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ORIGINAL ARTICLE

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Hybrid versus open repair of aortic arch aneurysms: comparison of postoperative and mid-term outcomes with a propensity score-matching analysis

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Abstract

OBJECTIVES: Operative strategies for repairing aortic arch aneurysms should be re-evaluated following recent technical advances.

METHODS: Of 364 patients who underwent aortic arch repair between 2002 and 2014, 58 were high-risk subjects who received isolated hybrid arch repair (HAR) via median sternotomy (type I $n = 32$, type II $n = 1$ and type III $n = 25$). During this period, excluding patients with type A dissection or extensive aneurysms, 124 patients received isolated open arch repair via median sternotomy. The patients in the HAR and open arch repair groups were compared. A propensity score-matching analysis was applied to adjust for baseline risk factors.

RESULTS: The patients in the HAR group were older (77 years ± 6 vs 69 ± 9, $P < 0.0001$), exhibited a greater rate of malignancy (21 vs 4.8%, $P = 0.0022$) and had higher logistic EuroSCORE values (31 ± 18 vs 20 ± 15, $P < 0.0001$) than those in the open arch repair group. Following propensity score matching creating 38 matched pairs, the differences in preoperative risk diminished. Operative complications, including the mortality rate (2.6 vs 0%), were similar between the groups. Apart from the lower rates of cardiopulmonary bypass (CPB) and circulatory arrest, there was no apparent superiority of HAR with respect to patient recovery. The mean follow-up duration was 52.5 months, during which the rate of freedom from aortic events in the HAR and open arch repair groups was 79 and 99% at 24 months, respectively ($P < 0.0001$).

CONCLUSIONS: HAR achieves equivalent short-term results to standard open arch repair, with a decreased need for CPB. However, considering the inferior mid-term outcomes of this procedure, its indications should be limited to high-risk patients.

Keywords: Aortic arch aneurysm • Hybrid arch repair • Thoracic endovascular aortic repair

INTRODUCTION

The management of patients with aortic arch aneurysms is technically challenging and an area of ongoing development. Owing to refinements in operative techniques using selective cerebral perfusion (SCP), procedures for open arch repair, namely total arch replacement (TAR), can now be accomplished with acceptable surgical outcomes [1, 2]. However, patients with multiple comorbidities may still experience significant morbidity and mortality from various complications, primarily related to the use of cardiopulmonary bypass (CPB) and/or hypothermic circulatory arrest (HCA) [3].

In such high-risk patients, alternative approaches must be sought. The application of thoracic endovascular aortic repair (TEVAR) has broadened the spectrum of treatment options for repairing the thoracic aorta [4]. More recently, the combined open surgical and endovascular approach for the treatment of aortic arch aneurysms, hybrid arch repair, has emerged as a new treatment modality [5]. Based on the extent of the aortic arch lesion and locations of the proximal and distal landing zones [6], hybrid arch repair is classified into type I, type II and type III procedures according to the classification proposed by Bavaria *et al.* [7]. Essentially, these hybrid arch repair techniques comprise open surgical methods for achieving arch vessel reconstruction and the creation of a proximal landing zone followed by the endoluminal exclusion of aortic arch aneurysms. Previous reports have demonstrated the feasibility of these procedures, with acceptable mortality and neurological outcomes [7, 8].

Given this background, operative strategies for repairing aortic arch aneurysms should be re-evaluated due to technical advances in the hybrid approach and improvements in the outcomes of open arch repair. The purpose of the present study was to compare the early and mid-term outcomes of open arch repair and hybrid arch repair for aortic arch aneurysms at our institution.

PATIENTS AND METHODS

Inclusion and exclusion criteria

The present study was designed to compare the typical form of open arch repair and hybrid total arch repair for complex aortic arch aneurysms. Patients undergoing operative repair of aortic arch aneurysms at our institution in the period from 2002 to March 2014 were included in the analysis. The exclusion criteria included arch aneurysms extending below the level of the pulmonary hilum, acute aortic dissection, traumatic or mycotic aneurysms and patients receiving concomitant cardiac procedures other than coronary artery bypass grafting (CABG). More specifically, in the open arch repair (OAR) group, in order to minimize procedure-related bias, the study population included patients treated with TAR via median sternotomy. Patients undergoing repair via median sternotomy with an additional thoracotomy incision (L-incision) were included [9]. However, individuals treated with hemiarch replacement were excluded, as were those undergoing proximal descending aortic procedures treated solely via left thoracotomy.

In the hybrid arch repair (HAR) group, patients treated with type I, type II or type III hybrid total arch repair were included in the analysis. In individuals treated with these types of repair, the proximal landing zone of TEVAR should be either native zone 0 or a proximally implanted prosthetic graft (elephant trunk or replaced aortic graft) according to the definition of the procedure. Patients undergoing TEVAR with zones 1, 2 or 3 for the landing zone were not included in the present study. Practically, TEVAR with a zone 2 or 3 landing site is generally not considered to be a form of hybrid arch repair, and we did not normally perform TEVAR with a zone 1 landing site. In addition, subjects treated with the frozen elephant trunk procedure were excluded in the present study due to significant differences in the operative technique and patient population (usually aneurysms extending more distally).

In the period from January 2002 to date, a total of 364 patients underwent surgery to repair the aortic arch at our institute. Employing the above inclusion criteria, the present study included 124 subjects who underwent isolated OAR (TAR) and 58 subjects who underwent isolated hybrid total arch repair [type I ($n = 32$), type II ($n = 1$) or type III hybrid arch repair ($n = 25$)]. Arch repair with concomitant CABG was classified as an isolated arch repair technique, as described above. The records of these patients were retrospectively reviewed and analysed. Hybrid arch repair is essentially indicated for patients with a limited life expectancy, in particular elderly patients and those with a greater comorbidity burden, including active malignancy. For patients with active malignant disease, aortic surgery was only indicated if the life expectancy was at least more than one year and the risk of aortic rupture exceeded the risk of death related to the malignant disease.

The selection of the type of aortic repair was made at the discretion of the multidisciplinary team. Owing to recent technical advances, hybrid arch repair is being performed with increasing frequency. In addition to the routine follow-up in the outpatient clinic, brief health assessment questionnaires were routinely sent to all patients by mail from the Department of Cardiac Surgery to confirm the long-term follow-up care. The present retrospective review study was approved by the Institutional Review Board of Nagoya University Graduate School of Medicine (IRB 655-2; individual consent waived).

OPERATIVE TECHNIQUES

Open arch repair

All patients in the OAR group underwent surgery using single-stage TAR. Median sternotomy was performed as the approach to repair aortic arch aneurysms. In exceptional cases, in order to obtain better exposure of the distal portion of the aortic arch, additional thoracotomy was performed with an L-incision (upper median hemisternotomy plus left thoracotomy) ($n = 12$). The details of the surgical technique for TAR have been previously published [10]. Briefly, the typical operative steps of TAR were as follows. Following the induction of HCA, the aortic arch was opened and balloon-tipped SCP cannulas were inserted. Open distal anastomosis was performed during HCA of the lower body. Stepwise distal anastomosis was frequently used to obtain an easy and secure anastomosis [11]. A branched aortic arch graft was connected to the interposed tube graft. The arch vessels were reconstructed individually using the branched graft.

Hybrid arch repair

Hybrid arch repair is classified into three types according to previous reports [7]. These hybrid arch repair techniques are routinely performed via full median sternotomy in our institute; therefore, all patients in the HAR group in the present study underwent surgery via median sternotomy. Of the 58 patients treated with HAR, a two-stage approach was applied in 28 patients.

Type I hybrid arch repair. Thirty-two patients underwent type I hybrid arch repair. Type I hybrid arch repair entails the reimplantation of all aortic arch vessels (total debranching) with stent graft implantation landing proximally in zone 0 (ascending aorta–innominate origin) (Fig. 1). Type I hybrid arch repair is performed in patients with aortic arch aneurysms, where the ascending and descending thoracic aorta is not aneurysmal. Specifically, the diameter of the ascending aorta should be <42 mm due to the size of the stent graft. In addition, because the side clamp must be applied to the ascending aorta, patients with an ascending aorta exhibiting heavy calcification or a 'shaggy' internal surface are not suitable for this procedure.

For the debranching process, we used commercially prepared trifurcated prosthetic grafts (Gelweave trifurcate arch graft; VASCUTEK Ltd, a TERUMO Company, Renfrewshire, Scotland, UK) sewn to the native ascending aorta just above the sinotubular junction in a side-to-side fashion usually using a side-biting clamp. After completing arch vessel debranching, the stent grafts were deployed via the proximal limb of the graft into the aortic arch. The through-and-through wire technique was used for the stable and precise deployment of the stent graft. With this approach, debranching TEVAR was completed in a single stage ($n = 28$). Alternatively, TEVAR may be delayed and the stent graft deployed later via a retrograde femoral approach. This two-stage approach was used in our early case series ($n = 4$). Usually, the procedure is performed without CPB ($n = 29$) using a side-biting clamp, although it can also be completed under CPB ($n = 3$) when

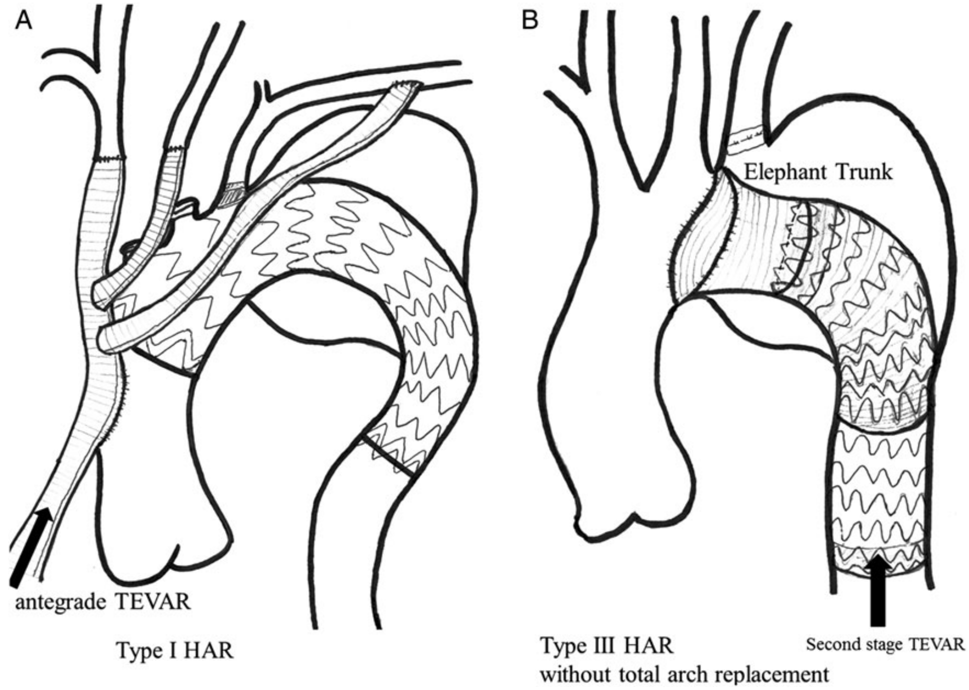

Figure 1: (**A**) Type I hybrid arch repair. (**B**) Type III hybrid arch repair without total arch replacement (elephant trunk procedure). HAR: hybrid arch repair; TEVAR: thoracic endovascular aortic repair.

haemodynamic instability was expected during proximal anastomosis, especially in our early case series.

Type II hybrid arch repair. One patient underwent type II hybrid arch repair. This procedure is usually undertaken in patients with proximal extension of aneurysmal disease into the ascending aorta (diameter >42 mm). Type II repair entails the replacement of the ascending aorta to create an appropriate proximal landing zone with arch vessel debranching. TEVAR is deployed later using a graft landing zone via a retrograde femoral approach.

Type III hybrid arch repair. Type III hybrid arch repair is an elephant trunk procedure followed by the complete endovascular repair of the descending aorta. The elephant trunk procedure was initially introduced as the first-stage procedure for the 'open' two-stage repair of extensive aortic lesions [12]. For the hybrid approach, this technique is generally used to create a proximal landing zone in patients with extensive aortic lesions that involve the transverse arch and/or descending thoracic aorta [13]. Alternatively, it can also be applied to treat patients with distal arch aneurysms who lack a good quality proximal landing zone [14]. The elephant trunk procedure can be performed with or without TAR depending on the shape of the proximal aortic arch (Fig. 1).

The elephant trunk procedure without TAR (type III HAR without TAR) (n = 12) is outlined as follows. Transverse arch aortotomy is performed under HCA. The elephant trunk graft is first inserted into the descending thoracic aorta with the aid of the guide wire placed in the true lumen [15]. The graft is then anastomosed to the wall of the aortic arch, usually just distal to the left common carotid artery at the greater curvature and more proximally at the shorter curvature in a bevelled fashion. Closure of the aortotomy site is performed simultaneously. The left subclavian artery is closed at its origin and reconstructed with another small graft anastomosed to the ascending aorta.

In contrast, the operative steps of the elephant trunk procedure with TAR (type III HAR with TAR) (n = 13) are similar to those for TAR described above. The main difference is that the arch is reconstructed proximally to the aneurysm [16]. A long elephant trunk graft is inserted into the aneurysm creating the landing zone for TEVAR. In this manner, proximal and distal arch aneurysms may be treated while avoiding a deep and difficult distal anastomosis, which could potentially cause unmanageable life-threatening bleeding.

In the type III HAR procedure, concomitant TEVAR completion was generally avoided (n = 24) in order to reduce the risk of spinal cord ischaemia, except in urgent situations (n = 1). As described in the inclusion and exclusion section, the so-called frozen elephant trunk procedure was not included in the hybrid arch repair technique in this study.

Definitions

Our definitions for postoperative outcomes, including various postoperative complications, were determined based on the Japan Adult Cardiovascular Surgery Database (JACVSD) protocols, which are almost identical to those used in the Society of Thoracic Surgeons National Database [17]. Aortic events were defined as aortic dissection, rupture or unplanned reintervention for any aortic pathology.

To evaluate the functional recovery of activities of daily living (ADLs), the modified Rankin scale [18] was applied on admission to the hospital prior to the surgery and 1 month after the procedure. According to the JACVSD criteria, moderately affected ADL is defined as a modified Rankin scale score ≥4, which means that the patient is unable to walk without assistance. An increase in the modified Rankin scale score of 2 or more points generally indicates the occurrence of a significant disabling event.

Statistical analysis

Continuous variables are expressed as the mean ± standard deviation and were compared using Student's t-test or Welch's t-test.

Category variables were compared using the χ^2 test or Fisher's exact test. The survival and aortic reintervention free rates were estimated using the Kaplan–Meier method, and differences between the groups were determined using a log-rank analysis. *P*-values <0.05 were considered to be statistically significant.

Because hybrid arch repair is generally indicated for high-risk patients with multiple comorbidities, a propensity score-matching analysis was performed to compensate for baseline differences. We conducted a one-to-one matched analysis without replacement based on the estimated propensity score, calculated from the variables for each patient collected from the baseline characteristics listed in Table 1. The log odds of the probability that a patient received HAR (the 'logit') was modelled as a function of the confounders identified and included in our dataset. Using the estimated logit function, we first randomly selected a patient in the group undergoing HAR and then matched that patient with a patient in the group receiving OAR with the closest estimated logit value. Patients in the group undergoing HAR with an estimated logit within 0.6 SD of the selected patients in the group receiving OAR were eligible for matching [19]. We selected a value of 0.6 SD because it has been shown to eliminate ~90% of the bias present in observed confounders (*C*-statistic of the propensity model: 0.803). The statistical analyses were performed using the JMP version 10 software package (SAS Institute, Inc., Cary, NC, USA).

RESULTS

Analysis of the overall cohort

The patient characteristics of the overall cohort are reported in Table 1. The patients in the HAR group were older (77 years ± 6 vs 69 ± 9, $P < 0.0001$) and exhibited a higher frequency of active malignant disease (21 vs 4.8%, $P = 0.0022$) and congestive heart failure (10 vs 0.8%, $P = 0.0046$). All haemodialysis patients in the present study received HAR mainly due to their limited life expectancy and high operative risks. The HAR group displayed higher logistic European System for Cardiac Operative Risk Evaluation (EuroSCORE) values (31 ± 18 vs 20 ± 15, $P < 0.0001$).

Despite being performed in the higher-risk group, the operative mortality of HAR was similar to that of OAR (3.4 vs 0.0%, $P = 0.10$). Other postoperative morbidities are listed in Tables 2 and 3. The rate of tracheostomy was higher in the HAR group (9 vs 1.6%, $P = 0.035$). Otherwise, there were no significant differences in early morbidity between the groups. The frequency of the need for CPB was lower in the HAR group (50 vs 100%, $P < 0.0001$). Similarly, the frequency of the need for lower body circulatory arrest was lower in the HAR group [(43 vs 100%) $P < 0.0001$]. A severe low-output status requiring delayed sternal closure ($n = 2$) and/or intra-aortic balloon pumping ($n = 3$) was noted only in the OAR group ($n = 3$ in total), including one case related to perioperative myocardial infarction in a patient treated without concomitant CABG. There were no cases of noted graft occlusion.

Analysis of the matched cohorts using propensity score matching

Following propensity score matching creating 38 matched pairs, the differences in preoperative risk factors between the two groups decreased. There were no significant differences in the baseline patient characteristics of the matched pairs (listed in Table 1). The early mortality rate was similar in the groups (2.6% in the HAR group and 0% in the OAR group), and there were no significant differences in early morbidity between the groups (listed in Tables 3). However, the incidence of stroke was somewhat higher in the HAR group, although the difference was statistically non-significant. Even after propensity score matching, the rate of a functional recovery was similar in the groups according to the modified Rankin scale. An increase in the modified Rankin scale score of 2 or more after surgery occurred in 34% of the HAR patients and 32% of the OAR patients ($P = 1.00$). Therefore, the propensity matching analysis failed to show the superiority of HAR as a less invasive approach with regard to functional recovery

Table 1: Baseline characteristics of the patients

	Overall cohort		*P*-values	Matched pairs		*P*-values
	OAR (n = 124)	HAR (n = 58)		OAR (n = 38)	HAR (n = 38)	
Age (years)	69 ± 9	76 ± 6	<0.0001	74 ± 6	75 ± 6	0.48
Male gender	90 (73%)	49 (84%)	0.093	30 (79%)	32 (84%)	0.77
Chronic lung disease (moderate to severe)	4 (3%)	6 (10%)	0.070	2 (5%)	4 (11%)	0.67
Renal dysfunction	10 (8%)	10 (17%)	0.077	3 (8%)	3 (8%)	1.00
Haemodialysis	0 (0%)	2 (3%)	0.10	0 (0%)	0 (0%)	1.00
History of CVA	19 (15%)	9 (16%)	1.00	2 (5%)	5 (13%)	0.43
PAD	34 (27%)	24 (41%)	0.063	15 (40%)	14 (37%)	1.00
History or presence of AAA	24 (19%)	16 (28%)	0.25	10 (26%)	10 (26%)	1.00
Malignant disease present	6 (5%)	12 (21%)	0.0020	5 (13%)	4 (11%)	0.10
Impaired LV function, EF < 50%	16 (13%)	12 (21%)	0.0050	5 (13%)	7 (18%)	1.00
Previous cardiac surgery	8 (6%)	6 (10%)	0.77	8 (21%)	6 (16%)	0.77
Aneurysm type; chronic dissection	10 (8%)	2 (3%)	0.34	3 (8%)	2 (5%)	1.00
Logistic EuroSCORE	20 ± 15	31 ± 18	<0.0001	25 ± 17	27 ± 16	0.71
Preoperative modified Rankin scale	0.3 ± 0.7 (range, 0–4)	0.2 ± 0.7 (range, 0–3)	0.76	0.3 ± 0.6 (range, 0–2)	0.2 ± 0.7 (range, 0–3)	0.74

BMI: body mass index; CVA: cerebrovascular accident; EF: ejection fraction; HAR: hybrid arch repair; OAR: open arch repair; LV: left ventricle; PAD: peripheral arterial disease.
Moderate chronic lung disease was defined as an FEV1 of 50–59% of predicted and/or the use of chronic steroid therapy for lung disease. Severe chronic lung disease was defined as an FEV1 of <50% predicted and/or room air PaO_2 of <60 mmHg or room air $PaCO_2$ of >50 mmHg.

Table 2: Intraoperative variables

	Overall cohort		P-values	Matched pairs		P-values
	OAR (n = 124)	HAR (n = 58)		OAR (n = 38)	HAR (n = 38)	
Urgent or emergent operation	4 (3.2%)	1 (1.7%)	1.000	2 (5.3%)	1 (2.6%)	1.0
Additional thoracotomy (L-incision)	10 (8%)	0 (0%)	<0.0001	1 (2.6)	0 (0%)	1.0
Concomitant CABG	19 (15%)	9 (16%)	0.826	3 (7.9%)	6 (16%)	0.48
Use of CPB	124 (100%)	29 (50%)	<0.0001	38 (100%)	25 (66%)	<0.0001
Operation time (min)	464 ± 144	433 ± 101	0.089	475 ± 181	438 ± 24	0.29
Perfusion time [min (CPB case)]	238 ± 5	188 ± 48	<0.0001	237 ± 65	186 ± 50	<0.0001
Cardiac arrest time [min (CPB case)]	132 ± 48	86 ± 33	<0.0001	132 ± 48	84 ± 33	<0.0001
Use of lower body circulatory arrest	124 (100%)	25 (43%)	<0.0001	38 (100%)	21 (55%)	<0.0001
Two-stage approach	0	28 (48%)	<0.0001			

CABG: coronary artery bypass grafting; CPB: cardiopulmonary bypass.

Table 3: Postoperative outcomes

	Overall cohort		P-values	Matched pairs		P-values
	OAR n = (124)	HAR (n = 58)		OAR (n = 38)	HAR (n = 38)	
Operative mortality	0 (0%)	2 (3.4%)	0.10	0 (0%)	1 (2.6%)	1.00
Reoperation for bleeding	11 (9%)	4 (7%)	0.78	5 (13%)	4 (11%)	1.00
Renal failure	4 (3%)	4 (7%)	0.27	1 (2.6%)	2 (5%)	1.00
De novo haemodialysis	1 (0.8%)	2 (3.4%)	0.24	1 (2.6%)	1 (2.6%)	1.00
Severe LOS; IABP or delayed sternal closure	3 (2.4%)	0 (0%)	0.56	1 (2.6%)	0 (0%)	1.00
Atrial fibrillation	34 (27%)	25 (43%)	0.042	13 (34%)	16 (42%)	0.64
Mediastinitis	1 (0.8%)	0 (0%)	1.00	0 (0%)	0 (0%)	1.00
Prolonged ventilation	24 (19%)	19 (33%)	0.061	9 (24%)	15 (40%)	0.22
Postoperative ventilation time (h)	103 ± 319	144 ± 279	0.40	177 ± 554	154 ± 269	0.81
Tracheostomy	2 (1.6%)	5 (9%)	0.035	0 (0%)	4 (11%)	0.12
Stroke	15 (12%)	10 (17%)	0.36	3 (8%)	9 (24%)	0.11
Paraplegia	1 (0.8%)	1 (1.7%)	0.54	0 (0%)	1 (2.6%)	1.00
Transient paraparesis	2 (1.6%)	2 (3.4%)	0.59	1 (2.6%)	2 (5.3%)	1.00
Aortic dissection	0 (0%)	2 (3.4%)	0.10	0 (0%)	0 (0%)	1.00
Transfusion	109 (88%)	52 (90%)	0.81	35 (92%)	35 (92%)	1.00
Length of ICU stay (days)	4.51 ± 4.37	8.65 ± 12.00	0.011	4.52 ± 1.28	8.55 ± 10.37	0.030
Compromised ADLs	12 (10%)	9 (16%)	1.00	6 (16%)	6 (16%)	1.00
Modified Rankin scale increase ≥2	40 (32%)	21 (36%)	0.62	12 (32%)	13 (34%)	1.00
Postoperative hospital stay	33 ± 20	38 ± 29	0.15	33 ± 22	38 ± 18	0.33

Compromised ADLs indicate a modified Rankin scale score ≥4 (unable to walk without assistance) at the time of discharge.
ADLs: activities of daily living; GI: gastrointestinal; IABP: intra-aortic balloon pumping; ICU: intensive care unit; LOS: low output syndrome.

or complication rates. Hence, HAR achieves equivalent results to standard OAR with a decreased need for CPB and circulatory arrest.

Procedure-specific problems

Aortic dissection. Although the incidence was not statistically significantly different between the two groups, 2 cases of Stanford type A aortic dissection occurred in the HAR group only (3.4% of all HAR procedures). Both events occurred in patients undergoing type I HAR without CPB with a relatively large ascending aorta (42 mm in diameter in both cases). The side clamp was applied on the ascending aorta during the proximal anastomosis of the debranching process. The dissection was not detected during the operation, but rather found on postoperative computed tomography (CT) scans before discharge (Fig. 1). Neither patient wished further intervention and were therefore managed conservatively. Fortunately, the diameter of the ascending aorta remained consistent during the follow-up in both cases. Based on the findings of the CT scans, the dissection may have been induced by the placement of the side-biting clamp on the relatively large ascending aorta.

Proximal anastomotic leakage and type I endoleaks. In 3 cases of type III HAR without TAR (elephant trunk procedure), contrast leakage occurred at the proximal anastomotic line of the elephant trunk on CT scans [early onset $n = 2$, delayed onset $n = 1$ (Fig. 2)]. During the type III HAR without TAR procedure, the elephant trunk graft is anastomosed to the aortic wall, and the proximal landing zone of TEVAR is located inside the elephant trunk. The leakage of contrast arose from the proximal anastomotic line and continued to the space inside the aneurysm, outside the elephant trunk, suggestive of anastomotic leakage. Of

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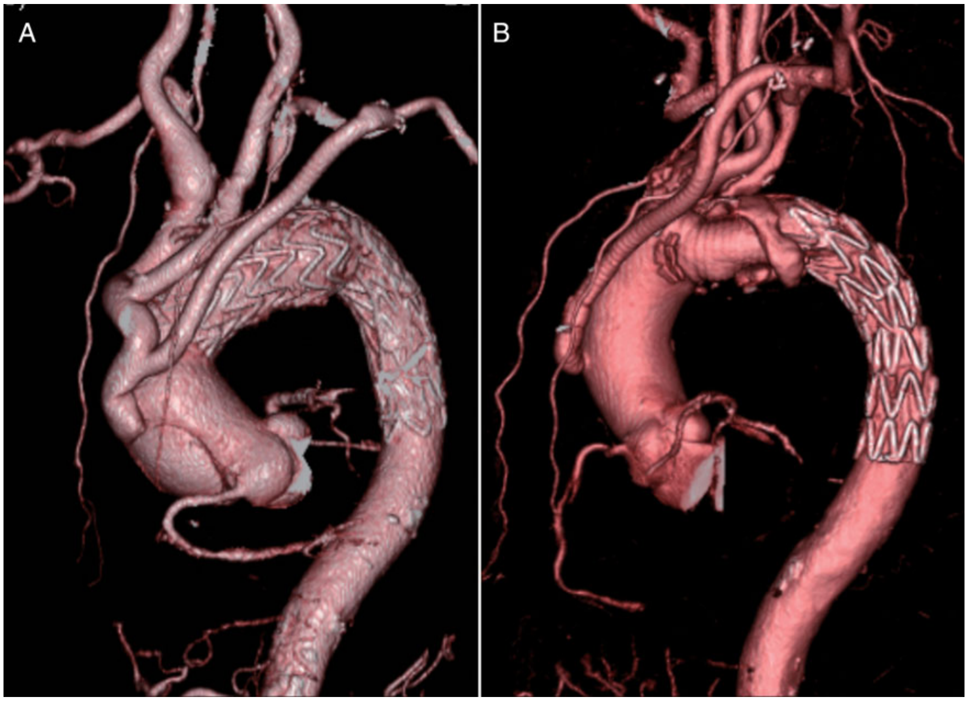

Figure 2: (**A**) Aortic dissection following type I hybrid arch repair. Preoperatively, the patient had a relatively large ascending aorta, with a diameter of 42 mm. For debranching, a branched trifurcated graft was anastomosed to the ascending aorta in a side-to-side fashion using a side-biting clamp without cardiopulmonary bypass. (**B**) Anastomotic leakage at the proximal anastomosis of the implanted elephant trunk. The patient underwent hybrid arch repair with elephant trunk placement (Type III hybrid arch repair). The elephant trunk graft was anastomosed to the aortic wall just distal to the left carotid artery. Contrast arose from the proximal anastomotic line and continued to the space inside the aneurysm, outside the elephant trunk.

the 3 patients with proximal anastomotic leakage, 1 underwent redo repair of the leakage, 1 died of aortic rupture presenting with massive haemoptysis, and 1 was carefully observed and resolution of the leak was later confirmed.

Uncompleted two-stage repair. Of the 58 patients in the HAR group, 28 were intended to receive two-stage repair. Shrinkage of the aneurysm was reported if complete thrombosis occurred outside the elephant trunk [20]. We intentionally withheld the second-stage TEVAR procedure in 2 patients in this situation following type III HAR. These patients were carefully followed with serial CT scans in the outpatient clinic. Excluding these 2 cases, there were 3 cases of uncompleted two-stage HAR (11% of the two-stage HAR procedures). The reasons for not performing second-stage repair included early operative death ($n = 1$) (perioperative pneumonia) and cerebrovascular accidents ($n = 2$) (1 patient with perioperative stroke and one patient with cerebral haemorrhage unrelated to the operation).

Survival and aortic events: midterm outcomes

The mean follow-up duration was 52.5 months (range: 2–151 months); 15.6 months in the HAR group (2–50 months) and 69.7 months in the OAR group (2–151 months). Figure 3A shows the Kaplan–Meier curves for survival in the overall cohort. The overall survival rates in the HAR and OAR groups were 88 and 96% at 12 months and 80 and 93% at 24 months ($P = 0.066$), respectively. The OAR group exhibited a tendency towards better survival, although the difference was not statistically significant. There were 29 deaths during the follow-up period. The causes of death are outlined in Table 4.

Figure 3B shows the freedom from aortic events in the overall cohort. There were 10 aorta-related events, namely dissection ($n = 2$), rupture ($n = 6$) and unplanned reintervention for any aortic pathology ($n = 2$). Compared with the HAR group, the OAR group had a significantly higher rate of freedom from aortic events. The rates of freedom from aortic events in the HAR and OAR groups were 87 and 99% at 12 months and 79 and 99% at 24 months ($P < 0.0001$), respectively. According to the propensity matching analysis, within the matched pairs, the survival rates in the HAR and OAR groups were 88 and 97% at 12 months and 77 and 92% at 24 months ($P = 0.17$), respectively. The rates of freedom from aortic events were 88 and 100% at 12 months and 76 and 100% at 24 months ($P = 0.0031$), respectively. The OAR group had a significantly higher rate of freedom from aortic events, in the propensity matching analysis, Table 5.

DISCUSSION

The present results showed that the current surgical techniques of TAR with the preferable use of stepwise anastomosis and SCP result in a very low mortality rate with good short-term outcomes. OAR also yielded a very low incidence of aortic events. Therefore, conventional standard OAR is a reliable gold standard treatment for aortic arch aneurysms. On the other hand, even in high-risk populations, HAR achieves equivalent results to standard OAR with a decreased need for CPB and circulatory arrest. Nevertheless, the propensity matching analysis performed in the present study indicated that the patients' recovery was similar after both HAR and OAR based on the short-term outcomes and modified Rankin scale scores. Therefore, contrary to current assumptions, the present

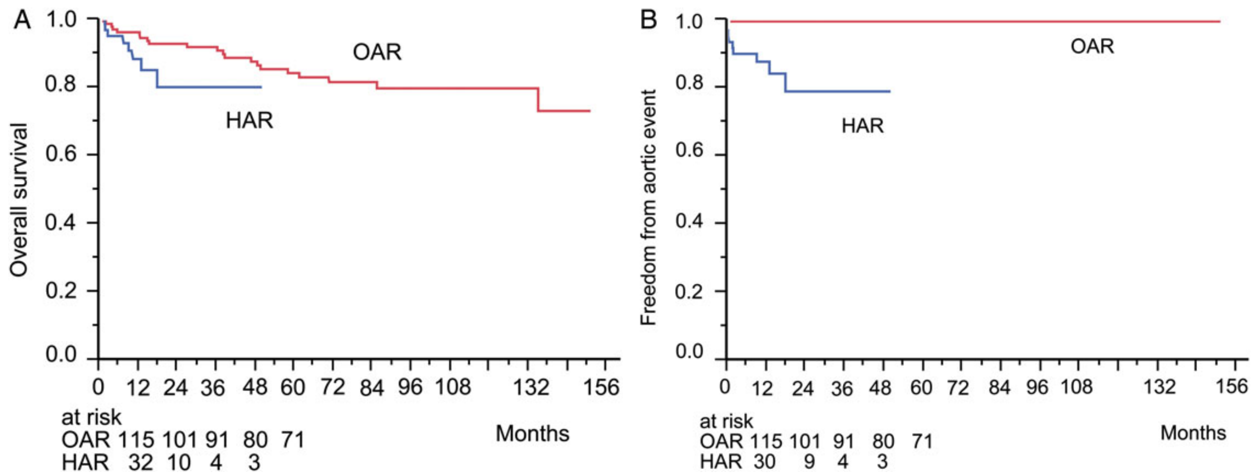

Figure 3: (**A**) Overall survival of the overall cohort. (**B**) Freedom from aortic events in the overall cohort. HAR: hybrid arch repair; OAR: open arch repair.

Table 4: Causes of death

	Total	OAR	HAR
Malignancy	8	6	2
Pneumonia and respiratory failure	8	7	1
Aortic rupture	5	1 Abdominal aorta 1	4 Aortic arch 3[a] Descending aorta 1
CVA	3	3	
CHF	2	2	
Sepsis	2	1	1
DIC	1	1	

CHF: congestive heart failure; CVA: cerebrovascular accident; DIC: disseminated intravascular coagulation.
[a]Causes of aortic arch rupture included incomplete two-stage repair (*n* = 1), aorto-oesophageal fistula (*n* = 1) and proximal anastomotic leakage at the elephant trunk (*n* = 1).

Table 5: Aortic events

	Total	OAR	HAR
Dissection	2		2 Perioperative type A dissection 2
Unplanned aortic intervention	2		2 Reintervention of proximal anastomotic leakage of elephant trunk 1 Reintervention of abdominal aortic aneurysm 1
Aortic rupture	6	1 Abdominal aorta 1	5 Aortic arch 3[a]Abdominal aorta 2 (subsequent rupture of descending aorta 1)

[a]For cause of aortic arch rupture, see Table 4.

findings failed to show apparent superiority of HAR as a less invasive alternative, even in the matched analysis.

However, it should also be noted that, of the 58 HAR patients, only 38 were fit for propensity matching. The remaining 20 patients (34%) in the HAR group did not have corresponding subjects with similar propensity characteristics in the OAR group. In the other words, these patients were so high-risk that similar individuals were not treated with open arch repair. For these high-risk patients, HAR is likely the only available treatment option. In this situation, although the results of the two approaches cannot be easily compared, HAR is expected to be a good safe alternative to OAR for high-risk patients.

There have been similar reports comparing the results of hybrid and open arch repair [21–23]. These studies concluded that the hybrid approach is a good alternative to open arch repair. The superiority of HAR over OAR, however, was not evident, with the exception of fewer in-hospital days, even in the matched analysis.

In the hybrid approach assessed in these previous studies, the proximal landing zones were often zones 1 or 2 and not only limited to zone 0. As the long-term durability of HAR is thought to be greatly influenced by the presence of proximal type I endoleaks, we have sought to create a proximal landing zone more aggressively since the introduction of the hybrid approach. In the hybrid approach used in the present study, the proximal landing zone was either zone 0 (type I HAR) or an implanted prosthetic graft (type II and type III HAR). In addition, because it has been reported that the rate of late occlusion is 4% in cases of extra-anatomical reconstruction of the arch vessels [24], the carotid arteries were reconstructed in anatomical position in our approach; therefore, median sternotomy was used to gain full access to the arch vessels and the ascending aorta. Even with the attempt to create a more secure proximal landing zone, aortic events continued to occur more frequently in the HAR group than in the OAR group. Physicians should therefore recognize the lack of reliable long-term data required to ascertain the durability of HAR.

Technical considerations

Less superior midterm outcomes of the HAR approach were demonstrated in the present study, especially with regard to aortic events. Hence, technical modifications must be reconsidered.

There were 2 cases of perioperative aortic dissection among the type I HAR cases. Both patients had relatively large ascending aortas, with a diameter of 42 mm preoperatively. The intimal tears in these cases were possibly induced by the placement of the side clamp on the large ascending aortas. Bavaria *et al*. [7] recommended that the ascending aorta should be replaced if its diameter is >40 mm; they select type II HAR rather than type I HAR in such cases. As a drawback, type II and III HAR require CPB. The risks and benefits of using CPB or circulatory arrest must be carefully evaluated in individual cases.

Among our cases of type III HAR without TAR (elephant trunk procedure), there were 3 cases of proximal anastomotic leakage, including 1 patient with delayed onset leakage. Obviously, such harmful leakage must be avoided. During the procedure, the elephant trunk graft is anastomosed to the aortic arch wall. Secure suturing is mandatory to prevent leakage in such cases. Previously, we performed partial aortotomy followed by the placement of continuous running sutures to complete posterior wall anastomosis. Depending solely on the use of continuous sutures with the 'inclusion technique' is not adequate, and multiple transmural stitches must be applied. Alternatively, transection of the aorta, rather than partial aortotomy, may be an option to create a secure anastomotic line.

CONCLUSION

In the present study, OAR provided a very low mortality rate with good outcomes. Meanwhile, HAR achieved equivalent results to standard OAR with a decreased need for CPB and circulatory arrest. Regarding mid-term results, OAR provides apparently superior results to HAR. In particular, the potential for aortic dissection, proximal leakage and possible incomplete two-stage repair remains noteworthy in the hybrid approach. Based on the results, conventional OAR remains the gold standard for the treatment of aortic arch aneurysms. Nevertheless, elderly patients with significant comorbidities should be considered for the hybrid approach. Patient selection thus remains important for determining whether an individual should undergo conventional OAR versus HAR.

Conflict of interest: none declared.

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