INVITED REVIEW ARTICLE

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The frozen elephant trunk technique

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ABSTRACT

The frozen elephant trunk (FET) technique, which was an advanced version of the elephant trunk technique, is now the gold standard for distal aortic arch repair. The major advantage is that the distal anastomosis is fixed by the stent; therefore, anastomosis that has been used to be performed in the descending aorta can be performed on the more proximal side of the aortic arch. The FET technique has become widely used, causing the increased risk of spinal cord injury (SCI) to become a major concern. As the FET fixes the distal side, the risk of SCI increases depending on its landing zone and depth. To avoid SCI, stent length should be limited to about 10 cm, and the use stents of 15 cm in length or landing beyond Th8 should be avoided. Another problem after the FET technique is the distal site new entry (d-SINE) in the mid- and long-term stages. d-SINE can also occur after thoracic endovascular aortic repair (TEVAR), mainly due to its oversizing. The spring-back-force, which is also related to the stent strength, is also said to be a cause of d-SINE after the FET technique. I herein review the FET technique, its surgical outcomes, and complications.

Keywords: frozen elephant trunk, elephant trunk, distal aortic arch aneurysm

Abbreviations:
ET: elephant trunk
FET: frozen elephant trunk
TEVAR: thoracic endovascular aortic repair
SCI: spinal cord injury
d-SINE: distal stent graft-induced new entry

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INTRODUCTION: THE BIRTH OF THE "FROZEN ELEPHANT TRUNK"

The elephant trunk (ET) technique was developed by Borst et al[1] in 1983. It is a unique technique for managing extensive aortic aneurysms, wherein an artificial graft is inserted into the descending aorta at the first stage of the operation to serve as a scaffold for the next procedure. In 1992, the ET technique was modified to insert a folded artificial graft into the descending aorta, anastomosed, and pulled back to the proximal side. A branched graft was introduced in 2006. Shrestha et al reported the results of ET over a 30-year period from 1982 to 2012 at the

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University of Hannover (138 cases, 91 true aortic aneurysms and 47 aortic dissection cases).[2] The advantage of the ET technique is that it can reduce the cardiopulmonary bypass time and circulatory arrest time by dividing the extensive aortic aneurysm surgery into a two-stage operation, thereby reducing the invasiveness of the procedure. The disadvantage of the second-stage procedure is the mortality rate during the waiting period. The completion rate of the second stage of surgery was only 32% over the past 30 years, and it was also reported that approximately 70% of the patients did not reach to the second stage of surgery for various reasons.[2]

The Frozen ET (FET) technique is an advanced version of the ET technique, but its official origin is the "Open Stent Graft Technique", a hybrid surgery (a combination of endovascular surgery and open surgery) developed by Dr Masaaki Kato in 1994 and popularized in worldwide.[3] The major advantage of the FET technique is that the distal side is fixed by the stent, which used to be anastomosed in the descending aorta, and now surgeon could anastomose only the proximal side of the FET graft in the proximal aortic arch from zone 0 to zone 3 according to the patient's aortic pathology.

Although the name of FET is now well established, it was first published in the manuscript by Usui et al[4] in 2002 and by Karck et al[5] in 2003. The name of "FET technique" has become popularized, although it was reported under a different name of "stented elephant trunk method" by Flores et al[6] and Liu et al.[7]

SURGICAL OUTCOMES OF FET

The greatest benefit of the FET technique is that anastomosis can be performed on the proximal side compared with the classical procedure. Kato et al introduced a de-branching technique without using a cardiopulmonary bypass, in which the ascending aorta was clamped by the side-clamp, two branches were anastomosed, and a distal stent was inserted via one of the branches.[8,9]

Total arch replacement (TAR) can be performed even in the ascending aorta from zone 0 and can sometimes be performed without cardiopulmonary bypass. This could be the pioneer, and the origin of TAR performed only with endovascular treatment. It is also excellent in that it is applicable not only to true aortic arch aneurysms but to acute and chronic dissected aortic arch aneurysms as well. Especially when used for acute dissecting aortic aneurysms, insertion into the true lumen can close the entry into the false lumen and contribute to the closure of the false lumen.

The indication for its use in relatively extensive aortic arch aneurysms is increasing because the distal side is fixed by the stent. However, paraplegia is a major post-operative risk depending on the depth of stent fixation. This problem was introduced by Usui et al, who reported a 4% incidence of paraplegia.[4] Spindle-shaped atheroma is mentioned as a risk factor for paraplegia.[4] The incidence of paraplegia was also reported to be 24% in a 2006 report from another report, which also reported landings below Th7 and a history of abdominal aortic aneurysm treatment as significant risk factors, with groups including both of these factors being at an even higher risk.[6]

Bavaria et al[10] introduced three hybrid approaches that originated from Kato's hybrid procedure, and their results were reported in 2013. In Type 1 hybrid repair, the graft for branch reconstruction is anastomosed to the ascending aorta, and thoracic endovascular aortic repair (TEVAR) is performed from that branch. In Type 2 hybrid repair, only an ascending replacement is performed with a branch, and TEVAR is performed from that branch. In Type 3 hybrid repair, TEVAR is performed in two stages after arch replacement and ET insertion (Fig. 1, Table 1-a). The off-pump rate for Type 1 was 57%. Postoperative outcomes included a hospital mortality rate of 8%

overall and 11% alone, which occurred only in Type 1 (Table 1-b). Spinal cord injury ([SCI], SCI include paraplegia and paraparesis) occurred in 6% overall and 7% alone, this occurred only in Type 1 (Table 1-c). The treatment of Type 1 at my institution has been reported by Banno et al, but this technique is not currently the standard procedure because of the increased rate of stroke (20%), and partial dissection of the ascending aorta had occurred due to side clamping of the ascending aorta.[11]

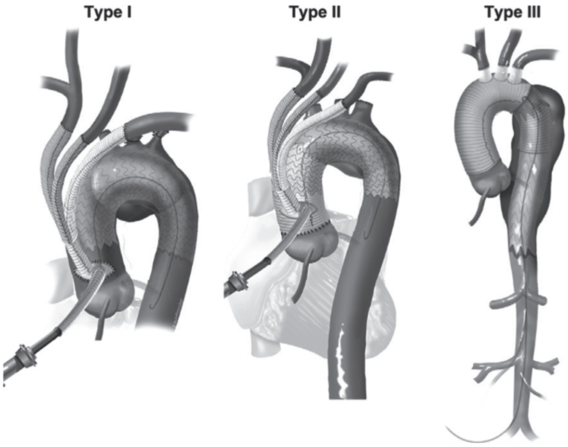

Fig. 1 Hybrid aortic arch repair
(Figure 1 from reference 10, reprinted with permission from Elsevier Inc.)

Table1-a Patients demographics of all hybrid techniques, Type 1 and Type 2

	All hybrids	Type 1	Type 2
Preoperative characteristics			
N	36	28	8
Age (y)	70.7 ± 8.0	69.3 ± 7.5	71.1 ± 8.3
Gender (N male)	23 (64%)	18 (64%)	5 (63%)
Prior CVA	15 (42%)	12 (43%)	3 (38%)
Chronic lung disease	14 (39%)	11 (39%)	3 (38%)
Prior MI	12 (33%)	9 (32%)	3 (38%)
Chronic renal insufficiency	6 (17%)	6 (21%)	0 (0%)
Smoker (current or history)	29 (81%)	23 (82%)	6 (75%)
Aortic disease			
Aneurysm	29 (81%)	25 (89%)	5 (63%)
Maximum diameter (mean, cm)	7.1 ± 1.5	7.1 ± 1.5	7.4 ± 1.4
Chronic dissection	4 (11%)	1 (4%)	3 (38%)
Failure of prior TEVAR	1	1	
Pseudoaneurysm (posttraumatic transection)	2 (6%)	2 (7%)	

CVA: cerebrovascular accident
MI: myocardial infarction
TEVAR: thoracic endovascular repair

Table 1-b Intraoperative variables of all hybrid techniques, Type 1 and Type 2

Intraoperative	All hybrids	Type 1	Type 2
N	36	28	8
Off pump	16 (44%)	16 (57%)	
CPB time (m)	215 ± 64	193 ± 58	259 ± 54
Aortic crossclamp time (m)	70 ± 55	44 ± 27	121 ± 63
Circulatory arrest	7 (19%)		7 (87%)
Circulatory arrest time (total, m)			19 ± 10
SACP time for arch debranching (m)			45.0 ± 13
Number of stents implanted (median)	2	2	1.5
Adjunct CABG	7 (19%)	6 (21%)	1 (13%)
Adjunct valve repair/replace	2 (6%)	1 (4%)	1 (13%)
Two-branch reimplantation with carotid-left subclavian bypass	8 (22%)	7 (25%)	1 (13%)

CPB: cardiopulmonary bypass
SACP: selective antegrade cerebral perfusion
CABG: coronary artery bypass grafting

Table 1-c Postoperative outcomes of all hybrid techniques, Type 1 and Type 2

Outcomes	All hybrids	Type 1	Type 2	*P* (type 1 vs type 2)
N	36	28	8	
In-hospital mortality	3 (8%)	3 (11%)	0	.45
Stroke	3 (8%)	3 (11%)	0	.45
Permanent paraplegia	2 (6%)	2 (7%)	0	.6
Transient heurologic deficit	5 (14%)	3 (11%)	2 (25%)	.3
Renal failure	3 (8%)	3 (11%)	0	.45
Renal failure requiring new hemodialysis	1 (3%)	1 (4%)	0	.78
Reoperation for bleeding	1 (3%)	1 (4%)	0	.78
Atrial fibrillation	15 (42%)	11 (39%)	4 (50%)	.44
Mean hospital stay (d)	17.2 ± 14.0	16.3 ± 14.0	22.0 ± 9.6	.28

(Table 1 from reference 10, reprinted with permission from Elsevier Inc.)

In extensive aortic arch aneurysms reaching the Th8 level, ET for the first-stage operation and second stage for TEVAR is now basic strategy, showing a significantly better SCI rate than the FET technique alone, because of its ability to spread the risk across two times surgeries. On comparing the FET group (Group A, 54 cases) with the ET+2nd TEVAR group (Group B, 37 cases), paraplegia occurred in 8 cases (15%) in the FET group and none (0%) in the ET+2nd TEVAR group. The ET+2nd TEVAR group had significantly superior results regarding the occurrence rate of SCI (Table 2).[12]

Table 2 Post-operative outcomes of FET vs ET+TEVAR

Variable	Group A (n = 54)	Group B (n = 37)	p Value
Hospital death	2 (3.7%)	0	0.487
Hospital Stay (Day)	45 ± 26	34 ± 11	0.028
ICU Stay (Day)	6.7 ± 8.3	3.6 ± 3.6	0.039
Re-exploration	3	4	0.335
Stroke	5 (9%)	3 (8%)	0.849
Paraplegia	8 (15%)	0	0.014
Paraparesis	1 (2%)	2 (5%)	0.351
SCI	9 (17%)	2 (5%)	0.106
Renal failure	4 (7%)	1 (3%)	0.348
Af	13 (24%)	13 (35%)	0.217
Prolonged ventilation	14 (26%)	9 (24%)	0.798

ET: elephant trunk
FET: frozen elephant trunk
TEVAR: thoracic endovascular aortic repair
ICU: intensive care unit
SCI: spinal cord injury
Af: atrial fibrillation
(Table 2 from reference 12, reprinted with permission from Nagoya Journal of Medical Science)

In 2020, Preventza et al group reported the results of a meta-analysis of more than 3000 cases, which included 3154 cases in total from 35 studies. The subgroup analysis showed that the risk of SCI was significantly increased in landing zones with a stent length greater than 15 cm and at the level of Th8, while the risk was decreased if stents used were limited to approximately 10 cm. The use of the FET technique for acute dissection has also been reported to increase incidence of adverse events, including death, stroke, and SCI, without a significantly difference. The final conclusion is that stent length should be limited to approximately 10 cm, and the use of 15-cm stents and landings exceeding the Th8 level should be avoided[13] (Fig. 2).

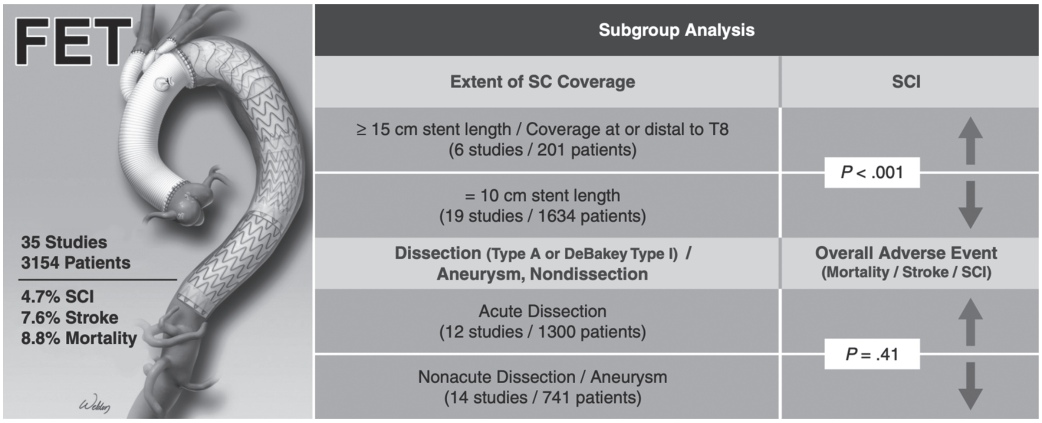

Fig. 2 Surgical outcomes of meta-analysis data
FET: frozen elephant trunk
SC: spinal cord
SCI: spinal cord ischemia
(Figure 2 from reference 13, reprinted with permission from Elsevier Inc.)

In 2024, a meta-analysis[14] compared open arch repair and hybrid arch repair and reported that hybrid arch repair was significantly associated with an increased incidence of paraplegia. Propensity score matching also showed that hybrid arch repair was significantly more likely than open arc repair to cause paraplegia.

In conclusion, perioperative complications, excluding paraplegia, reintervention, and stroke, were less common in the hybrid arch repair group than in the open arch repair group. In other words, paraplegia was more of a problem with hybrid arch repair than with open arch repair.

FET COMPLICATIONS

Key points are as follows:

1. The FET technique fixes the peripheral side of the anastomosis, so the risk of SCI increases depending on the landing site and depth.
2. To avoid SCI, stent length should be limited to about 10 cm, and 15-cm stents and landings beyond Th8 should be avoided.

SURGICAL OUTCOME OF FROZENIX

Frozenix (Japan Lifeline, Tokyo) is a device developed by Dr Kato and JUNKEN MEDICAL Corporation in 2014.

On the Japan Lifeline website (https://www.j-graft.com/frozenix/index.html), each expert describes the pitfalls of the surgery. Yamanaka[15] uses transesophageal echocardiography to show the point where the FET was above the aortic valve level. Ogino[16] explained the handling of non-stented areas, peripheral dislodgement, and other precautions. Usui[17] introduced the points to be considered when using FETs for residual dissection after ascending displacement in dissecting aortic aneurysms. Tochii[18] introduced aortic remodeling after surgery for Stanford type A aortic dissection. Yamamoto[19] introduced the effectiveness of arch replacement with FET from zone 0 in acute aortic dissection. These articles can be downloaded from the website for review.

In 2022, Ogino et al[20] reported the results of all Japanese data of 684 cases (369 FET and 315 conventional repair cases) from 2016–2019 with propensity score matching.

The FET group had more aortic dissection cases and a significantly higher rate of emergency surgery cases than classical aortic arch repair (Fig. 3). The 30-day and hospital mortality rates were not significantly different in the non-adjusted propensity score matching group, while the stroke and paraplegia rates were significantly higher in the non-adjusted FET group. However, the propensity score matching results were not significantly different (Fig. 3). Of note, a warning message regarding the development of SCI is given in the final conclusion.

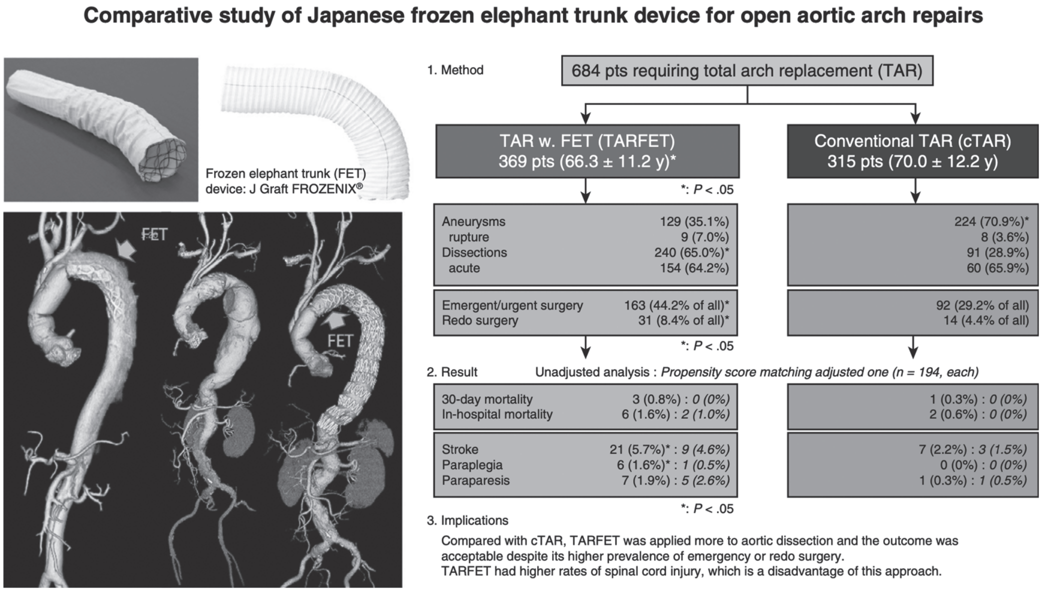

Fig. 3 Comparative study of Japanese TARFET vs cTAR
Left, patient demographics of TARFET and cTAR; right, comparative study of TARFET and cTAR with unadjusted analysis and adjusted analysis. *Significantly different.
TARFET: total arch replacement with frozen elephant trunk
cTAR: conventional total arch replacement
pts: patients
(Figure 3 from reference 20, reprinted with permission from Elsevier Inc.)

Institutional Frozenix results (79 cases before Bundle, 42 cases after Bundle) showed a significantly lower incidence of SCI than when using handmade (24 cases) FETs (paraplegia: handmade, 4 cases, 17%; before Bundle, 1 case, 1%; after Bundle, 1% in 1 case, 2% in 1 case). The incidence of paraplegia after the Bundle approach was also lower than that the handmade approach (handmade, 4 cases, 17%; pre-Bundle, 1 case, 1%; post-Bundle, 1 case, 2%). The incidence of the paraplegia in the post-Bundle approach is considered to have been unavoidable due to the post-operation of the descending aorta or thoracoabdominal aorta replacement and the shaggy aorta of the FET implantation site.

BUNDLE APPROACH

Three aspects are the following:

1. Prediction of optimal peripheral position of FET by workstation (3-Mensio)
2. Distal perfusion using 24-Fr balloon from the middle of anastomosis (shortening the lower body ischemia time)
3. Maintenance of mean postoperative blood pressure of 70 mmHg.

DISTAL STENT GRAFT-INDUCED NEW ENTRY

Distal stent graft-induced new entry (d-SINE) occurs early or several months after FET for dissecting aortic aneurysms. d-SINE can also occur after TEVAR and is mainly caused by oversizing. The “spring-back force” after the FET technique, which is also related to the stent strength, is said to be a cause of the d-SINE.

Pacicni et al[21] reported on the incidence of the d-SINE in 139 patients who underwent TEVAR for complicated type B dissection between 2007 and 2013. Among the patients, 27.8% developed d-SINE. They reported that d-SINE occurs more frequently in chronic dissection than in acute aortic dissection. Martin et al reported in 2020 that true lumen diameters were smaller preoperatively in the d-SINE group after TEVAR and FET and that this occurred significantly more frequently in over sizing cases.[22]

In 2022, Hiraoka et al reported in a multicenter study[23] the predictive factor for the d-SINE after FET use in 177 acute and chronic dissection cases from 2014 to 2021. The d-SINE incidence was 14.1%, with a cumulative incidence of 7.1% at 12 months, 12.4% at 36 months, and 21.4% at 60 months. In a multivariate analysis, an onset >48 h after aortic dissection was a significant risk factor for the d-SINE.

Pre-emptive TEVAR is also recommended in high-risk patients to prevent d-SINE. We changed institutional policy to preemptively perform TEVAR two or three months after surgery in patients with chronic aortic dissection who have a large false lumen diameter.

In general, the treatment after the occurrence of d-SINE is TEVAR. Li et al[24] reported that the long-term prognosis was also affected by the presence of the d-SINE treatment.

In summary, d-SINE can occur both acutely and chronically in the aortic dissection cases, and in the acute cases, anything beyond 48 h from the onset is already a risk factor. Chronic cases are more common than acute ones, and the risk is also increased if the true lumen is small, and an oversized FET is inserted. Therefore, simply sizing or downsizing for insertion into the true lumen for aortic dissection may need to be strongly recommended.

CONCLUSIONS

FET is a useful technique for the distal aortic arch repair for aneurysm or aortic dissection, and there are so many positive effects from the surgical aspects but also have many precautions that should be taken. When using FET, determine the landing site with an appropriate length is determined using the measurement tool. If the aneurysm extends to the descending aorta below the Th8 level, ET should be considered for the first and 2nd stage of TEVAR. When FET is used for dissecting aortic aneurysms, careful consideration of d-SINE and refraining from over sizing and pre-emptive TEVAR can be recommended in high-risk patients to prevent the d-SINE.

CONFLICT OF INTEREST

The authors declare no conflicts of interest in association with this study.

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