Systematic Review

A systematic review and meta-analysis of hybrid aortic arch replacement

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Background: Evolution in the endovascular era has influenced the management of aortic arch pathologies. Several studies have described the use of a combined endovascular and open surgical approach to the treatment of arch diseases. Hybrid repair of arch pathologies has been considered as a less invasive method, and is therefore an appealing option for high-risk patients who are unsuitable for open repairs. The aim of the present meta-analysis was to assess the efficacy of hybrid techniques in patients with aortic arch pathologies.

Methods: Extensive electronic literature search was undertaken to identify all articles published up to December 2012 that described hybrid aortic arch repair with intrathoracic supra-aortic branch revascularisation and subsequent stent graft deployment. Eligible studies were divided into two groups: group I included studies on the aortic arch debranching procedure and group II included studies that reported an elephant trunk technique (either "frozen" or stented). Separate meta-analyses were conducted in order to assess technical success, stroke, spinal cord ischemia (SCI), renal failure requiring dialysis, and cardiac and pulmonary complications rate, as well as 30-day/in-hospital mortality.

Results: Forty-six studies were eligible for the present meta-analysis: 26 studies with a total of 956 patients reported aortic arch debranching procedures, and 20 studies with 1,316 patients performed either 'frozen' or stented elephant trunk technique. The pooled estimate for 30-day/in-hospital mortality was 11.9% for the arch debranching group and 9.5% for the elephant trunk group. Cerebrovascular events of any severity were found to have occurred postoperatively at a pooled rate of 7.6% and 6.2%, while irreversible spinal cord injury symptoms were present in a pooled estimate of 3.6% and 5.0% in the arch debranching and elephant trunk group, respectively. Renal failure requiring dialysis occurred at 5.7% and 3.8% in both groups, while cardiac complications rate was 6.0% in the arch debranching cohort and pulmonary complication was 19.7% in the elephant trunk cohort.

Conclusions: Hybrid arch techniques provide a safe alternative to open repair with acceptable short- and mid-term results. However, stroke and mortality rates remain noteworthy. Future prospective trials that compare open conventional techniques with the hybrid method or the entirely endovascular methods are needed.

Keywords: Aortic arch; hybrid; debranching; frozen elephant trunk; stented elephant trunk

Submitted May 01, 2013. Accepted for publication May 20, 2013.
doi: 10.3978/j.issn.2225-319X.2013.05.06
Scan to your mobile device or view this article at: http://www.annalscts.com/article/view/1995/2725

Introduction

The management of patients with aortic disease that involves the ascending aorta, the aortic arch, and the descending aorta poses a technical challenge and is an area of ongoing development and innovation. Total arch replacement, although traditionally challenging and risky, has been the mainstay of therapy for aortic arch pathologies. However, this operation requires cardiopulmonary bypass and a period of profound hypothermia and circulatory arrest, which carries a substantial rate of mortality and morbidity (1,2). Protection from brain, spinal cord, cardiac, and visceral ischemia, as well as the avoidance of respiratory compromise due to prolonged circulatory arrest, are significant concerns. Despite higher standards of perioperative care, refinements in operative techniques, and the use of several protective adjuncts, the morbidity associated with total arch replacement is significant, and includes air embolism, stroke, myocardial infarct, and excessive bleeding (1,2). In addition, in cases of aortic arch involvement, entirely endovascular methods entail advanced technical skills (3), whereas the rate of neurological complications remains considerable.

Several studies have described the use of a combined endovascular and open surgical approach to the treatment of arch pathologies, resulting in a hybrid technique, which has been considered as a less invasive method. Consequently, it represents an appealing option for high-risk patients who are unsuitable for open repairs. These "hybrid techniques" involve arch debranching, thereby creating a proximal landing zone of adequate length, followed by stenting over the aortic arch (4,5) (*Figure 1*). For this purpose, highly specialized arch-debranching grafts have been developed. The endovascular component can be performed either simultaneously or in a staged mode, and in an antegrade or retrograde fashion. Among the evolving hybrid procedures is the so-called "frozen" or stented elephant trunk technique (6,7). Adapted from the classical elephant trunk technique that was first described by Borst *et al.* (8), this approach facilitates the repair of a concomitant aortic arch and proximal descending aortic aneurysms in a single stage under circulatory arrest. This technique is increasingly being used to treat extensive thoracic aortic disease and has shown promising results (6,7).

We undertook a systematic review to identify all published reports on hybrid aortic arch replacement. Eligible studies were combined into an extensive meta-analysis to assess the safety and efficacy of this technique.

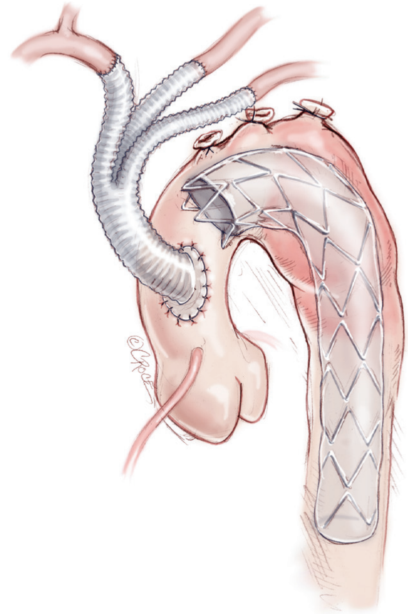

Figure 1 Hybrid aortic arch repair

Methods

Search strategy

An extensive electronic literature search was undertaken to identify all articles that were published up to December 2012 and described hybrid aortic arch repair (HAAR). The search was performed by using "aortic arch", "arch debranching", "frozen elephant trunk", "stented elephant trunk", "endovascular", and "hybrid" as exploded MeSH terms. Publications were retrieved via electronic search engines (Medline, Embase, Scopus, Google Scholar, Ovid, and the Cochrane Library). In addition, the reference lists of all retrieved articles were examined for further relevant series.

Definitions

Aortic arch zones are categorized according to classifications established by Mitchell and Ishimaru (9): zone 0 involves the ascending aorta proximal to the innominate artery. Zone 1 involves the aortic arch between the innominate and left common carotid artery. Zone 2 involves the aortic arch between the left common carotid artery and the left subclavian artery. Zone 3 involves the proximal descending thoracic aorta distal to the left subclavian artery. Zone 4 involves the mid-descending thoracic aorta.

Hybrid approaches are classified into three types according to the extent of aortic arch lesion and the presence of the proximal and distal landing zone:

(I) Type I: the debranching procedure consists of brachiocephalic bypass and endovascular repair of the aortic arch. This approach is reserved for patients with isolated aortic arch aneurysms that exhibit an adequate proximal landing zone in the ascending aorta and a distal landing zone in the descending thoracic aorta.

(II) Type II: this hybrid approach is designed for patients with ascending aortic lesions with a limited extension into the distal arch. A type II repair entails an open ascending aorta reconstruction that "creates" an appropriate proximal landing zone, great vessel revascularization, and endoluminal aneurysm exclusion.

(III) Type III: an elephant trunk procedure with a complete endovascular repair of the thoracoabdominal aorta. This technique is reserved for patients with extensive aortic lesions that involve the ascending, transverse arch, and descending thoracic aorta, or the "mega-aorta syndrome".

Eligibility inclusion and exclusion criteria

In the present review, eligible studies were categorized into two groups: group I, which included studies on the aortic arch debranching procedure (AD group) and group II, which included studies that report on the elephant trunk (ET group) technique (i.e., either "frozen" or stented).

An eligible study for the present meta-analysis must:

(I) Describe intrathoracic hybrid aortic arch repair.

(II) Provide baseline characteristics of the recruited patients.

(III) State the incidence of at least one of the basic outcome criteria.

(IV) Report on a series of at least 10 patients to prevent bias arising from small sample populations. This cutoff was chosen as the threshold criterion on the basis that experience with this technique from a center with more than 10 treated patients increases the homogeneity of the analysis, reflects institutional experience and, therefore, merits consideration.

Exclusion criteria included the following: articles in languages other than English, case reports, and series of <10 patients. When multiple publications on the same patient sample were identified or study populations overlapped, only the latest report was included unless the reported outcomes were mutually exclusive. Furthermore, in several studies, patients with combined visceral debranching and endovascular exclusion of thoracoabdominal pathologies were analyzed as a subgroup of a wider patient sample. These studies were excluded from the present meta-analysis because data regarding this subgroup of patients were not separately provided. All studies were assessed by two reviewers (K.M. and S.M.). Available data were extracted and analyzed, and a consensus was reached if discrepancies were observed.

Statistical analyses

Standard descriptive statistics (reported as means with 95% confidence intervals) were used to summarize demographic and baseline data of the recruited patients from all eligible studies. A separate meta-analysis was conducted, in accordance with the recommendations of the Meta-analysis of Observational Studies in Epidemiology (MOOSE) group, of the two cohorts (10). The primary endpoints of the meta-analysis consisted of technical success, 30-day/in-hospital mortality, spinal cord ischemia (SCI) symptoms, and pulmonary and cardiac complications. The pooled proportion was calculated as the back-transformation of the weighted mean of the transformed proportions by using the random effects model proposed by DerSimonian-Laird (11). Heterogeneity among studies was estimated by using the chi-square test and the Cochran Q score (reported as I^2 and representing the percent value of the heterogeneity). Funnel plots were constructed, and the identified extreme studies were excluded to increase the robustness of our analyses. Frequency study-specific estimates were pooled and are reported as proportions with 95% confidence intervals (CI). The possibility of publication bias was assessed for both aims by using use the Begg-Mazumdar adjusted rank correlation test (12). The meta-analysis and the publication bias assessment were conducted by using the Comprehensive Meta-analysis Package (Biostat, Englewood, NJ) statistical software.

Results

The literature search yielded 196 publications (*Figure 2*). After an extensive review, a total of 75 articles were considered relevant. Of these 75 articles, 29 publications were excluded in the subsequent evaluation based on the inclusion/exclusion criteria. Forty-six studies were eligible for the present meta-analysis: 26 studies, with a total of 956 patients, examined the aortic arch debranching procedure,

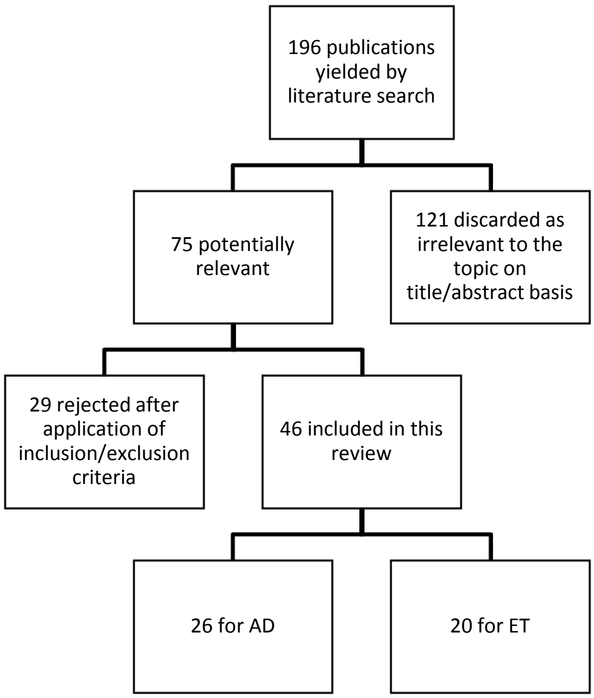

Figure 2 Study flow diagram. Forty-six publications were included in the analysis. AD, arch debranching group; ET, elephant trunk group

and 20 studies, with a total of 1,316 patients, focused on a technique that involved either a "frozen" or stented elephant trunk (*Tables 1,2*). Demographic variables and comorbidities of the patients are detailed in *Table 3*.

Arch debranching group

The majority of the patients (62.0%) underwent arch debranching attributable to degenerative aneurysms, with 28.6% attributable to aortic dissection, 2.2% attributable to a pseudoaneurysm or traumatic transection, and 7.2% attributable to other aortic pathologies such as penetrating ulcers, intramural hematomas, aortobronchial fistula, intracranial aneurysm, endoleak correction after thoracic aortic aneurysm, and floating thrombus in the aortic arch. Zone 0 was involved in 342/820 (41.7%) patients, Zone 1 in 237/820 (28.9%) patients, and Zone 2 in 241/820 (29.4%). Almost 74% of the patients were referred for elective treatment, with the remainder operated on in an emergent/urgent setting. A single-stage approach was implemented in 52.9% of patients, while 47.1% underwent a staged procedure with a mean intra-procedural interval of 18.5 days (95% CI: 7.6-29.4 days). Cardiac arrest was utilized in 9.2% (67/731) of the patients. Mean ICU stay was 2 days (95% CI: 1.1-3.0 days), and mean length of hospital stay was 12.1 days (95% CI: 8.2-15.9 days). Mean follow-up period was 22.1 months (95% CI: 18.2-26.1 months).

With respect to the primary technical success, which was defined as complete aortic arch debranching and successful stent-graft deployment, the pooled estimate was 92.8% (95% CI: 89.1-95.3%) (*Figure 3*). Of the 894 patients for whom both stages of the procedure were completed, 149 (16.6%) experienced an endoleak. In particular, 165 endoleaks were detected in follow-up CT scans: 106 type I, 51 type II, and 8 type III. Among 17 studies which provided relative data, retrograde type A dissection was observed with a pooled rate of 4.5% (95% CI: 2.9-6.8%) (*Figure S1*).

Mortality and morbidity in the arch debranching group

The pooled estimate for 30-day/in-hospital mortality was 11.9% (95% CI: 9.4-14.9%) (*Figure 4*). A cerebrovascular event of any severity was found to occur postoperatively at a pooled rate of 7.6% (95% CI: 5.9-9.7%) (*Figure 5*). Irreversible SCI symptoms were present at a pooled estimate of 3.6% (95% CI: 2.5-6.1%) (*Figure 6*). Data regarding the need for cardiac support were available in 16 out of the 26 AD studies, with a pooled cardiac complications rate of 6.0% (95% CI: 3.0-11.8%) (*Figure S2*). Additionally, the pooled estimate for pulmonary complications among 15 studies which provided adequate data was 12.6% (95% CI: 7.4-20.6%) (*Figure S3*). However, there was a substantial level of heterogeneity between studies (I^2=68% and I^2=75% for cardiac and pulmonary complications, respectively). Renal failure requiring dialysis was found at a pooled rate of 5.7% (95% CI: 3.6-8.9%) (*Figure 7*).

Elephant trunk group (ET)

The indication for ET in 72.4% of patients was chronic or acute aortic dissection that involved the ascending aorta, a degenerative atherosclerotic aneurysm in 27.3% of patients, and 0.3% was due to other aortic pathologies. The treatment was elective in 58.4% of the patients, with the remainder operated on in an emergency or urgent setting. The mean cardiopulmonary bypass (CPB) time was 193 minutes (95% CI: 171-214 minutes), mean ICU stay was 5.7 days (95% CI: 1.0-10.7 days), mean length of the hospital stay was 21 days (95% CI: 17.1-24.8 days), and the mean follow-up period was 43.7 months (95% CI: 34.2-53.2 months).

Mortality and morbidity in the elephant trunk group

The pooled estimate for 30-day/in-hospital mortality was

Table 1 Descriptive characteristics of eligible studies in the arch debranching group

Author	Study period	N	Mean age (years)	Male [%]	Dissection [%]	Mode of procedure (one stage/staged)	Proximal landing zone (0/1/2)	FU (months)
Andersen *et al*. 2012 (13)	2005-2012	48	65	26 [54]	18 [38]	39/9	48/0/0	28.4
Antoniou *et al*. 2010 (14)	2003-2009	33	63	26 [79]	4 [12]	30/3	9/24/0	6
Bavaria *et al*. 2010 (15)	2005-2009	23	71	18 [78]	0	23/0	23/0/0	20.5
Bergeron *et al*. 2006 (16)	1999-2004	25	72	23 [92]	11 [44]	0/25	15/10/0	15
Canaud *et al*. 2010 (17)	1998-2008	34	ND	ND	ND	24/10	6/4/24	29.9
Chan *et al*. 2008 (18)	2005-2007	16	65	13 [81]	6 [38]	16/0	5/8/3	14
Chiesa *et al*. 2010 (19)	1999-2009	116	70	97 [84]	21 [18]	ND	24/27/65	29
Czerny *et al*. 2012 (4)	2003-2011	66	70	45 [68]	11 [17]	38/28	66/0/0	25
Donas *et al*. 2010 (20)	2005-2008	20	70	15 [75]	1 [5]	20/0	14/2/4	14
Deriu *et al*. 2012 (21)	2004-2010	48	ND	ND	ND	48/0	12/9/27	ND
Ferrero *et al*. 2012 (22)	ND	27	ND	ND	4 [15]	27/0	ND	16.7
Geisbüsch *et al*. 2011 (23)	1997-2009	47	64	33 [70]	15 [32]	24/23	10/25/12	21.4
Gelpi *et al*. 2010 (24)	2004-2009	15	70	12 [80]	2 [13]	3/12	3/7/5	31.4
Gottardi *et al*. 2008 (25)	1996-2007	73	71	ND	9 [12]	0/73	ND	37
Holt *et al*. 2010 (5)	2001-2009	78	67	52 [67]	40 [51]	28/50	9/17/52	12
Hughes *et al*. 2009 (26)	2005-2008	28	64	15 [54]	10 [36]	21/7	13/8/7	14
Ingrund *et al*. 2010 (27)	2007-2009	12	56	6 [50]	9 [75]	ND	4/8/0	11
Ishibashi *et al*. 2012 (28)	2009-2011	12	73	12 [100]	0	0/12	0/12/0	10.2
Lee *et al*. 2011 (29)	2005-2009	37	63	23 [62]	3 [8]	0/37	ND	ND
Lotfi *et al*. 2012 (30)	1997-2011	51	71	34 [67]	11 [22]	10/41	4/31/16	15
Lu *et al*. 2011 (31)	2001-2009	17	49	19 [112]	12 [71]	4/13	1/5/11	27.1
Ma *et al*. 2011 (32)	2005-2010	24	42	16 [67]	24 [100]	ND	3/10/11	33.3
Murashita *et al*. 2012 (33)	2007-2010	27	77	22 [81]	ND	27/0	4/19/4	7
Saleh *et al*. 2006 (34)	2002-2005	15	74	9 [60]	0	0/15	15/0/0	18
Vallejo *et al*. 2012 (35)	2002-2010	38	65	27 [71]	20 [53]	24/14	27/11/0	28.1
Weigang *et al*. 2009 (36)	ND	26	ND	20 [77]	6 [23]	ND	26/0/0	ND

ND, no data; FU, follow-up

9.5% (95% CI: 7.8-11.4%) (*Figure 8*). A cerebrovascular event of any severity was found to occur postoperatively at a pooled rate of 6.2% (95% CI: 4.6-8.3%) (*Figure 9*). However, irreversible SCI symptoms were present at a pooled estimate of 5.0% (95% CI: 3.7-6.6%) (*Figure 10*). The pooled rates for renal failure that required dialysis and pulmonary complications were 3.8% (95% CI: 2.7-5.3%) and 19.7% (95% CI: 17.1-22.1%), respectively (*Figure 11*, *Figure S4*). In 11 studies within the elephant trunk group, data regarding re-exploration for bleeding were provided. A separate meta-analysis of these studies revealed a pooled incidence of the secondary intervention due to bleeding of 8.6% (95% CI: 6.9-10.6%) (*Figure S5*).

Discussion

Our study aims to review the results of hybrid techniques which have been applied for the treatment of aortic arch pathologies and extensive arch lesions. Although the hybrid approach is considered appropriate for high-risk patients and has been applied within urgent and emergency settings, varied lesion patterns and patient characteristics result in a significant heterogeneity among reported studies. With the intention of pooling the published results, we have classified these methods into two separate categories according to the need for ascending aorta reconstruction: the "total arch debranching procedure", and "elephant trunk" technique and its variation (i.e., the "stented elephant trunk" procedure).

Table 2 Descriptive characteristics of eligible studies in the elephant trunk group

Author	Study period	N	Mean age (years)	Male [%]	Dissection [%]	Urgent/ emergent [%]	FU (months)
Andersen *et al*. 2012 (13)	2005-2012	20	59	11 [55]	10 [50]	2 [10]	23.4
Baraki *et al*. 2007 (37)	2001-2006	39	62	24 [62]	21 [54]	0	22
Chen *et al*. 2010 (38)	2004-2009	28	51	22 [79]	28 [100]	28 [100]	30.1
Flores *et al*. 2006 (39)	1996-2004	25	73	19 [76]	5 [20]	2 [8]	35
Hofferberth *et al*. 2012 (40)	2003-2011	19	59	16 [84]	19 [100]	19 [100]	59
Hoffman *et al*. 2012 (41)	2009-2012	32	58	26 [81]	32 [100]	32 [100]	17
Jakob *et al*. 2011 (7)	2005-2010	274	60	204 [75]	190 [69]	81 [30]	59
Jim *et al*. 2011 (42)	2005-2009	10	68	3 [30]	3 [30]	0	35.1
Kawaharada *et al*. 2009 (43)	2001-2007	31	70	24 [77]	4 [13]	0	31
Lee *et al*. 2011 (29)	2005-2009	21	68	13 [62]	4 [19]	2 [10]	ND
Lima *et al*. 2012 (44)	2001-2010	50	61	33 [66]	31 [62]	23 [46]	17
Nishi *et al*. 2011 (45)	2004-2011	61	70	44 [72]	19 [31]	14 [23]	ND
Pochettino *et al*. 2009 (46)	2005-2008	36	59	ND	36 [100]	36 [100]	15.9
Shi *et al*. 2011 (47)	2007-2010	46	53	35 [76]	46 [100]	5 [11]	13.7
Shimamura *et al*. 2008 (48)	1994-2004	126	68	86 [68]	57 [45]	37 [29]	60.4
Shimamura *et al*. 2009 (49)	2004-2007	69	66	55 [80]	33 [48]	13 [19]	20.3
Shrestha *et al*. 2012 (50)	2010-2011	34	60	25 [74]	20 [59]	18 [53]	ND
Sun *et al*. 2011 (6)	2003-2008	291	45	238 [82]	291 [100]	143 [49]	42.5
Uchida *et al*. 2011 (51)	1997-2010	80	67	36 [45]	80 [100]	80 [100]	74.3
Zhao *et al*. 2012 (52)	2006-2011	24	41	19 [79]	24 [100]	0	36.5

FU, follow-up; ND, no data

Table 3 Demographic variables and comorbidities of the patients

	AD	ET
Total number of studies	26	20
Total number of patients	956	1,316
Gender (male %)	71.9	72.9
Mean age (years)	67.1 (64.3-70.0)	58.5 (54.2-62.8)
Comorbidities		
Nicotine consumption	63.5% (48.7-78.3%)	53.7% (35.3-72.1%)
DM	20.7% (12.6-28.9%)	8.0% (4.2-11.8%)
Hypertension	92.3% (86.6-97.9%)	77.5% (70.8-74.1%)
Renal impairment	19.0% (12.9-25.1%)	8.7% (5.9-11.5%)
Cerebrospinal disease	17.6% (10.6-24.7%)	9.9% (4.7-15.1%)
CAD	31.4% (24.0-38.7%)	15% (9.7-20.2%)
COPD	29.8% (22.8-36.8%)	16.8% (8.3-25.4%)
History of previous cardiovascular surgery (thorax, abdomen)	30.1% (21.6-38.5%)	32.1% (23.8-40.4%)

AD, arch debranching group; ET, elephant trunk group; DM, diabetes mellitus; CAD, coronary artery disease; COPD, chronic obstructive pulmonary disease

Technical success in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al.* 2012	0.958	0.848	0.990	4.341	0.000
Antoniou *et al.* 2010	0.818	0.650	0.916	3.333	0.001
Bavaria *et al.* 2010	0.979	0.741	0.999	2.694	0.007
Bergeron *et al.* 2006	0.920	0.731	0.980	3.313	0.001
Canaud *et al.* 2010	0.676	0.505	0.811	2.012	0.044
Chan *et al.* 2008	0.971	0.664	0.998	2.436	0.015
Chiesa *et al.* 2010	0.871	0.797	0.921	6.892	0.000
Czerny *et al.* 2012	0.985	0.900	0.998	4.143	0.000
Deriu *et al.* 2012	0.990	0.857	0.999	3.218	0.001
Donas *et al.* 2010	0.976	0.713	0.999	2.594	0.009
Ferrero *et al.* 2012	0.982	0.770	0.999	2.808	0.005
Geisbusch *et al.* 2011	0.915	0.794	0.968	4.543	0.000
Gelpi *et al.* 2010	0.933	0.648	0.991	2.550	0.011
Gottardi *et al.* 2008	0.993	0.901	1.000	3.517	0.000
Holt *et al.* 2010	0.974	0.903	0.994	5.078	0.000
Hughes *et al.* 2009	0.983	0.777	0.999	2.834	0.005
Ingrund *et al.* 2010	0.833	0.523	0.958	2.078	0.038
Ishibashi *et al.* 2012	0.962	0.597	0.998	2.232	0.026
Lee *et al.* 2011	0.757	0.595	0.868	2.962	0.003
Lotfi *et al.* 2012	0.863	0.739	0.933	4.518	0.000
Lu *et al.* 2011	0.972	0.678	0.998	2.479	0.013
Ma *et al.* 2011	0.875	0.676	0.959	3.153	0.002
Murashita *et al.* 2012	0.982	0.770	0.999	2.808	0.005
Saleh *et al.* 2006	0.969	0.650	0.998	2.390	0.017
Vallejo *et al.* 2012	0.974	0.835	0.996	3.563	0.000
Weigang *et al.* 2009	0.981	0.764	0.999	2.781	0.005
	0.928	**0.891**	**0.953**	**11.094**	**0.000**

Event rate and 95% CI

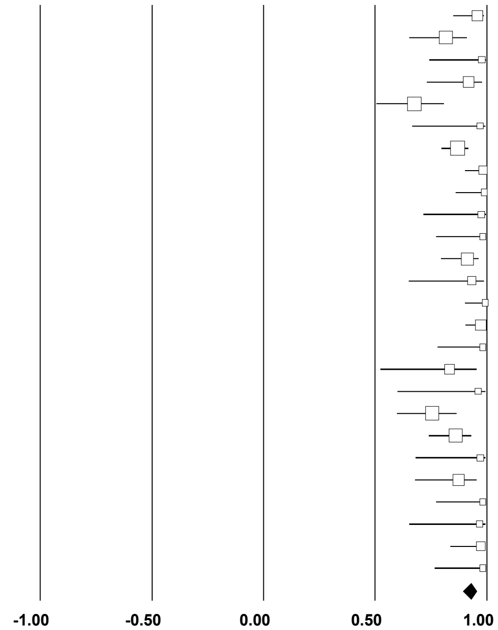

Figure 3 Forest plot of technical success rate in the arch debranching group. AD, arch debranching

30-day/in-hospital mortality in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al.* 2012	0.208	0.116	0.346	-3.756	0.000
Antoniou *et al.* 2010	0.212	0.105	0.383	-3.082	0.002
Bavaria *et al.* 2010	0.130	0.043	0.335	-3.064	0.002
Bergeron *et al.* 2006	0.080	0.020	0.269	-3.313	0.001
Canaud *et al.* 2010	0.206	0.101	0.373	-3.183	0.001
Chan *et al.* 2008	0.029	0.002	0.336	-2.436	0.015
Chiesa *et al.* 2010	0.043	0.018	0.099	-6.781	0.000
Czerny *et al.* 2012	0.091	0.041	0.188	-5.378	0.000
Deriu *et al.* 2012	0.083	0.032	0.202	-4.592	0.000
Donas *et al.* 2010	0.150	0.049	0.376	-2.770	0.006
Ferrero *et al.* 2012	0.111	0.036	0.293	-3.396	0.001
Geisbusch *et al.* 2011	0.191	0.103	0.329	-3.885	0.000
Gelpi *et al.* 2010	0.031	0.002	0.350	-2.390	0.017
Gottardi *et al.* 2008	0.068	0.029	0.154	-5.633	0.000
Holt *et al.* 2010	0.077	0.035	0.161	-5.848	0.000
Hughes *et al.* 2009	0.017	0.001	0.223	-2.834	0.005
Ingrund *et al.* 2010	0.167	0.042	0.477	-2.078	0.038
Ishibashi *et al.* 2012	0.038	0.002	0.403	-2.232	0.026
Lee *et al.* 2011	0.162	0.075	0.317	-3.682	0.000
Lotfi *et al.* 2012	0.098	0.041	0.215	-4.713	0.000
Lu *et al.* 2011	0.118	0.030	0.368	-2.677	0.007
Ma *et al.* 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al.* 2012	0.037	0.005	0.221	-3.197	0.001
Saleh *et al.* 2006	0.067	0.009	0.352	-2.550	0.011
Vallejo *et al.* 2012	0.237	0.128	0.396	-3.066	0.002
Weigang *et al.* 2009	0.154	0.059	0.345	-3.136	0.002
	0.119	**0.094**	**0.149**	**-14.878**	**0.000**

Event rate and 95% CI

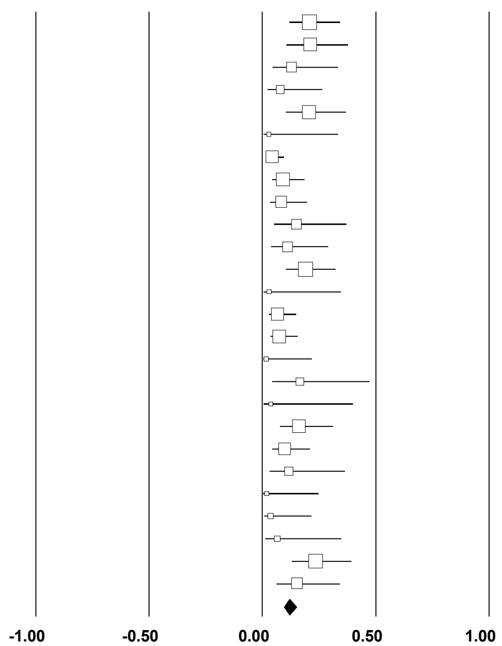

Figure 4 Forest plot of mortality rate in the arch debranching group. AD, arch debranching

Stroke in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al.* 2012	0.042	0.010	0.152	-4.341	0.000
Antoniou *et al.* 2010	0.121	0.046	0.282	-3.714	0.000
Bavaria *et al.* 2010	0.130	0.043	0.335	-3.064	0.002
Bergeron *et al.* 2006	0.080	0.020	0.269	-3.313	0.001
Canaud *et al.* 2010	0.059	0.015	0.207	-3.804	0.000
Chan *et al.* 2008	0.188	0.062	0.447	-2.289	0.022
Chiesa *et al.* 2010	0.043	0.018	0.099	-6.781	0.000
Czerny *et al.* 2012	0.045	0.015	0.132	-5.152	0.000
Deriu *et al.* 2012	0.010	0.001	0.143	-3.218	0.001
Donas *et al.* 2010	0.150	0.049	0.376	-2.770	0.006
Ferrero *et al.* 2012	0.018	0.001	0.230	-2.808	0.005
Geisbusch *et al.* 2011	0.064	0.021	0.180	-4.501	0.000
Gelpi *et al.* 2010	0.031	0.002	0.350	-2.390	0.017
Gottardi *et al.* 2008	0.014	0.002	0.091	-4.247	0.000
Holt *et al.* 2010	0.064	0.027	0.145	-5.800	0.000
Hughes *et al.* 2009	0.017	0.001	0.223	-2.834	0.005
Ingrund *et al.* 2010	0.038	0.002	0.403	-2.232	0.026
Ishibashi *et al.* 2012	0.083	0.012	0.413	-2.296	0.022
Lee *et al.* 2011	0.108	0.041	0.255	-3.986	0.000
Lotfi *et al.* 2012	0.118	0.054	0.238	-4.636	0.000
Lu *et al.* 2011	0.059	0.008	0.320	-2.690	0.007
Ma *et al.* 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al.* 2012	0.074	0.019	0.252	-3.437	0.001
Saleh *et al.* 2006	0.031	0.002	0.350	-2.390	0.017
Vallejo *et al.* 2012	0.132	0.056	0.280	-3.932	0.000
Weigang *et al.* 2009	0.019	0.001	0.236	-2.781	0.005
	0.076	**0.059**	**0.097**	**-18.330**	**0.000**

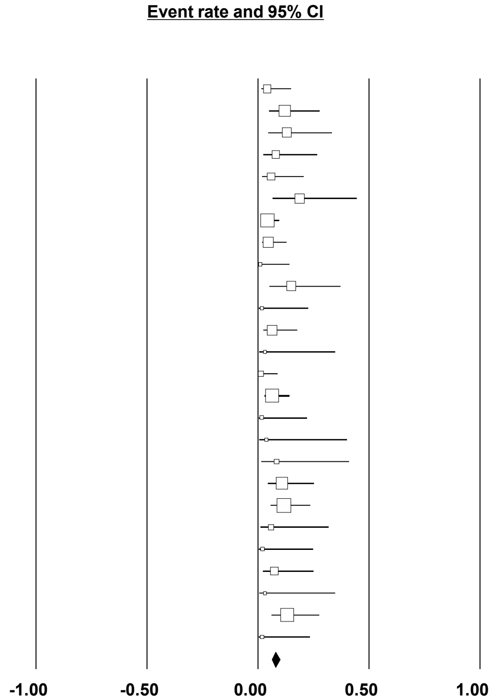

Figure 5 Forest plot of stroke rate in the arch debranching group. AD, arch debranching

Irreversible SCI in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.010	0.001	0.143	-3.218	0.001
Antoniou *et al*. 2010	0.061	0.015	0.212	-3.757	0.000
Bavaria *et al*. 2010	0.087	0.022	0.289	-3.177	0.001
Bergeron *et al*. 2006	0.019	0.001	0.244	-2.753	0.006
Canaud *et al*. 2010	0.029	0.004	0.181	-3.445	0.001
Chan *et al*. 2008	0.029	0.002	0.336	-2.436	0.015
Chiesa *et al*. 2010	0.017	0.004	0.066	-5.668	0.000
Czerny *et al*. 2012	0.030	0.008	0.113	-4.826	0.000
Deriu *et al*. 2012	0.042	0.010	0.152	-4.341	0.000
Donas *et al*. 2010	0.024	0.001	0.287	-2.594	0.009
Ferrero *et al*. 2012	0.037	0.005	0.221	-3.197	0.001
Geisbusch *et al*. 2011	0.064	0.021	0.180	-4.501	0.000
Gelpi *et al*. 2010	0.031	0.002	0.350	-2.390	0.017
Gottardi *et al*. 2008	0.007	0.000	0.099	-3.517	0.000
Holt *et al*. 2010	0.026	0.006	0.097	-5.078	0.000
Hughes *et al*. 2009	0.036	0.005	0.214	-3.236	0.001
Ingrund *et al*. 2010	0.038	0.002	0.403	-2.232	0.026
Ishibashi *et al*. 2012	0.038	0.002	0.403	-2.232	0.026
Lee *et al*. 2011	0.013	0.001	0.178	-3.033	0.002
Lotfi *et al*. 2012	0.039	0.010	0.144	-4.434	0.000
Lu *et al*. 2011	0.028	0.002	0.322	-2.479	0.013
Ma *et al*. 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al*. 2012	0.074	0.019	0.252	-3.437	0.001
Saleh *et al*. 2006	0.031	0.002	0.350	-2.390	0.017
Vallejo *et al*. 2012	0.026	0.004	0.165	-3.563	0.000
Weigang *et al*. 2009	0.019	0.001	0.236	-2.781	0.005
	0.036	**0.025**	**0.051**	**-17.512**	**0.000**

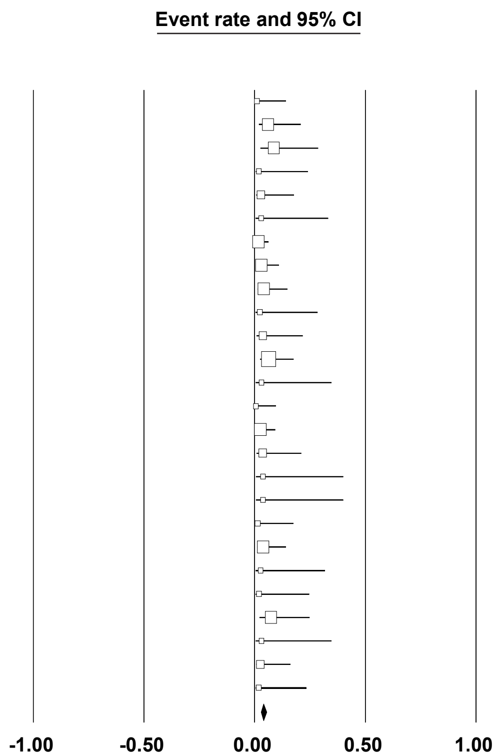

Figure 6 Forest plot of irreversible spinal cord injuries in the arch debranching group. AD, arch debranching

Renal failure requiring dialysis in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.042	0.010	0.152	-4.341	0.000
Antoniou *et al*. 2010	0.182	0.084	0.350	-3.333	0.001
Bavaria *et al*. 2010	0.043	0.006	0.252	-3.023	0.003
Chan *et al*. 2008	0.029	0.002	0.336	-2.436	0.015
Chiesa *et al*. 2010	0.017	0.004	0.066	-5.668	0.000
Geisbusch *et al*. 2011	0.128	0.058	0.256	-4.397	0.000
Gelpi *et al*. 2010	0.031	0.002	0.350	-2.390	0.017
Holt *et al*. 2010	0.051	0.019	0.129	-5.684	0.000
Hughes *et al*. 2009	0.017	0.001	0.223	-2.834	0.005
Ingrund *et al*. 2010	0.038	0.002	0.403	-2.232	0.026
Ishibashi *et al*. 2012	0.038	0.002	0.403	-2.232	0.026
Lotfi *et al*. 2012	0.010	0.001	0.136	-3.261	0.001
Lu *et al*. 2011	0.028	0.002	0.322	-2.479	0.013
Ma *et al*. 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al*. 2012	0.037	0.005	0.221	-3.197	0.001
Vallejo *et al*. 2012	0.079	0.026	0.218	-4.084	0.000
	0.057	**0.036**	**0.089**	**-11.628**	**0.000**

Event rate and 95% CI

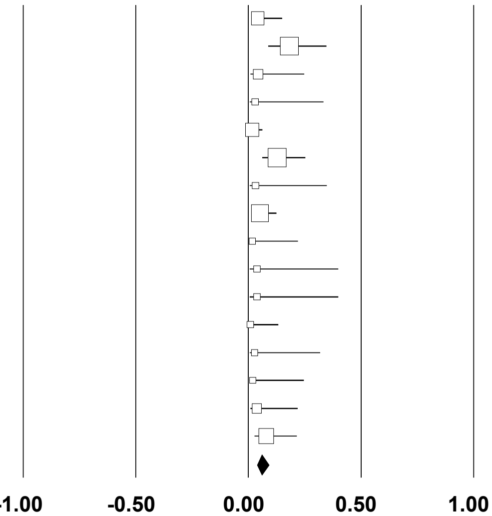

Figure 7 Forest plot of renal failure requiring dialysis in the arch debraching group. AD, arch debranching

30-day/in-hospital mortality in ET group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.100	0.025	0.324	-2.948	0.003
Baraki *et al*. 2007	0.128	0.054	0.273	-4.002	0.000
Chen *et al*. 2010	0.143	0.055	0.324	-3.318	0.001
Flores *et al*. 2006	0.120	0.039	0.313	-3.237	0.001
Hofferberth *et al*. 2012	0.053	0.007	0.294	-2.813	0.005
Hoffman *et al*. 2012	0.031	0.004	0.191	-3.380	0.001
Jakob *et al*. 2011	0.150	0.112	0.197	-10.259	0.000
Jim *et al*. 2011	0.100	0.014	0.467	-2.084	0.037
Kawaharada *et al*. 2009	0.065	0.016	0.224	-3.658	0.000
Lee *et al*. 2011	0.190	0.073	0.412	-2.604	0.009
Lima *et al*. 2012	0.080	0.030	0.195	-4.685	0.000
Nishi *et al*. 2011	0.033	0.008	0.122	-4.707	0.000
Pochettino *et al*. 2009	0.139	0.059	0.293	-3.786	0.000
Shi *et al*. 2011	0.022	0.003	0.139	-3.765	0.000
Shimamura *et al*. 2008	0.032	0.012	0.082	-6.726	0.000
Shimamura *et al*. 2009	0.072	0.030	0.163	-5.490	0.000
Shrestha *et al*. 2012	0.088	0.029	0.240	-3.862	0.000
Sun *et al*. 2011	0.031	0.016	0.058	-10.173	0.000
Uchida *et al*. 2011	0.050	0.019	0.126	-5.740	0.000
Zhao *et al*. 2012	0.042	0.006	0.244	-3.069	0.002
	0.095	**0.078**	**0.114**	**-21.513**	**0.000**

Event rate and 95% CI

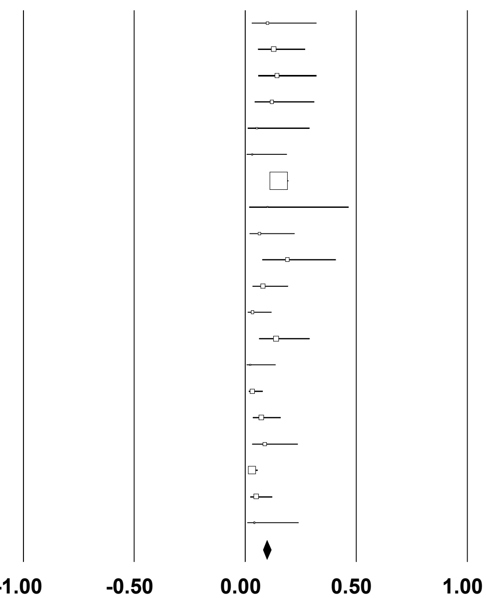

Figure 8 Forest plot of mortality rate in the elephant trunk group. ET, elephant trunk

Stroke in ET group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.050	0.007	0.282	-2.870	0.004
Baraki *et al*. 2007	0.128	0.054	0.273	-4.002	0.000
Chen *et al*. 2010	0,107	0.035	0.284	-3.470	0.001
Flores *et al*. 2006	0.160	0.061	0.357	-3.040	0.002
Hofferberth *et al*. 2012	0,105	0.026	0.337	-2.863	0.004
Hoffman *et al*. 2012	0.015	0.001	0.201	-2.929	0.003
Jakob *et al*. 2011	0.058	0.036	0.093	-10.792	0.000
Jim *et al*. 2011	0.045	0.003	0.448	-2.103	0.035
Kawaharada *et al*. 2009	0.016	0.001	0.206	-2.907	0.004
Lee *et al*. 2011	0.095	0.024	0.311	-3.028	0.002
Lima *et al*. 2012	0.100	0.042	0.219	-4.661	0.000
Nishi *et al*. 2011	0.049	0.016	0.142	-5.002	0.000
Pochettino *et al*. 2009	0.028	0.004	0.173	-3.506	0.000
Shi *et al*. 2011	0.011	0.001	0.149	-3.188	0.001
Shimamura *et al*. 2008	0.071	0.038	0.132	-7.415	0.000
Shimamura *et al*. 2009	0.058	0.022	0.144	-5.412	0.000
Sun *et al*. 2011	0.024	0.012	0.050	-9.679	0.000
Uchida *et al*. 2011	0.025	0.006	0.094	-5.116	0.000
Zhao *et al*. 2012	0.020	0.001	0.251	-2.724	0.006
	0.062	**0.046**	**0.083**	**-16.928**	**0.000**

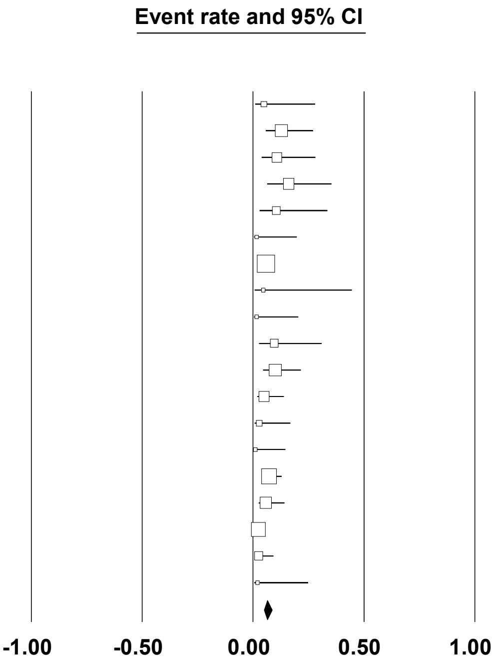

Figure 9 Forest plot of stroke rate in the elephant trunk group. ET, elephant trunk

Irreversible SCI in ET group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.024	0.001	0.287	-2.594	0.009
Baraki *et al*. 2007	0.013	0.001	0.171	-3.070	0.002
Chen *et al*. 2010	0.107	0.035	0.284	-3.470	0.001
Flores *et al*. 2006	0.160	0.061	0.357	-3.040	0.002
Hofferberth *et al*. 2012	0.025	0.002	0.298	-2.558	0.011
Hoffman *et al*. 2012	0.015	0.001	0.201	-2.929	0.003
Jakob *et al*. 2011	0.073	0.048	0.110	-10.944	0.000
Jim *et al*. 2011	0.045	0.003	0.448	-2.103	0.035
Kawaharada *et al*. 2009	0.016	0.001	0.206	-2.907	0.004
Lee *et al*. 2011	0.023	0.001	0.277	-2.629	0.009
Lima *et al*. 2012	0.020	0.003	0.129	-3.853	0.000
Nishi *et al*. 2011	0.049	0.016	0.142	-5.002	0.000
Pochettino *et al*. 2009	0.014	0.001	0.182	-3.013	0.003
Shi *et al*. 2011	0.011	0.001	0.149	-3.188	0.001
Shimamura *et al*. 2008	0.024	0.008	0.071	-6.355	0.000
Shimamura *et al*. 2009	0.029	0.007	0.109	-4.894	0.000
Sun *et al*. 2011	0.007	0.002	0.027	-7.009	0.000
Uchida *et al*. 2011	0.006	0.000	0.091	-3.582	0.000
Zhao *et al*. 2012	0.020	0.001	0.251	-2.724	0.006
	0.050	**0.037**	**0.066**	**-18.840**	**0.000**

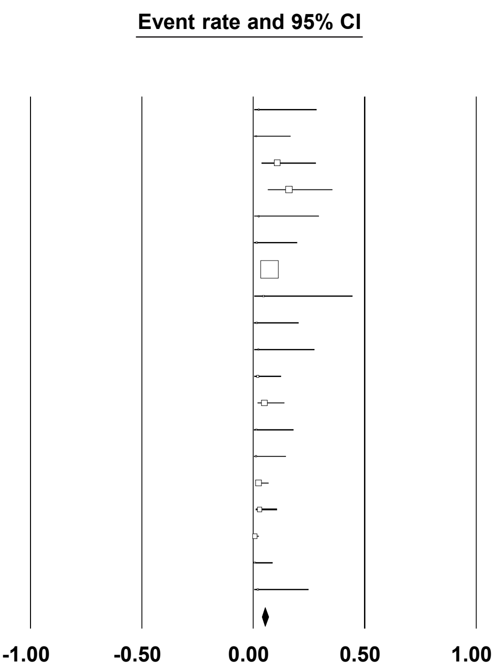

Figure 10 Forrest plot of irreversible spinal cord injuries in the elephant trunk group. ET, elephant trunk

Renal failure requiring dialysis in ET group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.050	0.007	0.282	-2.870	0.004
Chen *et al*. 2010	0.071	0.018	0.245	-3.495	0.000
Hofferberth *et al*. 2012	0.025	0.002	0.298	-2.558	0.011
Jakob *et al*. 2011	0.036	0.020	0.066	-10.161	0.000
Jim *et al*. 2011	0.045	0.003	0.448	-2.103	0.035
Lee *et al*. 2011	0.023	0.001	0.277	-2.629	0.009
Lima *et al*. 2012	0.060	0.019	0.170	-4.621	0.000
Nishi *et al*. 2011	0.033	0.008	0.122	-4.707	0.000
Pochettino *et al*. 2009	0.083	0.027	0.229	-3.976	0.000
Shimamura *et al*. 2008	0.048	0.022	0.102	-7.161	0.000
Shimamura *et al*. 2009	0.029	0.007	0.109	-4.894	0.000
Sun *et al*. 2011	0.010	0.003	0.031	-7.865	0.000
Uchida *et al*. 2011	0.006	0.000	0.091	-3.582	0.000
	0.038	**0.027**	**0.053**	**-18.428**	**0.000**

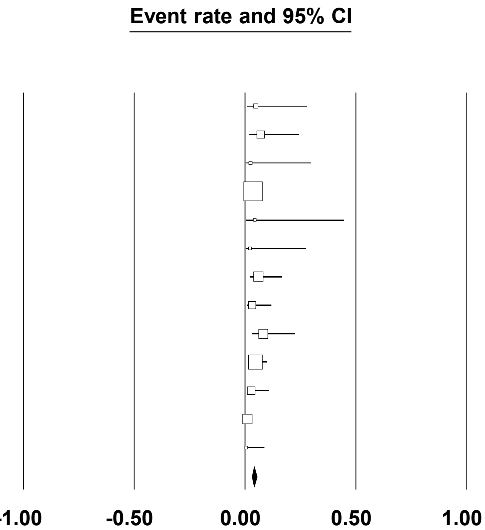

Figure 11 Forrest plot of renal failure requiring dialysis in the elephant trunk group. ET, elephant trunk

Both methods consist of two steps: the open surgical portion and the endovascular component. They can be conducted either as one- or two-stage procedures. The elimination of the need for extensive arch and thoracic aorta dissection and the reduced time of total circulatory arrest, which is not required in all cases of hybrid reconstruction, generate significant appeal for this strategy in selected patients.

The above-referenced debranching procedure was most commonly used for the treatment of degenerative arch aneurysms in Zone 0 and/or Zone 1. Several points have been studied in this meta-analysis. The 30-day mortality rate for the "debranching" procedures was 11.9%. The stroke rate was 7.6% and the spinal cord ischemia rate was 3.6%, while pulmonary complications were observed on average in 12.6% of patients. Cardiac complications, such as myocardial infarction and cardiac arrhythmias, were present in 6.0% and renal insufficiency requiring permanent hemodialysis occurred in 5.7% of patients within the studies. The spinal cord ischemia rate of 3.6% indicates a fairly low incidence that can likely be explained by two main reasons. Firstly, during debranching procedures, there is no need for total aortic cross-clamping, which eliminates the ischemia time of the spinal cord. Secondly, for arch aneurysms, the length of aortic coverage with the endo-graft is relatively short. Thus, the intercostal arteries remain intact while the left subclavian artery and consequently, the left internal mammary artery, are revascularized.

Another point that merits consideration from the present results is the low mortality rate in this sensitive group of patients. These patients are considered unfit for the traditional open repair of arch aneurysms which precludes total circulatory arrest and deep hypothermia. In our study, almost all of the patients of the AD group were hypertensive or taking anti-hypertensive agents, with one in five patients suffering from diabetes, renal impairment or cerebrovascular disease, and one in three patients having a history of coronary artery disease or previous cardiovascular surgery. The debranching procedure is believed to be less invasive as there is no need for aortic cross clamping and cardiopulmonary bypass. Furthermore, we found a pooled rate of 92.8% for the technical success of this method. Although such an outcome seems to be reasonable, we could not neglect the considerable rate of endoleaks (16.6%), the majority of which were type I, as well as the fact that postoperative retrograde type A dissection was presented in 4.5% of the patients. These findings could be attributed to the quality of the ascending aorta. Residual atherosclerosis or retrograde dissection may jeopardize this procedure.

The "frozen" or stented elephant trunk technique was adapted from the classic elephant trunk technique. According to this method the repair of concomitant aortic arch and proximal descending aortic aneurysms can be performed in a single stage under circulatory arrest, eliminating the need for a second posterolateral thoracotomy. In our review, 72.4% of the procedures were conducted in order to treat aortic dissections, leaving

27.3% for the repair of aneurismal disease and 0.3% for other pathologies (e.g., pseudoaneurysm repair of the aortic arch). A great number of urgent procedures (41.6%) were performed with the above technique, which may be responsible for the variability of the results among the different series. We observed significant heterogeneity of results between the eligible studies, especially with respect to the 30-day mortality rate and incidence of spinal cord ischemia complications. This heterogeneity can be partially explained by the differences between elective and urgent operations and because the elephant trunk technique was mostly used for the treatment of aortic dissections. Despite the severity of the pathologies, the pooled 30-day mortality rate was approximately 9.5%, which is an acceptable outcome. In addition, the stroke rate ranged around 6.2%.

With regard to the other outcomes in the ET group, the fact that surgical prosthetic material provides a safe landing zone for the stent-graft in ET procedures eliminates the risk for type Ia endoleak. However, the re-exploration rate for bleeding was estimated at approximately 8.6%, which is not a negligible rate. The main cause for postoperative bleeding is the coagulopathy disorders attributed to deep hypothermia and the heparin administration during total circulatory arrest. In addition, pulmonary complications in the present meta-analysis occurred at a pooled rate of 19.7%, leading to a prolonged stay in the ICU. In contrast, a relatively low incidence of irreversible spinal cord ischemia and permanent renal insufficiency were observed. In fact, the pooled estimate for SCI symptoms and renal impairments requiring dialysis were 5% and 3.8%, respectively. Both complications are main concerns when extensive reconstructions of large aortic segments, such as thoracoabdominal aneurysms, are required. We believe that the cooling of the patient, decreased ischemic time during the application of the trunk and central anastomosis, together with the application of various adjunctive measures such as CSF drainage, may result in a minimized risk of permanent spinal cord or renal injury.

Our study is the largest up-to-date review on the hybrid approach for aortic arch diseases. However, it has the inherent limitations associated with meta-analyses. The great heterogeneity among studies regarding the patient's characteristics and surgical methods are potential factors that can attenuate the pooled estimates. Furthermore, the lack of raw patient data is a prohibitive impediment for subset analysis (e.g., differences in outcomes in different aortic pathologies). In addition, a direct comparison between the two groups could not be appropriate as the applied methods have separate indications. However, a noteworthy observation is that despite the difference in terms of risk stratification between the two patients sets (as shown in *Table 3*), the outcomes were comparable.

It is still debatable whether a hybrid technique is comparable to total open repair, as the former strategy is reserved for high-risk patients who are unable to withstand an open repair. According to the available literature and taking into account the less invasive nature of hybrid repair, it could be speculated that short-term mortality and morbidity should appear to be reduced in hybrid repair patients. A recent meta-analysis attempted to elucidate this issue (53). However, it was based on four non-randomized observational studies, which makes the analysis prone to selection and patient profile biases. Surprisingly, this study showed that a hybrid repair did not significantly improve operative mortality, whereas it was associated with a slight but non-significant increase in permanent neurologic deficits. A non-significant trend towards increased late mortality was observed in the hybrid group.

Conclusions

Hybrid arch techniques provide a safe alternative to open repair with acceptable short- and mid-term results. However, stroke and mortality rates remain noteworthy. Future prospective trials that compare open conventional techniques with the hybrid method or the entirely endovascular method are needed.

Acknowledgements

Disclosure: The authors declare no conflict of interest.

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Cite this article as: Moulakakis KG, Mylonas SN, Markatis F, Kotsis T, Kakisis J, Liapis CD. A systematic review and meta-analysis of hybrid aortic arch replacement. Ann Cardiothorac Surg 2013;2(3):247-260. doi: 10.3978/j.issn.2225-319X.2013.05.06

Retrograde type A dissection in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.063	0.020	0.177	-4.542	0.000
Bergeron *et al*. 2006	0.040	0.006	0.235	-3.114	0.002
Canaud *et al*. 2010	0.029	0.004	0.181	-3.445	0.001
Chan *et al*. 2008	0.029	0.002	0.336	-2.436	0.015
Czerny *et al*. 2012	0.076	0.032	0.169	-5.377	0.000
Gelpi *et al*. 2010	0.031	0.002	0.350	-2.390	0.017
Gottardi *et al*. 2008	0.014	0.002	0.091	-4.247	0.000
Hughes *et al*. 2009	0.017	0.001	0.223	-2.834	0.005
Ingrund *et al*. 2010	0.083	0.012	0.413	-2.296	0.022
Ishibashi *et al*. 2012	0.038	0.002	0.403	-2.232	0.026
Lee *et al*. 2011	0.027	0.004	0.168	-3.535	0.000
Lotfi *et al*. 2012	0.059	0.019	0.167	-4.659	0.000
Lu *et al*. 2011	0.028	0.002	0.322	-2.479	0.013
Ma *et al*. 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al*. 2012	0.018	0.001	0.230	-2.808	0.005
Saleh *et al*. 2006	0.031	0.002	0.350	-2.390	0.017
Vallejo *et al*. 2012	0.026	0.004	0.165	-3.563	0.000
	0.045	**0.029**	**0.068**	**-13.670**	**0.000**

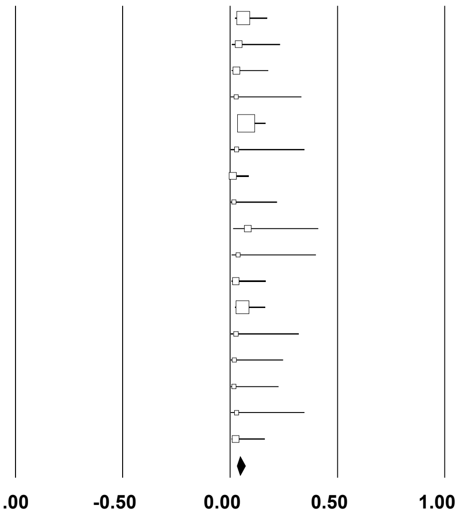

Figure S1 Forrest plot of retrograde dissection in AD Group. AD, arch debranching

Cardiac support in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.010	0.001	0.143	-3.218	0.001
Antoniou *et al*. 2010	0.061	0.015	0.212	-3.757	0.000
Bavaria *et al*. 2010	0.435	0.252	0.637	-0.624	0.533
Bergeron *et al*. 2006	0.019	0.001	0.244	-2.753	0.006
Chan *et al*. 2008	0.188	0.062	0.447	-2.289	0.022
Chiesa *et al*. 2010	0.004	0.000	0.065	-3.846	0.000
Donas *et al*. 2010	0.150	0.049	0.376	-2.770	0.006
Geisbusch *et al*. 2011	0.149	0.073	0.281	-4.254	0.000
Gelpi *et al*. 2010	0.031	0.002	0.350	-2.390	0.017
Hughes *et al*. 2009	0.017	0.001	0.223	-2.834	0.005
Ishibashi *et al*. 2012	0.038	0.002	0.403	-2.232	0.026
Lotfi *et al*. 2012	0.020	0.003	0.126	-3.873	0.000
Lu *et al*. 2011	0.059	0.008	0.320	-2.690	0.007
Ma *et al*. 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al*. 2012	0.018	0.001	0.230	-2.808	0.005
Vallejo *et al*. 2012	0.053	0.013	0.187	-3.979	0.000
	0.060	**0.030**	**0.118**	**-7.281**	**0.000**

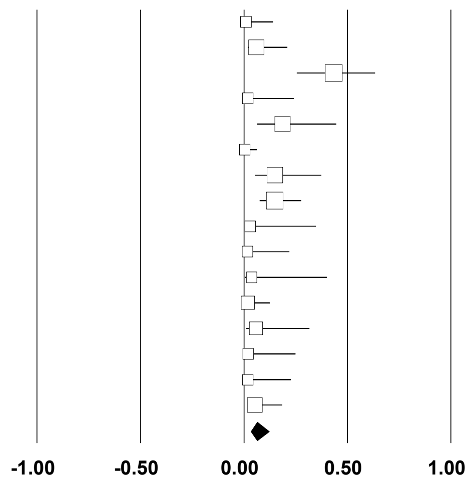

Figure S2 Forrest plot of need for cardiac support in AD Group. AD, arch debranching

Pulmonary complications in AD group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.083	0.032	0.202	-4.592	0.000
Antoniou *et al*. 2010	0.121	0.046	0.282	-3.714	0.000
Bergeron *et al*. 2006	0.019	0.001	0.244	-2.753	0.006
Chan *et al*. 2008	0.313	0.136	0.567	-1.462	0.144
Chiesa *et al*. 2010	0.043	0.018	0.099	-6.781	0.000
Deriu *et al*. 2012	0.292	0.181	0.434	-2.794	0.005
Donas *et al*. 2010	0.150	0.049	0.376	-2.770	0.006
Geisbusch *et al*. 2011	0.255	0.151	0.398	-3.200	0.001
Gelpi *et al*. 2010	0.031	0.002	0.350	-2.390	0.017
Hughes *et al*. 2009	0.071	0.018	0.245	-3.495	0.000
Ishibashi *et al*. 2012	0.038	0.002	0.403	-2.232	0.026
Lotfi *et al*. 2012	0.118	0.054	0.238	-4.636	0.000
Ma *et al*. 2011	0.020	0.001	0.251	-2.724	0.006
Murashita *et al*. 2012	0.037	0.005	0.221	-3.197	0.001
Vallejo *et al*. 2012	0.474	0.323	0.630	-0.324	0.746
	0.126	**0.074**	**0.206**	**-6.431**	**0.000**

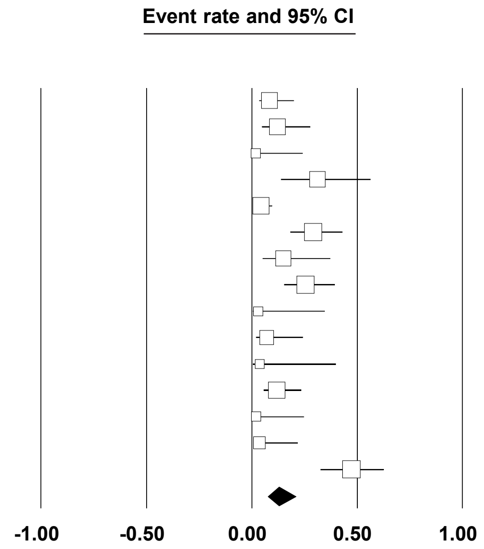

Figure S3 Forrest plot of pulmonary complications in AD Group. AD, arch debranching

Pulmonary complications in ET group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Andersen *et al*. 2012	0.100	0.025	0.324	-2.948	0.003
Chen *et al*. 2010	0.393	0.233	0.580	-1.125	0.261
Flores *et al*. 2006	0.120	0.039	0.313	-3.237	0.001
Hofferberth *et al*. 2012	0.368	0.187	0.597	-1.133	0.257
Hoffman *et al*. 2012	0.250	0.130	0.426	-2.691	0.007
Jakob *et al*. 2011	0.332	0.279	0.390	-5.446	0.000
Jim *et al*. 2011	0.045	0.003	0.448	-2.103	0.035
Lee *et al*. 2011	0.048	0.007	0.271	-2.924	0.003
Lima *et al*. 2012	0.040	0.010	0.146	-4.404	0.000
Nishi *et al*. 2011	0.033	0.008	0.122	-4.707	0.000
Shimamura *et al*. 2008	0.063	0.032	0.122	-7.366	0.000
Shimamura *et al*. 2009	0.029	0.007	0.109	-4.894	0.000
Sun *et al*. 2011	0.072	0.048	0.108	-11.273	0.000
Uchida *et al*. 2011	0.075	0.034	0.157	-5.919	0.000
	0.197	**0.171**	**0.227**	**-15.495**	**0.000**

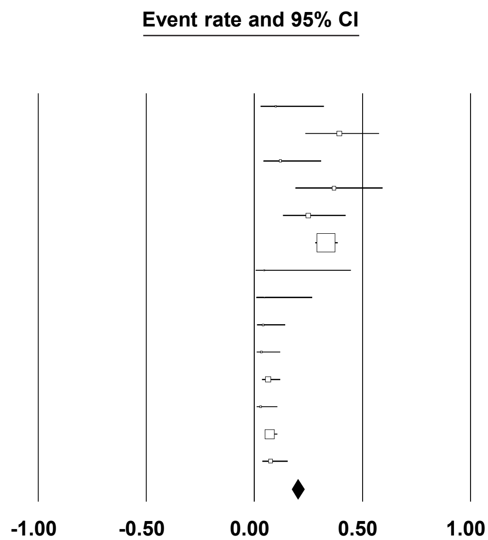

Figure S4 Forrest plot of pulmonary complications in ET Group. ET, elephant trunk

Re-exploring for bleeding in ET group

Study name	Event rate	Lower limit	Upper limit	Z-value	P-value
Chen *et al*. 2010	0.107	0.035	0.284	-3.470	0.001
Hofferberth *et al*. 2012	0.105	0.026	0.337	-2.863	0.004
Hoffman *et al*. 2012	0.125	0.048	0.289	-3.640	0.000
Jakob *et al*. 2011	0.139	0.103	0.185	-10.448	0.000
Nishi *et al*. 2011	0.049	0.016	0.142	-5.002	0.000
Shi *et al*. 2011	0.043	0.011	0.158	-4.275	0.000
Shimamura *et al*. 2008	0.024	0.008	0.071	-6.355	0.000
Shimamura *et al*. 2009	0.029	0.007	0.109	-4.894	0.000
Sun *et al*. 2011	0.052	0.031	0.084	-10.985	0.000
Uchida *et al*. 2011	0.050	0.019	0.126	-5.740	0.000
Zhao *et al*. 2012	0.042	0.006	0.244	-3.069	0.002
	0.086	**0.069**	**0.106**	**-19.671**	**0.000**

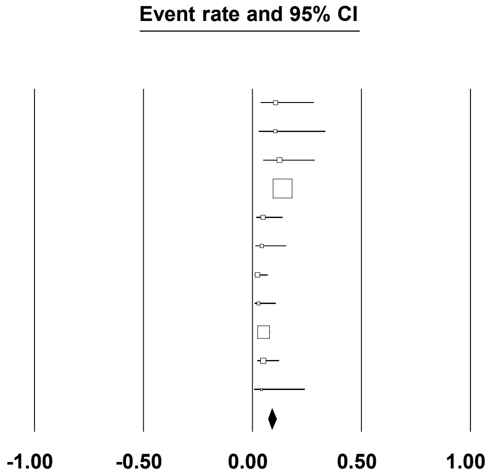

Figure S5 Forrest plot of reexploration for bleeding in ET Group. ET, elephant trunk