with cold blood. After exposing a critical ICA, a 10-mm prosthetic vascular graft was anastomosed in an end to side fashion to the thoracic aortic wall. A balloon-tipped 12-Fr catheter (MERA Balloon Catheter, SENKO MEDICAL INSTRUMENT Mfg, Co., Ltd. Tokyo) was inserted into the graft to perfuse with 15 °C blood. Neighboring ICAs were also perfused in the same fashion. D-HIAP perfusion pressure was adjusted to the systemic mean arterial pressure, which enabled us to measure a perfusion flow rate on an individual ICA. Serial monitoring of CSFT was performed (Fig. 1).

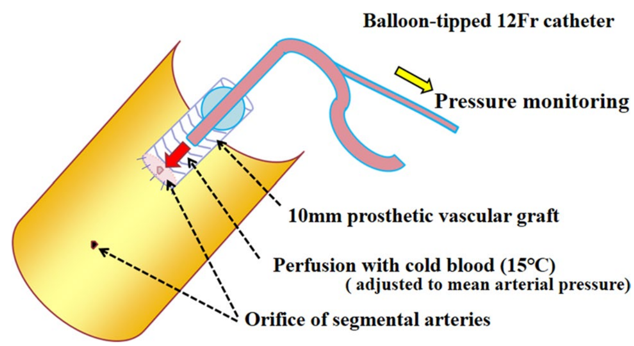

Fig. 1 Procedures for differential selective hypothermic intercostal artery perfusion (D-HIAP). Hypothermic (15 °C) cold blood is selectively perfused via a balloon-tipped 12-Fr catheter situated within a short prosthetic graft being anastomosed to a critical intercostal artery, while cerebrospinal fluid temperature is monitored

Table 1 Patient characteristics (N = 50)

Age (year, mean ± SD)	58.3 ± 11.5
Sex (male:female)	36:14
Aortic pathology	
Non-dissection	12
Dissection	38
Crawford classification	
I	5
II	25
III	13
IV	6
V	1
Marfan's syndrome	13
Epidural cooling	22

Patients and methods

Between January 2011 and January 2015, D-HIAP was employed in 50 patients. Forty-seven had preoperatively identified AKA being located within the reconstructed aortic lesion either by multi-detector computed tomography or MRI [14, 15]. The AKA was not preoperatively detected in the remaining 3 patients even with those advanced technologies. Patient characteristics are summarized in Table 1. Mean age was 58.3 ± 11.5 years with range of 35–81, and 36 cases were male. Thirty-eight cases had aortic dissection as an etiology, 11 patients had degenerative atherosclerotic aneurysm, and infectious aneurysm was diagnosed in one patient. The extent of the aortic aneurysm was Crawford type I in 5, II in 25, III in 13, IV in 6 and Crawford–Safi V in 1 patient, respectively. Epidural perfusion cooling [13] was performed in 22 cases, when applicable.

Data analysis

Categorical variables are presented as frequencies and percentages, and continuous variables are expressed as the mean ± standard deviation. An independent-sample Student's t test and the χ^2 test were used for group comparisons of continuous variables, and the non-parametric Mann–Whitney U test and Fisher's exact test were used for group comparisons of categorical variables. All reported P values were two sided, and $P < 0.05$ was considered statistically significant. All statistical analyses were performed using JMP version 11.0 (SAS Institute Inc., Cary, NC).

Results

CSFT changing patterns

Significant CSFT drop was recorded after initiation of D-HIAP in 42 (84%) patients. We attempted to classify the CSFT changing patterns into the following types (Table 2). Thirty-four (68%) patients showed significantly lowered CSFT with D-HIAP into a single critical ICA. Of those, CSFT drop was achieved with D-HIAP into a patent single critical ICA (pattern 1, 28 cases (56%)) or a single alternative collateral artery connected to an occluded critical ICA (pattern 1co, 6cases (12%)). Perfusion into plural intercostal arteries was necessary for CSFT drop (pattern 2a, 2 cases (4%)), and plural intercostal artery perfusion further enhanced CSFT drop that had been modestly achieved by single intercostal artery perfusion (pattern 2b, 6 cases (12%)). Eight (16%) patients did not exhibit a significant drop in CSFT even when D-HIAP was employed for the critical and neighboring intercostal arteries (pattern 3). With regard to 3 patients whose AKA was not detected preoperatively, 2 of these patients exhibited pattern 1 CSFT drop, and another patient showed pattern 2a changes. Postoperative CT confirmed the AKA connecting to the reconstructed ICAs.

Serial changes in the CSFT (intrathecal temperature) and systemic temperature recorded from the representative pattern 1 case are depicted in Fig. 2. The patient had a Crawford type III degenerative TAAA. The AKA was preoperatively diagnosed as derived from the right 9th ICA. Systemic temperature was maintained approximately at 32 °C by cardiopulmonary bypass. As an effect of epidural cooling, CSFT decreased by 6 °C. After D-HIAP was commenced into the right 9th ICA, the CSFT significantly dropped down to 16 °C, and the initial change was minus 5° within 5 min. Additional D-HIAP into the left 10th ICA did not alter the CSFT. After the interposing grafts were anastomosed to the aortic main graft and reperfused with systemic blood, the CSFT quickly approached the systemic temperature.

Likewise, serial changes in two temperature parameters of pattern 2a case are shown in Fig. 3. The patient had a Crawford type III compatible dissecting TAAA with the AKA derived from the right 9th ICA. Epidural cooling was

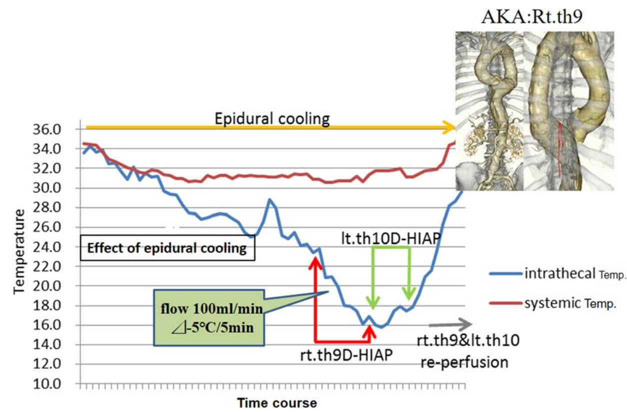

Fig. 2 Serial changes in intrathecal cerebrospinal fluid temperature (CSFT) and systemic temperature during D-HIAP in the representative case of pattern 1 temperature change. After D-HIAP was commenced into the right 9th ICA, the CSFT significantly dropped down to 16 °C. D-HIAP, differential selective hypothermic intercostal artery perfusion; AKA, Adamkiewicz artery; Rt., right; th, thoracic

Table 2 Results ($N=50$)

CSFT changing pattern	1	28
	1co	6
	2a	2
	2b	6
	3	8
Average number of reconstructed ICAs per patient		2.0±1.2
Early patency rate for reconstructed ICAs (%)		84.8%
Early mortality		0
Complications	SDH	6
	Pneumothorax	4
Paraplegia		2
Paraparesis		2

CSFT cerebrospinal fluid temperature, *ICA* intercostal artery, *SDH* subdural hematoma

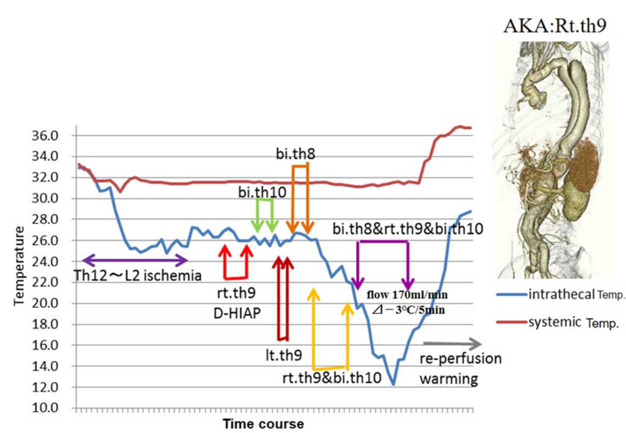

Fig. 3 Serial changes in intrathecal CSFT and systemic temperature during D-HIAP in the representative case of pattern 2a temperature change. Simultaneous D-HIAP into multiple ICAs achieved significant drop in the CSFT, whereas D-HIAP into a single critical ICA did not. *L* lumbar, *lt.* left, *bi*, bilateral

not employed in this case. Despite D-HIAP being initiated into the "critical" right 9th ICA, there was no change in the CSFT. Alternatively, bilateral 10th ICAs, left 9th ICA, or bilateral 8th ICAs were perfused with resultant no significant temperature changes. Of note, the CSFT started to decrease after simultaneous perfusion into the right 9th and bilateral 10th ICAs was commenced and further decreased after additional D-HIAP into the bilateral 8th ICAs was performed. Reperfusion with systemic blood resulted in prompt resumption of the CSFT.

Figure 4 illustrates pattern 3 temperature changes from a representative case. The patient had a Crawford type III degenerative TAAA with the AKA derived from the left 9th ICA. D-HIAP was performed into the "critical" left 9th ICA; however, the CSFT did not change at all. The consistency in the temperature was observed even after the additional D-HIAP was attempted into the left 10th and 8th ICAs.

Lastly, Fig. 5 shows the case of pattern 1co temperature changes whose left 9th ICA giving rise to the AKA had occluded at the aortic side. D-HIAP successfully helped to identify probable major alternative collateral source of left 11th ICA with this technique.

CSFT drop pattern according to Crawford type classification was examined and is shown in the supplementary table 1. There was no statistically significant difference in proportion of each CSFT drop pattern between the Crawford types ($p = 0.889$).

Average flow rate in selective hypothermic intercostal artery perfusion

The average flow rates were calculated according to the pattern of CSFT drop (Table 3). There were no statistical differences between the groups, although the flow rate per single ICA tended to be higher when we observed significant CSFT drop (pattern 1 or 1co). As for patterns 2a and 2b, the average flow rate was obtained by dividing the total flow rate by the number of simultaneously perfused ICAs.

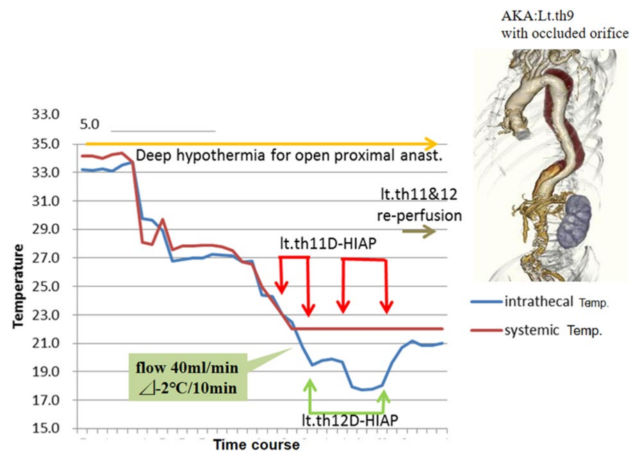

Fig. 5 Serial changes in intrathecal CSFT and systemic temperature during D-HIAP in the representative case in whom the major collateral source was identified as left 11th ICA when the orifice of critical 9th ICA was occluded

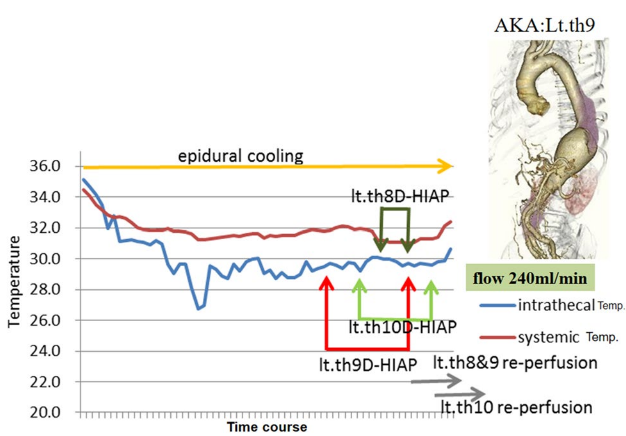

Fig. 4 Serial changes in intrathecal CSFT and systemic temperature during D-HIAP in the representative case of pattern 3 temperature change. The consistency in the temperature was observed after critical ICA was perfused with D-HIAP technique and even after the additional D-HIAP into the neighboring ICAs

Surgical outcomes

The number of the reconstructed ICA was 2.0 ± 1.2 per patient. The postoperative overall patency rate of the reconstructed ICA as confirmed by enhanced CT was 84.8%. Surgical mortality was not observed in this patient cohort. There was no in-hospital mortality related to D-HIAP maneuver.

Table 3 Average flow rate with selective hypothermic intercostal artery perfusion

Pattern	Flow (ml/min)
1	59.8 ± 24.9
1co	73.3 ± 24.2
2a	(44.7 ± 17.5)
2b	(61.5 ± 14.4)
3	47.1 ± 23.5

The number in parenthesis is the average flow rate per intercostal artery

There were no statistically significant differences between the pattern groups ($p = 0.266$)

Spinal cord injury

In terms of spinal cord injury, two (4%) patients who were categorized into pattern 1 temperature change temporally experienced paraparesis. One patient was Crawford type III and the other was type IV. All the reconstructed intercostal arteries were patent in these two patients postoperatively. In the former case who had a history of previous descending thoracic aortic replacement elsewhere, postoperative MRI revealed a focal ischemic change in the spinal cord at the 3rd thoracic vertebral level. Another two (4%) patients who were categorized into pattern 3 temperature change developed paraplegia. Of those, one Crawford type IV patient having previous histories of aortic arch replacement and abdominal aortic Y-grafting developed focal infarction at the lower spinal cord. His AKA was diagnosed as derived from the left 2nd lumbar artery which we attempted to reconstruct. However, the postoperative computed tomography revealed that the reconstructed segmental artery was the left 1st lumbar artery. Another paraplegia patient was found to be Crawford III patient whose reconstructed two intercostal arteries were occluded postoperatively (Table 2).

With regard to the incidence of spinal cord injury according to Crawford type classification, there were no statistically significant differences between the groups ($p = 0.064$), although the incidence of spinal cord injury tended to be higher in Crawford III and IV compared to the other types (supplementary table 2). In terms of the incidence of spinal cord injury according to the patterns of CSFT drop, there were no significant differences between the groups classified by patterns of CSFT ($p = 0.356$), although pattern 3 tended to be associated with higher SCI incidence (supplementary table 3).

Influence of epidural cooling on spinal cord protection

Spinal cord injury consisted of 2 cases of paraparesis and 2 cases of paraplegia all found in the patients who underwent epidural cooling. There was a statistically significant increase in the incidence of spinal cord injury in the epidural cooling group ($n = 22$) compared with that in the non-epidural cooling group ($n = 28$) in our present cohort ($p = 0.019$).

Discussion

Dynamically proved physiological significance of AKA by D-HIAP

The detection of a disparity in temperature between the intrathecal space and blood generated by D-HIAP revealed individual variability in CSFT changes, which may imply a complexity in spinal cord perfusion. As mentioned previously, there is a controversy on spinal cord perfusion. The circulation in the spinal cord is largely dependent on the blood supply via the dominant AKA, whereas collateral circulation also seems to be significant to maintain spinal cord function. Bishoff et al. reported an experimental model of paraplegia after complete ligation of the segmental artery [16], which showed that only half of the experimental models developed paraplegia. This consequence implies the above two concepts on spinal cord perfusion are valid. It also indicates that even in the animals for experiment, there is significant variability in the anatomical aspects related to blood supply to the spinal cord, which is reflected in our present outcome associated with D-HIAP.

Currently, multiple methods are clinically applied as strategies for spinal cord protection, for instance, preoperative identification of AKA with advanced diagnostic tools, intraoperative distal perfusion, segmental aortic cross-clamp, control of back flow from segmental arteries to prevent the steal phenomenon, etc. Among these, preoperative identification of AKA has been achieved in large number of cases; however, there are still some cases in whom AKA is not practically identifiable in a real clinical setting. In fact, AKA was not identified in 3 (6%) of our patients. In that situation, spinal cord perfusion depends on unrevealed collateral sources, but it is often times difficult to identify a main or a major collateral source for spinal perfusion preoperatively and even more difficult during open surgery. With that in mind, we attempted D-HIAP in those 3 patients whose critical ICA was not detected preoperatively. Two of these patients exhibited pattern 1 CSFT drop, and another patient showed pattern 2a changes. Thus, intraoperative D-HIAP might help to identify a preoperatively unidentified major blood supply for spinal cord perfusion. More to the point, even when a single critical segmental artery is detected on preoperative CT or MR angiography, the orifice of a critical ICA is not infrequently reported to be occluded. Neighboring ICA is suspected as an alternative collateral source to the AKA by the same modality. We could observe significant drop in the CSFT after initiating D-HIAP into an ICA near the occluded “critical” ICA as demonstrated in Fig. 5. Hence, intraoperative D-HIAP may help to assure a major blood supply for spinal cord perfusion and underlying collateral source.

Uncertainty in intraoperative identification of critical segmental artery and vulnerability of the upper spinal cord to ischemia

With regard to one of the patients who developed paraplegia, the preoperatively detected critical lumbar artery was not accurately identified during the surgery. One can appreciate that miscarriage of identifying a specific segmental artery can be a reality due to anatomical variation in each patient. In that instance, the CSFT temperature changes with pattern 3 after D-HIAP may serve as an alarming tester to assure a target segmental artery in some patients, if not all.

One patient developing paraparesis was found to have developed high thoracic spinal cord infarction despite the patency of all the reconstructed ICAs. One of the speculative mechanisms to this phenomenon may be explained by poor upward perfusion from the top of the AKA hairpin curve. Svensson et al. elucidated the vascular anatomy of the anterior spinal artery in baboon implicating its similarity to that in man [17] and demonstrated that the size of the AKA was smaller above (0.278 mm) than below (0.744 mm) the entry of the arteria radicularis magna. They also calculated that the resistance to flow was more than 50 times greater in the higher area of the anterior spinal artery as compared with the lower part of this artery. Shiiya et al. classified the spinal cord arteries into isolated hairpin-shaped and confluence-shaped or multiple type [18]. In isolated hairpin-shaped type, they postulated that spinal cord perfusion proximal to the hairpin curve is vulnerable to ischemia even with the use of distal aortic perfusion due to the great size discrepancy at the narrowing point. Taken together with these previous findings along with the postoperative MRI findings in the above-mentioned our present case, the flow to the upper spinal cord might be insufficient despite selective intercostal artery perfusion.

Possible prediction of postoperative paraplegia

When we observed significant drop in CSFT in 42 (84%) of our patients including patterns 1, 1co, 2a and 2b, the incidence of spinal cord injury was 4.8% (2 out of 42 patients); whereas, when we did not detect significant CSFT drop in 8 (16%) of the patients, i.e., pattern 3, the incidence of spinal cord injury was 25.0% (2 out of 8 patients), which tended to be higher, although it did not reach statistical significance ($p = 0.053$). Once we observe significant CSFT drop intraoperatively, there is a high chance to be able to succeed in protection of the spinal cord.

What are the roles of D-HIAP in our present clinical practice? We deem that fundamental role of D-HIAP is to assure whether or not a reconstructed ICA is connected to spinal cord feeding artery. After an interposed short prosthetic graft is anastomosed to a main body graft, we can re-assure that the reconstructed ICA is well perfused judging from rewarmed CSFT. In addition, as discussed above, intraoperative D-HIAP may help us identify a preoperatively unidentified major blood supply for spinal cord perfusion. Further to the point, D-HIAP can provide some additional protection to the spinal cord by cooling. Once appropriate hypothermic cooling of the spinal cord is carried out, safety margin for spinal cord ischemic time is extended; hence, the remaining surgical procedure can be done without rushing. Finally, D-HIAP can play a role to probe complex physiology in spinal cord perfusion that has not yet been elucidated completely even in the modern era.

Although D-HIAP has a promise to resolve the detailed mechanisms involved in spinal cord circulation and to decrease the unpredictable occurrence of paraplegia after TAAA repair, the number of patients in this study is limited; therefore, further accumulation of cases undergoing D-HIAP is warranted.

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