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Contemporary results of open thoracic and thoracoabdominal aortic surgery in a single United Kingdom centre

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ARTICLE HIGHLIGHTS

Type of Research: Single centre, retrospective cohort study

Key Findings: Among 430 patients that underwent open repair; our 30-day mortality in elective surgery was 3.1% after DTA repair and 9.9% after TAAA repair. Predictors of in-hospital mortality were age ≥70, extent II repair, non-elective surgery, out-of-hours surgery, left ventricular ejection fraction <30% and surgery for degenerative aneurysm.

Take Home Message: Our study shows that outcomes in thoracoabdominal aortic surgery improves with experience, although extent of aortic replacement and advanced age, among other factors, predict mortality.

Table of Contents Summary

Age ≥70, extent II repair, non-elective surgery, out-of-hours surgery, left ventricular ejection fraction of <30% and surgery for degenerative aneurysm were predictors of in-hospital mortality in this single centre retrospective cohort study of 430 patients from United Kingdom. The study suggests that understanding these risks is fundamental for patient selection and the consent process of potential candidates for surgery particularly in the elderly

Abstract

Objective: To report outcome and identify predictors of mortality after open descending thoracic aneurysm (DTA) and thoracoabdominal aortic aneurysm (TAAA) repair in a specialist aortic centre.

Methods: This was a retrospective observational cohort study. Consecutive patients who underwent surgery at our institution between October 1998 and December 2019 were included. The main outcome measures were mortality and major morbidity. Multivariate analysis was used to identify predictors of mortality.

Results: 430 patients underwent DTA (n=157) and TAA (n=273) repair; 151 underwent surgery non-electively. Forty-eight (11.6%) died within 30 days of surgery. Thirty-day mortality was lower after elective surgery (3.1% after DTA repair and 9.9% after TAAA repair), whereas non-elective surgery carried a 30-day mortality of 17.9%. Fourteen additional patients died in hospital after 30 days, one after non-elective DTA repair and 13 after TAAA repair (10 elective), all but one extent II. In-hospital mortality for the whole cohort improved over time, as the activity volume increased, except for patients undergoing extent II TAAA repair. Predictors of in-hospital mortality were: age ≥70 (OR 3.36; 95%CI=1.79-6.32, P<0.001); extent II repair (OR 4.39; 95%CI=2.34-8.21), P<0.001); non-elective surgery (OR 2.72; 95%CI=1.44, 5.12), P=0.002); out-of-hours surgery (OR 8.17; 95%CI=2.16-30.95), P=0.002), left ventricular ejection fraction <30% (OR 9.86; 95%CI=1.91-50.86, P<0.006) and surgery for degenerative aneurysm (OR=2.20; 95%CI=1.12-4.31, P=0.02).The incidence of stroke and paraplegia was 7.1% and zero after DTA repair; 9.9% and 3.3% after TAAA repair. Haemodialysis was necessary in 5.1% of cases after DTA repair and 22.7% after TAAA repair.

Conclusion: Open thoracoabdominal aortic surgery carries significant risk to life, which is related to age, extent of aortic replacement, timing of surgery and left ventricular function. Morbidity is considerable. Understanding these risks is fundamental for patient selection and the consent process of potential candidates for surgery particularly in the elderly.

Introduction

Surgery on the thoracoabdominal aorta remains a formidable undertaking, whether through an open, endovascular or hybrid approach.[1-2] In the United Kingdom, open surgery is performed in specialized and high volume centres with a larger geographical service cover.[3] At present, there is no official guidance or service specification for centres performing this type of surgery hence service provision and outcomes have been variable.[3] Over the last two decades, our unit has developed into a national referral centre for complex pathology of the aorta, resulting in the provision of increasingly high volume, multidisciplinary care for patients with thoracic and thoracoabdominal aortic disease. This care includes open and endovascular repair of descending thoracic aneurysms (DTA) and thoracoabdominal aneurysms (TAAA). The aim of this study was to review and report the outcome of patients who have undergone open DTA and TAAA repair in our centre, and to identify predictors of mortality.

Materials and Methods

We performed a retrospective observational review of our practice between October 1998 and December 2019 during which comprehensive records exist. In this period, data for all interventions performed in our centre has systematically been reported to the National Outcomes for Cardiovascular Outcomes Research (NICOR) and our electronic records have been designed to collect relevant data on all patients undergoing aortic surgery. This study was registered in our institution as a service review, therefore ethical approval and informed consent were not deemed necessary. All patients undergoing open DTA or TAAA repair during this period were included. Interventions on the DTA through sternotomy including resection of proximal aorta and arch repairs with frozen elephant trunks, and all endovascular or hybrid interventions were excluded. Data was extracted from our database and included demographics, comorbidity, anatomical and pathological features of aneurysms, morbidity and mortality (at 30 days, in-hospital and during follow-up). The primary outcome measures of the study were 30-day and in-hospital mortality. Secondary outcome measures were the incidence of neurological morbidity (stroke and paraplegia), the incidence of post-operative renal failure requiring haemodialysis and late survival. Other outcomes taken into consideration and reported are mortality by aortic pathology and extend of repaired pathologies (DTA vs TAAA), factors contributing to mortality rates such as age, left ventricular ejection fraction of <30%, urgency of the surgery and timing of operating intervention.

Statistical analysis

Proportions were described with absolute numbers and percentages, and compared with the chi squared test, with a continuity correction for 2 x 2 tables, or the Fisher's Exact test, where cell counts were low. Continuous variables were described with median and interquartile range (IQR), and univariate comparisons were performed with the Mann-Whitney U test. Survival curves were compared with the log-rank test. Logistic regression with backward elimination of unrelated factors was performed to identify independent predictors of in-hospital mortality. Covariates entered in this model were those with a potential association with mortality on univariate analysis ($P < .05$). Data was analysed with SAS version 9.4 (SAS Institute, Cary, North Carolina, USA).

Service arrangements and patient selection

Liverpool Cardiovascular Surgery consists of two major units in our city, which are based at the Liverpool Heart and Chest Hospital (LHCH) and Liverpool University Hospitals Foundation Trust (LUHFT). LUHFT is part of the Liverpool Vascular & Endovascular Service (LiVES), which provides secondary vascular services to Cheshire and Merseyside. Open thoracoabdominal aortic surgery is performed at LHCH by surgeons with a special interest in aortic disease. The service has been in existence for over two decades and its practice has evolved during this period. Patients follow different pathways dependent on their presentation.

1) Elective patient pathway

Patients are referred from either the local catchment area (North West of England, Isle of Man and North Wales) or from other units in the United Kingdom. Where appropriate, they are evaluated in a sub-specialised aortic clinic, set up as a one-stop shop, for surgical and anaesthetic assessment, after appropriate investigations. All candidates for intervention are referred for discussion to the multi-disciplinary team (MDT), which includes cardiac and vascular surgeons, interventional and imaging radiologists, adult and "congenital" cardiologists, clinical geneticists, anaesthetists and a physician with a special interest in vasculitides. The MDT recommends open surgery, endovascular intervention (including complex branched and fenestrated repair, were appropriate) or best medical therapy, according to pathology, aortic anatomy, patient fitness and patient preference.

2) Non-elective patient pathway

All referrals enter the “Liverpool Acute Network for Thoraco-abdominal Aortic Services” (LANTAS) pathway and are discussed within *ad hoc* cross-site “virtual MDTs”, which is able to offer both open, endovascular intervention, and best medical therapy; the default for most patients requiring interventional treatment of acute aortic disease is endovascular repair (TEVAR), where technically possible. Open surgery is preferred in certain cases, particularly in young patients with connective tissue disorders and/or when aortic anatomy is unsuitable for TEVAR. Interventions on non-elective patients are preferentially scheduled on planned, daytime, weekday surgical lists, staffed by experienced members of the aortic team. Patients presenting out of hours, who are relatively stable but require complex surgery, are admitted to critical care for rapid assessment, optimisation and consent. Occasionally, patients require out of hours surgery due to haemodynamic instability on arrival or because they become unstable during the evaluation process.

3) Patient assessment

Patients undergo a typical and basic medical assessment including investigations such as electrocardiography, blood tests and pulmonary function tests. Special investigations include CT angiography of the whole aorta, echocardiography and, if required, coronary angiography (by CT and/or coronary catheterisation) and cardiac stress testing (usually dobutamine stress echocardiography or functional MRI). Where appropriate, we perform dementia and frailty assessment: all patients have a Rockwood score and, if > 4, an Edmonton frailty score. Patients suspected of dementia undergo formal delirium assessment according to local protocols. On the basis of this assessment, suitability for (and risk of) surgery is confirmed by a senior anaesthetist, in consultation with the surgical team, prior to formal consent.

Surgical technique

Surgical technique has evolved during the study period; the following description thus applies to our current approach. Typically, all but the simplest repairs are performed by two experienced aortic surgeons and a consultant anaesthetist with an interest in aortic surgery under general anaesthesia, with double-lumen endotracheal tube, invasive arterial pressure monitoring at multiple sites, trans-oesophageal echocardiography imaging, spinal drainage, motor evoked potentials and near infrared spectroscopy monitoring of bilateral cerebral perfusion. Patients are positioned on their right flank, with the pelvis secured in an open position. The surgical incision depends on the extent of the repair; for an extent II TAAA repair, it consists of a thoraco-laparotomy through the sixth intercostal space continued along the lateral edge of the left rectus abdominis muscle. A short segment of rib is excised posteriorly, and the diaphragm is incised circumferentially, to preserve innervation. The costal margin is transected. The abdominal aorta is exposed retro-peritoneally, whenever possible. The majority of repairs are performed on left heart bypass, with a venous cannula in the inferior pulmonary vein and an arterial cannula at a suitable distal access site, and multiple visceral lines for selective perfusion of the viscera (warm blood for coeliac and mesenteric arteries, cold blood for renal arteries). In these cases, two cell salvage machines and a rapid infuser are used for volume replacement intra-operatively. A minority of repairs are performed on cardiopulmonary bypass with or without deep hypothermic circulatory arrest, in which case cardiotomy suckers are also used to recover blood from the surgical field. Anticoagulation is monitored intra-operatively, with target activated clotting time depending on the type of circulatory support used and the presence of a reservoir. When extensive aortic replacement is needed, whenever possible, sequential clamping and selective re-implantation of key intercostal arteries are used. The repair is often performed beginning distally, in the abdominal aorta, with infra-renal cross-clamping and without circulatory support; then left heart bypass is commenced via a side-arm of the abdominal graft and the repair is extended proximally. Visceral arteries are generally re-implanted via separate grafts rather than as a single patch. Disappearance of motor-evoked potentials during the repair prompts an increase in distal perfusion pressure and/or immediate reimplantation of key intercostal arteries (which is otherwise the last step of the repair). Post-operatively, all patients are managed in critical care according to pre-specified protocols to ensure optimal haemodyamic support and spinal cord perfusion. All patients undergo clinical follow up at six weeks post-discharge, and yearly thereafter (life-long), with yearly cross-sectional imaging of the aorta. Additional clinical follow-up visits and/or aortic imaging are performed if/when clinically indicated.

Results

A total of 430 patients underwent open DTA (n=157) or TAAA repair (n=273) during the study period. Of these, 279 were operated electively and 151 on a non-elective basis, although all but 12 of the non-elective operations were performed within working hours. Median (IQR) age was 62 (47- 71) years for DTA repairs and 64 (53- 71) years for TAAA repairs. Some 154 (34%) were women, 32% in the DTA repair group and 38% in the TAAA repair group. Fifty patients had a proven connective tissue disorder at the time of repair. Most patients had degenerative (n=225) or chronic dissecting (n=113) aneurysms. Smoking habits and comorbid conditions are shown in Table 1: notably, only eight patients had a left ventricular ejection fraction <30% or an eGFR <30 mL/min/1.73m^2.

Forty-eight patients (11.6%) died within 30 days of surgery. Thirty-day mortality was lower after elective surgery (3.1% after DTA repair and 9.9% after TAAA repair), whereas non-elective surgery carried a 30-day mortality of 17.9% (supplementary table 1). An additional 14 patients died in hospital but after 30 days, one after non-elective DTA repair and 13 after TAAA repair (10 elective), all but one extent II. Further analysis of this sub-group demonstrated a significant effect of age on mortality (figure 1). In-hospital mortality for the whole cohort improved over time, as the activity volume increased. This improvement, however, was not evident in patients undergoing extent II TAAA repair (figure 2b).

On univariate analysis, factors associated with in-hospital mortality were: Age ≥ 70, extent II TAAA repair, non-elective surgery, surgery outside working hours, degenerative aetiology (supplementary table 2A). Patients with connective tissue disorders, who largely had surgery for chronic dissection, had a low in-hospital mortality (1/50; 2%). Other comorbidities, use of cardiopulmonary bypass, gender and previous aortic surgery were not associated with in-hospital mortality. In-hospital mortality by aneurysm aetiology is reported in supplementary table 2B. On multivariate analysis, independent variables associated with in-hospital mortality were age ≥70 years, extent II TAAA repair, non-elective surgery, surgery for degenerative aneurysm, out of hours surgery and left ventricular ejection fraction <30% (Table 2). Cause of death was recorded in 42 cases, with multiple organ failure being the commonest (n=24). Of the 14 patients who died after 30 days, seven were on haemodialysis, four had suffered a stroke, two had paraplegia and two paraparesis (a patient with paraparesis was also on haemodialysis). Whilst mortality decreased during the study period, the age of our patients remained constant, whereas the proportion of patients undergoing extent II repair varied significantly, with a peak of almost 50% in 2011/13 (supplementary figures 1-3). Figure 3 shows the 10-year survival curves in the elective and non-elective cohorts undergoing DTA (figure 3a) and TAAA (figure 3b) surgery respectively.

Post-operative complications are reported in table 3: paraplegia was lowest after elective DTA repair and highest after non-elective TAAA repair, whereas the incidence of stroke was highest after extent II and III TAAA repair. A sub-group analysis of morbidity and mortality after elective TAAA repair is reported in supplementary table 3. Median (IQR) critical care stay was 7 (4-19) days; 7 (4-21) days after elective surgery and 8 (4-17) days after non-elective surgery. Median hospital stay ranged from 17 days for elective DTA repairs to 26 days for non-elective TAAA repairs (supplementary table 4).

Discussion

We reported the largest single centre series of consecutive patients undergoing open DTA and TAAA repair in the United Kingdom, with 30-day elective and in-hospital mortality of 7.5% and 11.1% (3% and 3% after DTA repair and 9.9% and 15.5% after TAAA repair) irrespective of pathology or patient factors. Neurological and renal complications were relatively common, especially after TAAA repair. Age, poor left ventricular function, extent of aortic replacement, surgery for degenerative aneurysm and non-elective surgery were strong predictors of in-hospital mortality. In particular, patients aged 70 years or older undergoing extent II TAAA repair had a poor outcome. Ten-year survival was >50% and did not appear to be related to extent of aortic replacement or timing of surgery.

The apparently paradoxical increase in open surgery during the "endovascular era" reflects the gradual increase in out-of-area referrals. Whilst there have been no commissioning changes in the United Kingdom with regards to thoracoabdominal aortic surgery, professional societies have long recognized that the complexity of DTA and TAAA repair requires centralization. Consequently, most British "low volume" surgeons and hospitals have discontinued this type of surgery, choosing, instead, to refer to specialist units. It is notable that our group has been offering fenestrated endovascular aortic repair since 2003.[4] Indeed, the first operation of this type in Britain was performed in Liverpool and branched endovascular aortic repair since 2005.[5] Further drivers of the increase in practice are likely to include advances in operative and perioperative management and increased detection of thoraco-abdominal aortic pathologies.

Comparison with other series can be difficult, as age, aneurysm aetiology, timing of surgery and extent of aortic replacement vary among centres. The literature is dominated by a small group of North American aortic centres, with two Houston groups reporting the largest experiences. Estrera et al. published the outcome of 1896 consecutive patients undergoing DTA or TAAA repair (310 extent II) over 25 years, with a mortality of 15.9%, a need for post-operative haemodialysis of 16.6% and an incidence of post-operative permanent neurological deficit of 7.1%.[6] Coselli et al. reported the outcome of 3309 TAAA repairs (1066 extent II) performed over a period of almost 30 years, with a 7.5% operative mortality (6.2% in elective cases) increasing with age, a need for post-operative haemodialysis of 7.6% and an incidence of post-operative permanent spinal cord deficit of 5.4%.[7] Girardi et al. published the outcome of 783 consecutive patients undergoing DTA or TAAA repair (108 extent II) over 20 years, with a mortality of

5.6%, a need for post-operative haemodialysis of 5.2% and an incidence of post-operative spinal cord deficit of 2.6%.[8] These teams present impressive outcomes within the USA private health care system: no other centre, outside the United States, performs such volumes of work, therefore their results may not be reproducible in other settings. In the United Kingdom, practice in individual centres is very limited,[3,9] with little published data. Such data include a historical case series from St. Mary's hospital in London, which, in 1995, reported the outcome of 110 TAAA repairs (mostly extent IV) treated over a 10-year period, with mortality ranging from 15% after extent IV repairs to 42% after extent II repair (33% overall after elective surgery).[10] More recently, the Edinburgh group reported one death after 53 suprarenal and extent IV TAAA repairs.[11] The same team published the outcome of 37 TAAA repairs (mostly extent IV) performed over a period of 13 years in patients aged <60 years, with a mortality of 6%.[12] In wider Europe, the largest case series are from the Netherlands: some 542 patients underwent TAAA repair (285 extent II) in Nieuwegein over a 20-year period, with an in-hospital mortality of 10.9% and an incidence of permanent spinal neurological deficit of 5.9%; haemodialysis was needed in 23 cases only.[13] In all the publications mentioned above, age and extent of aortic replacement (extent II repair in particular) were associated with poorer outcome. Elective extent II TAAA surgery accounted for the majority of TAAA patients in our series (60%) and, in accordance to the literature, carried the highest 30 day and in-hospital mortality. Death was particularly common in elderly patients (aged 70 and over), with an in-hospital mortality of 50% in this group (9.6% in younger patient), indicating, perhaps, the need for better patient selection of septuagenarians in our practice. Interestingly there was little difference between in-hospital and 30 day mortality in all but the ≥70 year old group suggesting that many such patients may not have the physiological reserve to cope with major post-operative complications (all patients dying after day 30 suffered major renal or neurological morbidity). Clearly the most rigorous assessment is required in elderly patients requiring extent II TAAA repair. It is also important to highlight that our data shows a clear improvement of mortality outcomes in the entire group over time, as activity increased, except for extent II patients, the group dominated by the septuagenarian deaths. The implication of this finding is that patient co-morbidities and poor resilience, rather than team experience, may be the overriding factor in determining outcome in the elderly. It may thus appear that organisation of services and centralisation with a view to concentrating volume may be the key to good outcomes in thoracoabdominal aortic surgery, but that strict patient selection is still needed in the elderly requiring extensive aortic replacement. It is also notable that all patients who died after 30 days had suffered major renal and/or neurological complications, and that the need for renal replacement therapy in our series was high, compared to other studies,[7-8] despite the low prevalence of severe pre-operative renal impairment. It is thus possible that improved prevention of these complications, renal failure in particular, may result in decreased mortality.

Our series of non-elective patients included a proportion of ruptured aneurysms but also a range of pathologies including mycotic processes, infected stents, acute dissections, penetrating atherosclerotic ulcers, intramural haematomata and pseudo-aneurysms. The in-hospital mortality for this very heterogeneous group of patients was 15.3% after DTA repair and 23.9% after TAAA repair. These results compare well to those of a recent systematic review, which reported a mortality of 33.4% independently of the type of pathology and 47.7% in ruptured aneurysms.[1] We prefer to operate on non-elective patients within working hours, when appropriate expertise is available. Our approach to non-elective patients is to shepherd them into a sub-acute or chronic state over days or weeks to optimise their clinical condition prior to working hours intervention. This may entail, in some cases, discharge prior to elective surgery. Patients with haemodynamic instability, malperfusion, traumatic rupture are operated on at the time of presentation regardless of time of the day. Our data showed a mortality of 34.8% for DTA repair and 39.1% for TAAA repair when surgery could not wait and was performed outside of normal working hours. It is unclear whether this higher mortality, which is almost certainly related to the physiological status of the patients at the time of surgery, may also be influenced by not having the full team involved in surgery. The timing of open surgical intervention in patients with acute aortic syndromes has not been explored in literature, thus our work may provide some insight in the matter. Notably, none of our patients died awaiting staged or delayed intervention.

Our study has significant limitations. In particular, it is unclear if our results could be generalised to other units that perform open surgery on the thoraco-abdominal aorta, and whose case-mix may significantly differ from ours. The retrospective nature of the study is also a limitation. Whilst this is mitigated by the quality of the data source (a detailed, prospectively maintained electronic database), it is limited by its scope, its available fields and its completeness, which preclude a more granular analysis of patients' outcome. There are however, in our opinion, some messages that may be generalisable to other centres. Age is a highly significant independent risk factor for mortality outcome. When the whole thoraco-abdominal aorta must be replaced, mortality becomes almost prohibitive in septuagenarians. Surgery is probably best performed by an experienced team within working hours. The risk associated with open surgery on the thoraco-abdominal, the associated high demand on hospital resources and the low frequency at which open procedures are performed strongly suggest, in our opinion, that the management of DTA and TAAA should be centralised in very few dedicated units, where relevant multi-disciplinary expertise is readily available, and where open, endovascular and hybrid techniques can be offered to patients as deemed appropriate. Our data suggest an inverse relationship between overall volume and mortality outcomes apart from extent II TAAA repair in septuagenarians. Septuagenarians require rigorous assessment and consent, particularly in the elective setting. Considering present mortality and morbidity of extent II aortic replacement, more insight on life expectancy and quality of life of patients with type II TAAAs treated conservatively may also be beneficial. National prospective registries could provide invaluable information on outcomes and help define indications and contraindications for surgery.

Conclusion

Open thoracoabdominal aortic surgery is performed infrequently, carries significant risk to life and of serious life changing morbidity, and utilises significant hospital resources. Understanding risks helps guide doctors and patients in their choices and in the consent process.

Author contributions

- All of the authors of this publication made substantial contributions to the design of the work, analysis and interpretation of data.
- All of the authors were involved in the drafting of the work and subsequent revisions.
- All of the authors approve of the final version to be published and agree to be accountable for all aspects of the work.

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Table 1. Comorbidity and smoking habits

	DTA repair (n = 157)	TAAA repair (n = 273)
Body mass index (kg/m^2)	26.7 (24.3, 30.7)	26.1 (22.8, 29.4)
Unstable angina	2 (1.3)	1 (0.4)
NYHA class ≥ III	21 (13.4)	24 (8.8)
Current smoker	24 (15.3)	53 (19.4)
Diabetes	8 (5.1)	16 (5.9)
Hypercholesterolaemia	71 (45.2)	121 (44.3)
Hypertension	98 (62.4)	159 (58.2)
Previous stroke	13 (8.3)	22 (8.1)
Respiratory disease	25 (15.9)	42 (15.4)
On respiratory medications	11 (7.0)	20 (7.3)
FEV1 % predicted	78.6 (66.5, 97.1)	78.2 (64.3, 89.7)
Peripheral artery disease	54 (34.4)	91 (33.3)
eGFR (continuous)	81 (68, 107)	84 (67, 110)
eGFR ≥ 90	60 (38.2)	120 (44.0)
eGFR 60-89	78 (49.7)	110 (40.3)
eGFR 30-59	16 (10.2)	38 (13.9)
eGFR 15-29	2 (1.3)	3 (1.1)
eGFR <15	1 (0.6)	2 (0.7)
Left ventricular ejection fraction 30 - 50%	16 (10.2)	15 (5.5)
Left ventricular ejection fraction <30%	1 (0.6)	7 (2.6)
Non-elective presentation	59 (37.6)	92 (33.7)
Previous aortic surgery operation	55 (35.0)	87 (31.9)
Previous DTA operation	13 (8.3)	11 (4.0)
Previous TAAA operation	4 (2.6)	15 (5.5)
Previous TEVAR operation	5 (3.2)	10 (3.7)

Continuous variables are expressed as median (IQR). Categorical variables are expressed as absolute numbers (%).

NYHA: New York Heart Association; FEV: forced expiratory volume; eGFR: estimate glomerular filtration rate; DTA: descending thoracic aneurysm; TAAA: thoracoabdominal aortic aneurysm.

Table 2. Predictors of in-hospital mortality

	OR (95% CI)	*P* value
Age ≥ 70 years	3.36 (1.79, 6.32)	<0.001
Left ventricular ejection fraction <30%	9.86 (1.91, 50.86)	0.006
TAAA II surgery	4.39 (2.34, 8.21)	<0.001
Out of hours operation	8.17 (2.16, 30.95)	0.002
Non-elective operation	2.72 (1.44, 5.12)	0.002
Degenerative aneurysm pathology	2.20 (1.12, 4.31)	0.02

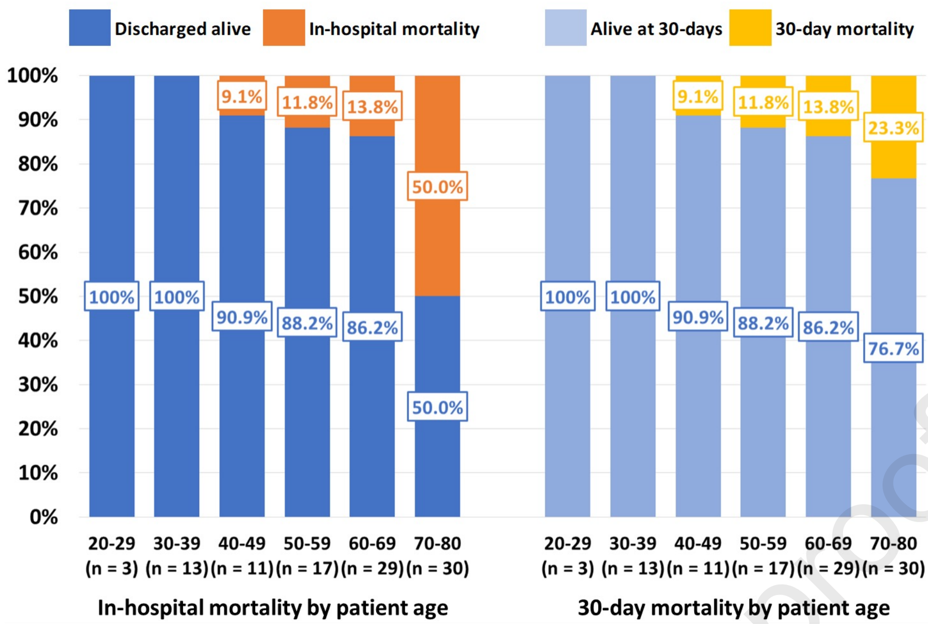
TAAA: thoracoabdominal aortic aneurysm.

Table 3. Post-operative complications

	All repairs			Elective repairs			Non-elective repairs		
	All (n=430)	**DTA (n = 157)**	**TAAA (n = 273)**	**All (n = 279)**	**DTA (n = 98)**	**TAAA (n = 181)**	**All (n=151)**	**DTA (n = 59)**	**TAAA (n = 92)**
Stroke	32 (7.4)	9 (5.7)	23 (8.4)	25 (9.0)	7 (7.1)	18 (9.9)	7 (4.6)	2 (3.4)	5 (5.4)
Paraplegia	13 (3.0)	0	13 (4.8)	6 (2.2)	0 (0)	6 (3.3)	7 (4.6)	0	7 (7.6)
Paraparesis	13 (3.0)	1 (0.6)	12 (4.4)	10 (3.6)	1 (1.0)	9 (5.0)	3 (2.0)	0	3 (3.3)
Return to theatre	33 (7.7)	10 (6.4)	23 (8.4)	24 (8.6)	8 (8.2)	16 (8.8)	9 (6.0)	2 (3.4)	7 (7.6)
Return to theatre for bleeding/tamponade	19 (4.4)	7 (4.5)	12 (4.4)	16 (5.7)	6 (6.1)	10 (5.5)	3 (2.0)	1 (1.7)	2 (2.2)
Acute renal failure	91 (21.2)	13 (8.3)	78 (28.6)	65 (23.3)	10 (10.2)	55 (30.4)	26 (17.2)	3 (5.1)	23 (25.0)
New renal failure requiring dialysis	66 (15.4)	7 (4.5)	59 (21.6)	46 (16.5)	5 (5.1)	41 (22.7)	20 (13.3)	2 (3.4)	18 (19.6)
Post-op creatinine > 200 mmol/L	25 (5.8)	6 (3.8)	19 (7.0)	19 (6.8)	5 (5.1)	14 (7.7)	6 (4.0)	1 (1.7)	5 (5.4)
Intubation time (hours)	22 (12, 81)	17 (11, 43)	27 (16, 90)	24 (14, 92)	19 (11, 75)	28 (17, 99)	19 (12, 56)	15 (11, 29)	24 (16, 77)
Prolonged ventilation (> 48h)	84 (19.5)	27 (17.2)	57 (20.9)	60 (21.5)	20 (20.4)	40 (22.1)	24 (15.9)	7 (11.9)	17 (18.5)
Re-intubation	66 (15.4)	20 (12.7)	46 (16.9)	49 (17.6)	16 (16.3)	33 (18.2)	17 (11.3)	4 (6.8)	13 (14.1)
Tracheostomy	71 (16.5)	20 (12.7)	51 (18.7)	44 (15.8)	11 (11.2)	33 (18.2)	27 (17.9)	9 (15.3)	18 (19.6)
Percutaneous tracheostomy	47 (10.9)	14 (8.9)	33 (12.1)	31 (11.1)	9 (9.2)	22 (12.2)	16 (10.6)	5 (8.5)	11 (12.0)
Mini tracheostomy	21 (4.9)	8 (5.1)	13 (4.8)	13 (4.7)	4 (4.1)	9 (5.0)	8 (5.3)	4 (6.8)	4 (4.4)
Standard tracheostomy	10 (2.3)	2 (1.3)	8 (2.9)	5 (1.8)	1 (1.0)	4 (2.2)	5 (3.3)	1 (1.7)	4 (4.4)
Critical care stay (days)	7 (4, 19)	5 (3, 12)	9 (4, 22)	7 (4, 21)	5 (3, 10)	9 (5, 23)	8 (4, 17)	6 (3, 12)	8 (4, 20)

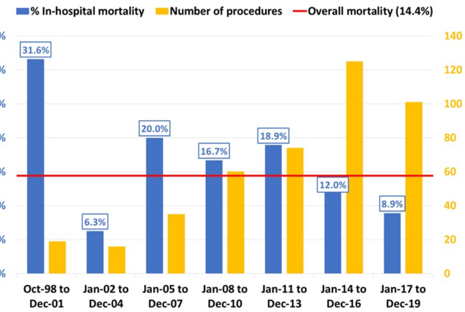
Continuous variables are expressed as median (IQR). Categorical variables are expressed as absolute numbers (%).

DTA: descending thoracic aneurysm; TAAA: thoracoabdominal aortic aneurysm.

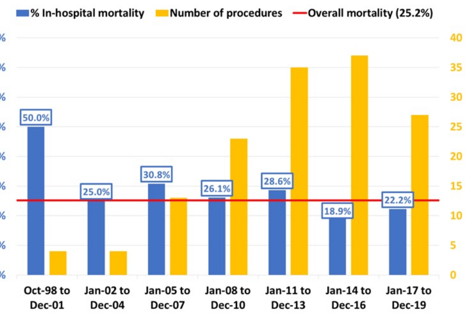


Discharged alive
In-hospital mortality
Alive at 30-days
30-day mortality
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
9.1%
11.8%
13.8%
50.0%
100%
100%
90.9%
88.2%
86.2%
50.0%
9.1%
11.8%
13.8%
23.3%
100%
100%
90.9%
88.2%
86.2%
76.7%
20-29 (n = 3)
30-39 (n = 13)
40-49 (n = 11)
50-59 (n = 17)
60-69 (n = 29)
70-80 (n = 30)
20-29 (n = 3)
30-39 (n = 13)
40-49 (n = 11)
50-59 (n = 17)
60-69 (n = 29)
70-80 (n = 30)
In-hospital mortality by patient age
30-day mortality by patient age

a


% In-hospital mortality
Number of procedures
Overall mortality (14.4%)
35%
30%
25%
20%
15%
10%
5%
0%
140
120
100
80
60
40
20
0
31.6%
6.3%
20.0%
16.7%
18.9%
12.0%
8.9%
Oct-98 to Dec-01
Jan-02 to Dec-04
Jan-05 to Dec-07
Jan-08 to Dec-10
Jan-11 to Dec-13
Jan-14 to Dec-16
Jan-17 to Dec-19

b


% In-hospital mortality
Number of procedures
Overall mortality (25.2%)
80%
70%
60%
50%
40%
30%
20%
10%
0%
40
35
30
25
20
15
10
5
0
50.0%
25.0%
30.8%
26.1%
28.6%
18.9%
22.2%
Oct-98 to Dec-01
Jan-02 to Dec-04
Jan-05 to Dec-07
Jan-08 to Dec-10
Jan-11 to Dec-13
Jan-14 to Dec-16
Jan-17 to Dec-19

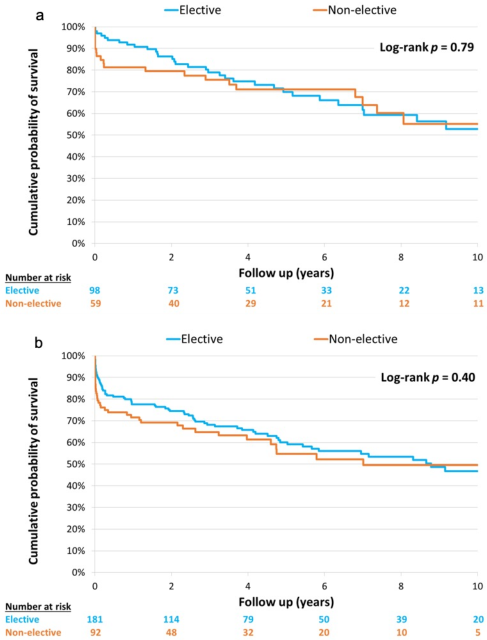

a
Elective
Non-elective
Log-rank p = 0.79
Cumulative probability of survival
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
2
4
6
8
10
Follow up (years)
Number at risk
Elective 98 73 51 33 22 13
Non-elective 59 40 29 21 12 11
b
Elective
Non-elective
Log-rank p = 0.40
Cumulative probability of survival
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
2
4
6
8
10
Follow up (years)
Number at risk
Elective 181 114 79 50 39 20
Non-elective 92 48 32 20 10 5

Figure legends

Figure 1 – Mortality after extent II Thoracoabdominal aortic aneurysm repair by age

Figure 2 – Relationship between operative volume, in-hospital mortality and time

a. Whole cohort
b. Extent II Thoracoabdominal aortic aneurysm repair

Figure 3 – 10-year survival stratified by priority

a. Descending thoracic aneurysm repair
b. Thoracoabdominal aortic aneurysm repair

Supplementary figure 1 – Patient age during the study period

Supplementary figure 2 - Estimated probability of in-hospital mortality during the study period

Supplementary figure 3 – Proportion of patients undergoing extent II repair during the study period

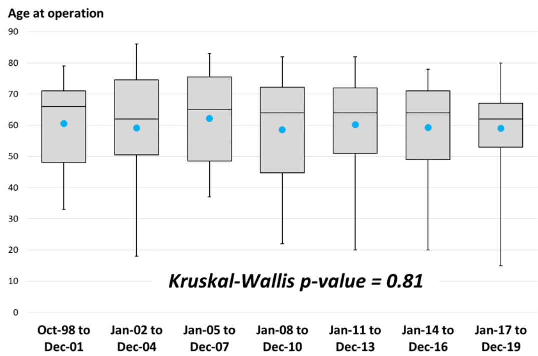
Supplementary tables

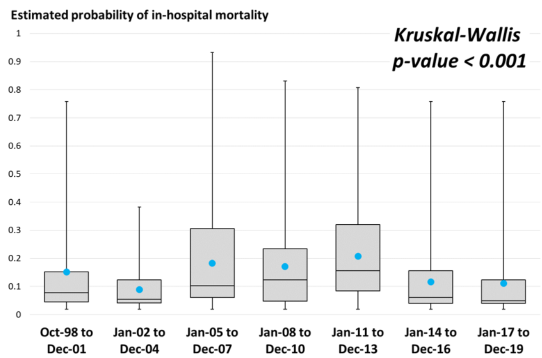
Supplementary table 1: Mortality by type and timing of surgery

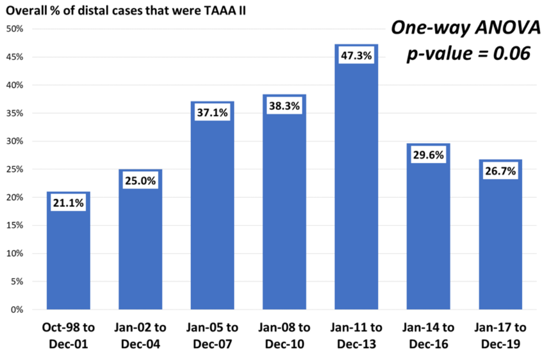
Supplementary table 2. Factors associated with in-hospital mortality on univariate analysis (A) and In-hospital mortality by aneurysm aetiology (B)

Supplementary table 3: Outcome after elective TAAA repair

Supplementary table 4: Hospital stay by type of surgery and timing


Age at operation
90
80
70
60
50
40
30
20
10
0
Kruskal-Wallis p-value = 0.81
Oct-98 to Dec-01
Jan-02 to Dec-04
Jan-05 to Dec-07
Jan-08 to Dec-10
Jan-11 to Dec-13
Jan-14 to Dec-16
Jan-17 to Dec-19


Estimated probability of in-hospital mortality
Kruskal-Wallis
p-value < 0.001
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Oct-98 to Dec-01
Jan-02 to Dec-04
Jan-05 to Dec-07
Jan-08 to Dec-10
Jan-11 to Dec-13
Jan-14 to Dec-16
Jan-17 to Dec-19


Overall % of distal cases that were TAAA II
One-way ANOVA
p-value = 0.06
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
21.1%
25.0%
37.1%
38.3%
47.3%
29.6%
26.7%
Oct-98 to Dec-01
Jan-02 to Dec-04
Jan-05 to Dec-07
Jan-08 to Dec-10
Jan-11 to Dec-13
Jan-14 to Dec-16
Jan-17 to Dec-19

Supplementary table 1: Mortality by type and timing of surgery

	n	In-hospital mortality	30-day mortality
All	430	62 (14.4)	48 (11.6)
Elective cases	279	31 (11.1)	21 (7.5)
Non-elective cases	151	31 (20.5)	27 (17.9)
TAAA	273	50 (18.3)	37 (13.6)
Elective cases	181	28 (15.5)	18 (9.9)
Non-elective cases	92	22 (23.9)	19 (20.7)
DTA	157	12 (7.6)	11 (7.0)
Elective cases	98	3 (3.1)	3 (3.1)
Non-elective cases	59	9 (15.3)	8 (13.6)

Values are absolute numbers (%).

DTA: descending thoracic aneurysm; TAAA: thoracoabdominal aortic aneurysm.

Supplementary table 2. Factors associated with in-hospital mortality on univariate analysis (A) and In-hospital mortality by aneurysm aetiology (B)

A. Factors associated with in-hospital mortality on univariate analysis	**Discharged alive (n = 368)**	**Died in-hospital (n = 62)**	***P***
DTA repair	145 (39.4)	12 (19.4)	0.002
TAAA repair	223 (60.6)	50 (80.6)	
Extent I-III-IV-V	127 (34.5)	10 (16.1)	0.004
Extent II	107 (29.1)	36 (58.1)	<0.001
Age at operation (years)	62 (48, 70)	71 (62, 73)	<0.001
Age ≥ 70 years	93 (25.3)	32 (51.6)	<0.001
Left ventricular ejection fraction <30%	4 (1.1)	4 (6.5)	0.02
Non-elective operation	120 (32.6)	31 (50.0)	0.008
Out of hours operation	5 (1.4)	7 (11.3)	<0.001
Degenerative aneurysm	180 (48.9)	45 (72.6)	<0.001
Chronic dissection	105 (28.5)	8 (12.9)	0.01
B. In-hospital mortality by aneurysm aetiology			
Degenerative	180 (48.9)	45 (72.6)	<0.001
Chronic dissection	105 (28.5)	8 (12.9)	0.01
Ruptured	18 (4.9)	2 (3.2)	0.75
Penetrating ulcer	13 (3.5)	0 (0)	0.38
Acute dissection	9 (2.4)	2 (3.2)	0.66
Mycotic	13 (2.5)	3 (4.8)	0.71
Traumatic	7 (1.9)	0 (0)	0.60
Intramural haematoma	3 (0.8)	1 (1.6)	0.46
Post-coarctation	6 (1.6)	0 (0)	0.60
Other congenital	2 (0.5)	0 (0)	>0.99
Pseudoaneurysm	6 (1.6)	0 (0)	0.60
Other	6 (1.6)	1 (1.6)	>0.99

DTA: descending thoracic aneurysm; TAAA: thoracoabdominal aortic aneurysm. Continuous variables are expressed as median (IQR). Categorical variables are expressed as absolute numbers (%).

Supplementary table 3 – Outcome after elective TAAA repair

	TAAA I (n = 35)	TAAA II (n = 104)	TAAA III (n = 28)	TAAA IV (n = 10)	TAAA V (n = 4)
In-hospital mortality	1 (2.9)	22 (21.2)	4 (14.3)	0	1 (25.0)
Stroke	2 (5.7)	13 (12.5)	3 (10.7)	0	0
Paraplegia	1 (2.9)	4 (3.9)	1 (3.6)	0	0
Paraparesis	0	5 (4.8)	2 (7.1)	0	2 (50.0)
Return to theatre	0	13 (12.5)	1 (3.6)	1 (10.0)	1 (25.0)
Return to theatre for bleeding/tamponade	0	8 (7.7)	1 (3.6)	1 (10.0)	0 (0)
Acute renal failure	3 (8.6)	36 (34.6)	12 (42.9)	1 (10.0)	3 (75.0)
New renal failure requiring dialysis	3 (8.6)	26 (25.0)	9 (32.1)	1 (10.0)	2 (50.0)
Postoperative creatinine >200 mmol/L	0	10 (9.6)	3 (10.7)	0	1 (25.0)
Intubation time (hours)	25 (16, 72)	39 (19, 216)	20 (11, 72)	48 (17, 85)	24 (7, 1000)
Prolonged ventilation (> 48h)	8 (22.9)	24 (23.1)	5 (17.9)	2 (20.0)	1 (25.0)
Re-intubation	4 (11.4)	21 (20.2)	4 (14.3)	2 (20.0)	2 (50.0)
Tracheostomy	4 (11.4)	21 (20.2)	4 (14.3)	2 (20.0)	2 (50.0)
Percutaneous tracheostomy	3 (8.6)	13 (12.5)	4 (14.3)	1 (10.0)	1 (25.0)
Mini tracheostomy	1 (2.9)	7 (6.7)	0	1 (10.0)	0
Standard tracheostomy	0	2 (1.9)	0	1 (10.0)	1 (25.0)
ITU stay (days)	6 (4, 19)	9 (5, 29)	9 (4, 22)	14 (7, 22)	12 (2, 33)
Post-operative stay (days)	15 (11, 29)	21 (13, 37)	18 (13, 25)	21 (18, 34)	30 (14, 46)

Continuous variables are expressed as median (IQR). Categorical variables are expressed as absolute numbers (%). TAAA: thoracoabdominal aortic aneurysm.

Supplementary table 4: Hospital stay by type of surgery and timing

	n	Pre-operative (days)	Post-operative (days)	Total (days)
All cases	430	1 (1, 3)	17 (10, 30)	20 (13, 34)
Elective	279	1 (1, 1)	17 (11, 30)	19 (12, 32)
Non-elective	151	3 (1, 8)	15 (9, 29)	21 (13, 37)
TAAA repair	273	1 (1, 3)	18 (11, 34)	22 (14, 38)
Elective	181	1 (1, 2)	19 (12, 34)	21 (14, 35)
Non-elective	92	4 (1, 10)	18 (10, 36)	26 (14, 45)
DTA repair	157	1 (1, 2)	15 (9, 22)	17 (10, 25)
Elective	98	1 (1, 1)	16 (9, 22)	17 (10, 25)
Non-elective	59	2 (1, 4)	13 (9, 20)	17 (11, 25)

Values are medians (IQR).

DTA: descending thoracic aneurysm; TAAA: thoracoabdominal aortic aneurysm.