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The effect of aortic arch replacement on pulse wave velocity after surgery

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Key question

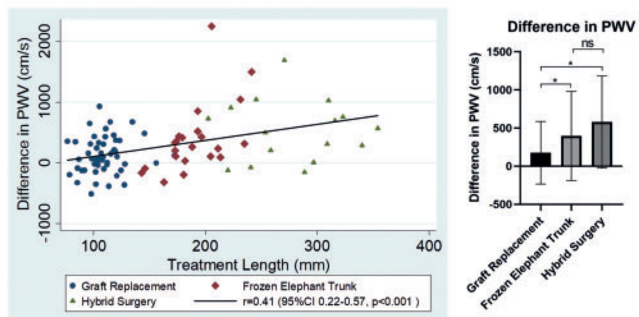
What are the factors that minimize the changes in pulse wave velocity (PWV) after aortic arch replacement?

Key finding(s)

Treatment length and postoperative beta blockers were associated with changes in PWV.

Take-home message

Minimizing the treatment length and use of postoperative beta blockers may attenuate the effect of a prosthesis on postoperative PWV.



Abstract

OBJECTIVES: The purpose of this study was to investigate the changes in pulse wave velocity (PWV) after aortic arch repair and to evaluate possible perioperative factors associated with an increase in PWV.

METHODS: Eighty-nine patients with preoperative and postoperative PWV measurements who underwent surgical treatment for true aortic arch aneurysm were included in the study. The patients were treated by prosthetic graft replacement with or without the frozen elephant trunk technique or by hybrid surgery with a stent graft. Changes in PWV and perioperative factors were evaluated.

RESULTS: Fifty-one patients were treated by prosthetic graft replacement; 22 patients were treated with the frozen elephant trunk procedure; and 16 patients were treated by hybrid surgery. A significant increase in PWV was observed in patients undergoing surgical treatment for aortic arch aneurysm regardless of the types of operations performed (all treatments: before, 1797 ± 397.8 cm/s vs after, 2061 ± 600.4 cm/s, $P < 0.001$; graft replacement: before, 1769 ± 398.1 cm/s vs after, 1895 ± 459.0 cm/s, $P = 0.004$; frozen elephant trunk procedure: before, 1911 ± 461.9 cm/s vs after 2307 ± 826.9 cm/s, $P = 0.005$; hybrid surgery: before, 1732 ± 273.3 cm/s vs after, 2254 ± 484.6 cm/s, $P < 0.001$). Differences in PWV were largest in patients treated with hybrid surgery and lowest in those treated with graft replacement ($P = 0.002$). In univariate analysis, an increase in PWV was positively correlated with treatment length ($r = 0.41$; $P < 0.001$); the use of a postoperative beta blocker was associated with a smaller increase in postoperative PWV (with: 165.0 ± 371.92 cm/s vs without: 439.4 ± 530.38 cm/s, $P = 0.005$). Multivariate analysis suggested that treatment length (coefficient 3.31, 95% confidence interval 0.056–6.562, $P = 0.046$) and postoperative beta blocker (coefficient −220.08, 95% confidence interval −401.972 to −38.183, $P = 0.018$) were factors independently associated with changes in PWV.

CONCLUSIONS: There was a significant increase in PWV after aortic arch repair. Treatment length and use of postoperative beta blockers were factors associated with changes in postoperative PWV. Minimizing the treatment length and using postoperative beta blockers may attenuate the effects of prostheses on postoperative PWV.

Keywords: Pulse wave velocity • Graft replacement • Frozen elephant trunk • Aortic arch aneurysm • Hybrid surgery • Treatment length

ABBREVIATIONS

CI	Confidence interval
PWV	Pulse wave velocity

INTRODUCTION

With advancements in surgical technology, many surgical approaches are available for treating aortic arch aneurysms. Although prosthetic graft replacement is the basic approach, use of the frozen elephant trunk technique has simplified surgical strategy by allowing surgeons to treat aortic arch aneurysm using a more proximal anastomosis. Further, hybrid surgery, which is a combination of graft replacement and stent-graft treatment, has allowed surgeons to treat patients with an aortic arch aneurysm extending to the descending aorta without the need for a left thoracotomy. These technologies have enabled the surgical treatment of more extensive aortic arch aneurysms requiring longer treatments.

Although aneurysms are treated for risk of aortic rupture, physiological changes after aortic surgery have been reported that may affect long-term outcomes [1–3]. Pulse wave velocity (PWV), which measures the velocity of blood flow in the circulatory system, is used to evaluate aortic stiffness. Replacement of aortic tissue with a prosthesis has been reported to increase PWV postoperatively. An increase in PWV results in aortic compliance mismatch, which increases the risk for long-term cardiovascular and cerebrovascular events [4–7]. Previous reports have shown that an increase in PWV after stent graft treatment of an aortic aneurysm was associated with changes in left ventricular dimensions, reduced left ventricular ejection fraction and diastolic dysfunction [1, 3, 8].

Although the frozen elephant trunk technique and the hybrid approach with a stent graft are useful in treating an extended aortic arch aneurysm, they are accompanied by a longer length of treatment due to the need for a landing zone. The purpose of this study was to investigate the changes in PWV in patients undergoing surgical treatment of an aortic arch aneurysm and to evaluate possible perioperative factors associated with an increase in PWV. The null hypotheses of this study were (i) there is no significant increase in PWV in patients undergoing surgical treatment for aortic arch aneurysm; (ii) surgical strategy does not affect PWV after surgery; and (iii) treatment length does not affect increase in PWV after surgery.

The result of this study may provide suggestions for modifying our surgical strategy and perioperative care to reduce the effect of surgery on PWV, thus reducing the risk for cardiovascular events in patients undergoing surgical repair for an aortic arch aneurysm.

PATIENTS AND METHODS

Ethical statement

The institutional review board of Saitama Medical Center, Jichi Medical University, approved the study and waived the need for informed consent (S20-204).

Patients

As a preoperative screening test, PWV has been measured in our daily clinical practice. Postoperative PWV measurements were also performed according to the preference of the surgeon. Patients included in this study were selected beginning in July 2009, which was when we started our endovascular programme. Patients seen through May 2021 were included to obtain as large a sample size as possible.

From July 2009 to May 2021, 388 patients underwent surgical treatment for an aortic arch aneurysm. Of these patients, 241 were treated for a true aortic aneurysm. A total of 105 patients had preoperative and postoperative PWV measurements that were obtained within 1 year of the operation. Patients were excluded from the study if systolic blood pressure measured at the time of the preoperative and postoperative PWV measurements differed by 20mmHg or more (Fig. 1). Systolic blood pressure of 20mmHg was chosen as a cut-off value based on the results of the previous study, which showed that a systolic blood pressure difference of 10–20mmHg showed a 40–90 cm/s difference in PWV, whereas a difference in the systolic blood pressure of 20–30mmHg was associated with 100–180 cm/s difference in PWV [9]. Overall, 89 patients were included in the study. Fifty-one patients were treated by prosthetic graft replacement, 22 patients were treated with the frozen elephant trunk technique and 16 patients were treated with hybrid surgery. Hybrid surgery comprised a combination of graft replacement and a stent graft in which a prosthetic graft was used as a landing zone for a stent graft.

Surgical strategy

Surgery was performed as previously described [10, 11]. For graft replacement, a J-Graft (Japan Lifeline Co., Ltd, Tokyo, Japan), Hemashield (Getinge, Goteborg, Sweden) and Triplex (Terumo, Tokyo, Japan) were used. Hemashield and Triplex were used in

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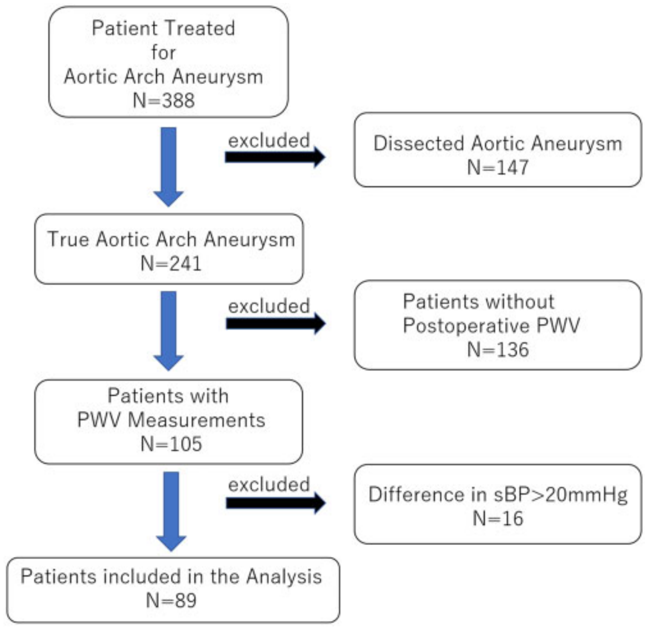


Figure 1: Flow chart of patient selection for this study. PWV: pulse wave velocity; sBP: systolic blood pressure.

2009, whereas the use of the J-Graft began in 2013. The type of graft used represented the preference of the surgeon. The commercially available stent graft cTAG (W.L. Gore & Associates, Inc., Newark, DE, USA) was available from 2009, followed by Talent and Valiant (Medtronic, Minneapolis, MN, USA) in 2010 and 2012, Zenith TX (Cook Medical, Bloomington, IN, USA) in 2011 and Relay (Bolton Medical, Sunrise, FL, USA) in 2013. Hybrid surgery was first performed in 2015, and the frozen elephant trunk technique was first used in 2016 with the introduction of the device (Frozenix: Japan Lifeline Co., Ltd, Tokyo, Japan). There were no changes in the strategy for performing an anastomosis, the cardiopulmonary bypass plan, anaesthesia and postoperative care during this period.

Pulse wave velocity measurement

The brachial-ankle PWV measurement was performed by a non-invasive device (Omron Colin, Tokyo, Japan). Simultaneous non-invasive recordings of the 2 different pulse waves were measured with pressure-sensitive transducers placed on the arm and the ankle. The pulse transit time and the distance between the transducers over the body surface were used to calculate PWV [PWV (cm/s) 1/4 travel distance (cm)/transit time (s)] [12]. PWV measurement was performed in the physiology laboratory, and the measurements were submitted as an official document by a board-certified clinical technician.

Data analyses

Normal distribution of the data was evaluated using the Kolmogorov–Smirnov test. For continuous variables, normally distributed data were analysed by the *Student's t-test* for comparing 2 groups (mean ± standard deviation); the analysis of variance test (mean ± standard deviation) was used to evaluate more than 3 groups. For non-normally distributed data, the Mann–Whitney test (median, Q1–3) was used to compare 2 groups and the Kruskal–Wallis test (median, Q1–3) was used to compare more than 3 groups. For the evaluation of paired variables, the paired *t*-test was used. The Fisher exact test (*n*, %) was used for categorical variables and Pearson's correlation coefficient was used to evaluate the correlation between continuous variables. Changes in PWV, before and after surgery, for each individual were evaluated by the paired *t*-test. Further, changes in PWV were evaluated by 2 variables: treatment length and procedure type. For PWV analysis, measurement of the right side was used, which may have less effect on PWV because the left subclavian artery in some patients was reconstructed via a bypass to the left axillary artery. A linear regression model for the difference in PWV was performed for the multivariate analysis including treatment length, surgical strategy and variables with $P < 0.10$ in the univariate analysis. *P* values <0.05 were considered significant, and the analysis was performed using Stata (version 13.1, Stata Corp, College Station, TX, USA) and Prism (version 8.0.2, GraphPad Software Inc., La Jolla, CA, USA). The data underlying this article will be shared on reasonable request to the corresponding author.

RESULTS

The demographics of the patients are shown in Table 1. There was a significant difference in the age of patients treated by graft replacement and those treated with the frozen elephant trunk technique (graft replacement: 68 ± 12.1 years vs frozen elephant trunk: 76 ± 7.6 years, $P = 0.017$). There was no significant difference in male gender (graft replacement: 70.6% vs frozen elephant trunk technique: 77.3% vs hybrid surgery: 68.8%, $P = 0.94$) among the 3 different types of treatments. No significant differences were observed in the prevalence of hypertension ($P = 0.91$), hyperlipidaemia ($P = 0.23$) and diabetes ($P = 1.0$). A significant difference was observed in the treatment length among the 3 groups (graft replacement: 109.0 ± 18.0 mm vs frozen elephant trunk technique: 189.9 ± 26.1 mm vs hybrid surgery: 278.3 ± 45.6 mm, $P < 0.001$; Table 1).

There was a significant increase in PWV in patients undergoing aortic arch repair (before: 1797 ± 397.8 cm/s vs after: 2061 ± 600.4 cm/s, $P < 0.001$; Fig. 2A). Further, a significant increase in PWV after surgery was observed in all types of treatments (graft replacement: before, 1769 ± 398.1 cm/s vs after, 1895 ± 459.0 cm/s, $P = 0.004$; frozen elephant trunk technique: before 1911 ± 461.9 cm/s vs after 2307 ± 826.4 cm/s, $P = 0.005$; hybrid surgery: before, 1732 ± 273.3 cm/s vs after 2254 ± 484.6c m/s, $P < 0.001$; Fig. 2B-D). In comparison with graft replacement, there was a significant difference in changes in preoperative and postoperative PWV for patients undergoing the frozen elephant trunk technique (graft replacement: 126.1 ± 302.1 cm/s vs frozen elephant trunk technique: 395.1 ± 584.9 cm/s, $P = 0.046$) and hybrid surgery (graft replacement: 126.1 ± 302.1 cm/s vs hybrid surgery: 521 ± 506.7 cm/s, $P = 0.005$). However, there was no significant difference between patients undergoing the frozen elephant trunk technique and hybrid surgery (frozen elephant trunk technique: 395.1 ± 584.9 cm/s vs hybrid surgery: 521.4 ± 506.7 cm/s, $P = 1.0$; Fig. 3).

There was a significant correlation between treatment length and changes in PWV postoperatively ($r = 0.41$, 95% confidence interval (CI) 0.22–0.57, $P < 0.001$; Fig. 4). In the subanalysis of each treatment, significant correlation between treatment length and change in PWV was observed in patients treated by the frozen elephant trunk technique ($r = 0.59$, 95% CI 0.22–0.81, $P = 0.004$). In

Table 1: Demographics of the patients included in the study

	Total *n* = 89	Graft replacement *n* = 51	Frozen elephant trunk procedure *n* = 22	Hybrid surgery *n* = 16	*P*-value
Age (years), mean ± SD	70 ± 10.6	68 ± 12.1	76 ± 7.6	71 ± 5.0	0.012
Gender (male), *n* (%)	64 (71.9)	36 (70.6)	17 (77.3)	11 (68.8)	0.94
Hypertension, *n* (%)	78 (87.6)	44 (86.3)	20 (90.9)	14 (87.5)	0.91
Hyperlipidaemia, *n* (%)	43 (48.3)	23 (45.1)	14 (63.6)	6 (37.5)	0.23
Diabetes, *n* (%)	15 (16.9)	9 (17.6)	4 (18.2)	2 (12.5)	1
Current smoker, *n* (%)	20 (22.5)	12 (23.5)	3 (13.6)	5 (31.3)	0.42
Angiotensin receptor blocker, *n* (%)	53 (59.6)	33 (64.7)	11 (50.0)	9 (56.3)	0.46
Calcium channel blocker, *n* (%)	62 (69.7)	36 (70.6)	14 (63.6)	12 (75.0)	0.61
Beta blocker, *n* (%)	30 (33.7)	16 (31.4)	7 (31.8)	7 (43.8)	0.65
HMG-CoA inhibitor, *n* (%)	40 (44.9)	23 (45.1)	11 (50.0)	6 (37.5)	0.77
Type of prosthetic graft used					0.25
J Graft, *n* (%)	64 (71.9)	34 (66.7)	19 (86.4)	11 (68.7)	
Triplex, *n* (%)	14 (15.7)	8 (15.7)	3 (13.6)	3 (18.8)	
Hemashield, *n* (%)	11 (12.4)	9 (17.6)	0 (0.0)	2 (12.5)	
Creatinine (mg/dl), mean ± SD	0.95 ± 0.413	0.97 ± 0.519	0.94 ± 0.224	0.92 ± 0.155	0.92
Haemoglobin (g/dl), mean ± SD	13.0 ± 1.54	13.0 ± 1.61	13.1 ± 1.59	12.7 ± 1.29	0.79
Left ventricular ejection fraction (%), mean ± SD	64 ± 8.0	64 ± 6.5	63 ± 11.4	65 ± 7.2	0.75
Preoperative pulse wave velocity (cm/s), mean ± SD	1797 ± 397.8	1769 ± 398.1	1911 ± 461.9	1732 ± 273.3	0.29
Postoperative pulse wave velocity (cm/s), mean ± SD	2061 ± 600.4	1895 ± 459.0	2307 ± 826.4	2254 ± 484.6	0.009
Preoperative systolic blood pressure (mmHg), mean ± SD	123 ± 15.6	122 ± 16.8	127 ± 13.9	120 ± 14.0	0.41
Postoperative systolic blood pressure (mmHg), mean ± SD	122 ± 16.4	123 ± 17.8	120 ± 12.2	120 ± 17.7	0.7
Treatment length (mm), mean ± SD	160 ± 70.4	109 ± 18.0	189.9 ± 26.1	278.3 ± 45.6	<0.001

SD: standard deviation.

these patients, there was no correlation between the length of the stented portion and the change in PWV ($r = 0.20$, 95% CI −0.246 to 0.571, $P = 0.38$). However, there was a significant correlation between the length of the graft portion and the difference in PWV ($r = 0.46$, 95% CI 0.044–0.737, $P = 0.032$). No significant correlation was observed in treatment length and change in PWV in patients treated by graft replacement ($r = 0.13$, 95% CI −0.15 to 0.39, $P = 0.35$) and hybrid surgery ($r = 0.01$, 95% CI −0.49 to 0.50, $P = 0.98$; Fig. 4).

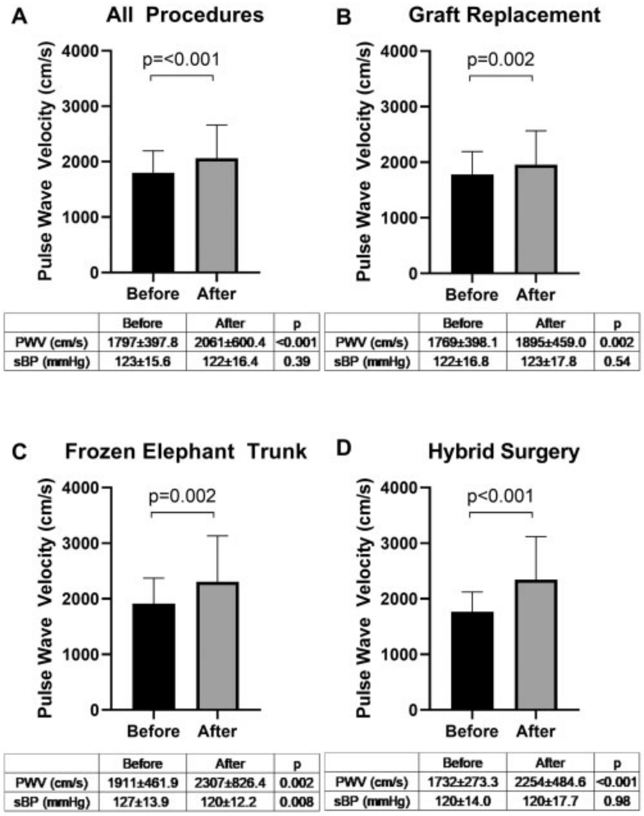
In the univariate analysis, the use of postoperative beta blockers was associated with fewer changes in PWV after surgery (with beta blocker: 165.0 ± 371.92 cm/s vs without beta blocker: 439.4 ± 530.38 cm/s, $P = 0.005$; Table 2). Although it was not statistically significant, there also was a trend towards a positive correlation between age and a difference in PWV ($r = 0.20$, 95% CI −0.0124 to 0.389, $P = 0.07$; Table 3). For the multivariate analysis, type of surgery, treatment length and variables with $P < 0.1$ in the univariate analysis were included. The difference in the systolic blood pressure at the time of PWV measurements was also added for a possible influence on PWV measurement, because a decrease in PWV was observed postoperatively in some patients that may have been due to decreased changes in blood pressure. A linear regression model showed that treatment length (coefficient 3.31, 95% CI 0.056–6.562, $P = 0.046$) and postoperative beta blockers (coefficient −220.08, 95% CI −401.972 to −38.183, $P = 0.018$) were independently associated with changes in PWV. The type of surgery performed was not an independent factor associated with the increase in PWV (Table 4).

DISCUSSION

Systemic haemodynamics is depended on the individual's cardiac function, valvular function, aortic compliance and peripheral resistance. In the circulatory system, compliance of the aorta acts as the *Windkessel*, which manages pulsatile flow to the peripheral vessels. PWV, which is a measure of blood flow velocity, increases with loss of aortic compliance [2]. As the PWV increases, the backward wave from the peripheral vessels reaches the ascending aorta during systole, which results in increased systolic pressure and decreased diastolic pressure. Increase in pulse pressure and in systemic afterload leads to major cardiac and cerebrovascular events. It is also known to affect renal function by damaging the microvascular system [4, 5, 7, 13].

With ageing, loss of aortic compliance occurs due to atherosclerotic changes. This phenomenon has been shown in previous reports in which the brachial-ankle PWV was positively correlated with ageing [14, 15]. Loss of aortic compliance may also occur in patients having aortic surgery in which the compliant aorta is replaced by a prosthesis. Although the aneurysm is already a diseased aorta itself, previous reports have shown a significant increase in PWV in patients undergoing endovascular treatment of aortic aneurysms [1, 16, 17]. The increase in PWV was also associated with worse long-term outcomes and cardiac diastolic dysfunction [1, 3]. Although the reliability of the PWV measurement device could be a concern, a previous report has shown that non-invasive devices including Complior Analyse (Alam Medical, Saint Quentin Fallavier, France); PulsePen ETT and PulsePen ET (DiaTecne, Milan, Italy) and SphygmoCor (CardieX, Sydney, NSW, Australia) appear to be reliable compared to invasive aortic PWV measurement methods [18]. The Colins system, which was used in our study, also showed a strong positive correlation and agreement with the SphygmoCor system measurement [19]. Further, the Colins system has been used in several studies to prove an association of PWV with cardiovascular diseases [19–21].

Previous studies have shown controversial results for changes in aortic stiffness in patients undergoing graft replacement of the



	Before	After	p
PWV (cm/s)	1797±397.8	2061±600.4	<0.001
sBP (mmHg)	123±15.6	122±16.4	0.39

	Before	After	p
PWV (cm/s)	1769±398.1	1895±459.0	0.002
sBP (mmHg)	122±16.8	123±17.8	0.54

	Before	After	p
PWV (cm/s)	1911±461.9	2307±826.4	0.002
sBP (mmHg)	127±13.9	120±12.2	0.008

	Before	After	p
PWV (cm/s)	1732±273.3	2254±484.6	<0.001
sBP (mmHg)	120±14.0	120±17.7	0.98

Figure 2: Bar graph of preoperative and postoperative pulse wave velocity (mean ± standard deviation). There was a significant increase in pulse wave velocity in patients undergoing surgical treatment for aortic arch aneurysm (**A**), graft replacement (**B**), the frozen elephant trunk technique (**C**) and hybrid surgery (**D**). There were no significant differences in preoperative pulse wave velocity among the 3 different procedures (graft replacement: 1769 ± 398.1 cm/s vs frozen elephant trunk technique: 1911 ± 461.9 cm/s vs hybrid surgery: 1732 ± 273.3 cm/s, $P = 0.29$). PWV: pulse wave velocity; sBP: systolic blood pressure.

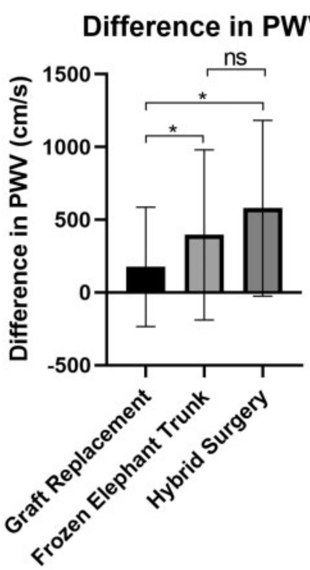


Figure 3: Bar graph of changes in pulse wave velocity for each type of surgery performed (mean ± standard deviation). There was a significant difference in changes in pulse wave velocity in patients undergoing the frozen elephant trunk technique and hybrid surgery in comparison with graft replacement. *$P < 0.05$. PWV: pulse wave velocity.

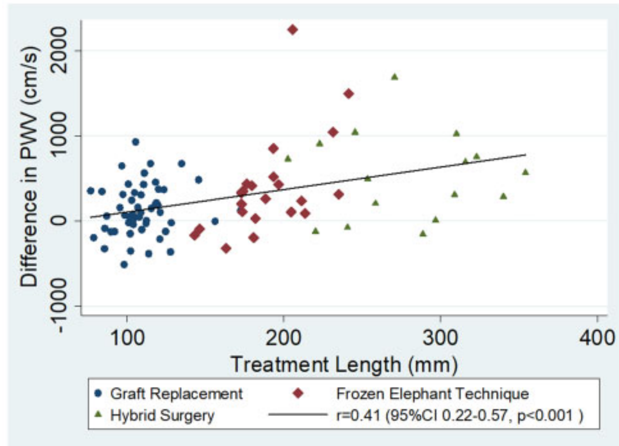


Figure 4: Scatter plot of changes in pulse wave velocity and treatment length. There was a positive correlation between treatment length and difference in pulse wave velocity. PWV: pulse wave velocity.

ascending aorta [4, 22]. The aortic arch, which is a small portion of the total aorta, contributes ∼50% of the total arterial compliance; thus, anatomical changes in the aortic arch may have a profound impact on systemic compliance [2]. With introduction of the frozen elephant trunk procedure and hybrid surgery via a stent graft, management of the aortic arch aneurysm has changed due to the reduced mortality and morbidity [23, 24]. Surgical solutions to overcome the anatomical difficulty of the aortic arch have been managed using these technologies. However, the physiological effects of these technologies on arterial compliance are not well known.

The present study showed that prosthetic graft replacement also has an effect on PWV after surgery. The major differences in the prosthetic graft and the stent graft can be seen in their respective designs: The stent graft comprises a stent skeleton with a fabric sewed onto it, whereas the prosthetic graft is made only from fabric. The fabric is thinner in stent grafts, but compliance may be less affected in the prosthetic graft due to the absence of a stented skeleton. Another difference can be seen in the placement of these devices. The stent graft is placed within the aorta, which is to be surrounded and contained by intra-aortic thromboses. On the other hand, the prosthetic graft replaces the diseased aorta, and the graft itself is not restricted within the diseased aorta, except for the postoperative adhesion from the surrounding tissue, which may have an effect on its compliance. Differences in prostheses may have different effects on PWV. The present study showed that hybrid surgery with a stent graft was associated with the greatest increase in PWV followed by the frozen elephant trunk procedure and graft replacement, respectively. However, these techniques are also strongly associated with treatment length, in which hybrid surgery is performed in patients with the most extensive aortic diseases. Multivariate analysis in the present study showed that treatment length was an independent risk factor for an increase in PWV postoperatively, but no significance was observed in the types of surgical procedures performed. Although further study is needed, the suggestion can be made in this era of hybrid surgery that in patients who need treatment for extended aortic diseases, there is a potential risk for a profound increase in PWV with the implantation of a longer aortic prosthesis.

Medication to treat aortic stiffness has also been suggested in previous reports. Anti-inflammatory drugs, antihypertensive

Table 2: Univariate analysis for difference in preoperative and postoperative pulse wave velocity for categorical variables

Variable	With	Without	*P*-value
Gender (male), mean ± SD	303.9 ± 488.36	155.3 ± 336.10	0.17
Hypertension, mean ± SD	270.3 ± 475.86	216.6 ± 233.62	0.71
Hyperlipidaemia, mean ± SD	195.7 ± 504.87	327.2 ± 392.12	0.17
Diabetes, mean ± SD	384.7 ± 594.59	239.1 ± 418.66	0.26
Current smoker, mean ± SD	285.1 ± 480.98	257.4 ± 447.25	0.81
Angiotensin receptor blocker (preoperative), mean ± SD	207.8 ± 409.08	345.9 ± 504.24	0.16
Angiotensin receptor blocker (postoperative), mean ± SD	202.1 ± 262.26	273.3 ± 475.73	0.62
Ca blocker (preoperative), mean ± SD	275.9 ± 511.81	235.4 ± 277.33	0.70
Ca blocker (postoperative), mean ± SD	341.4 ± 552.54	213.3 ± 370.64	0.19
Beta blocker (preoperative), mean ± SD	317.8 ± 597.43	236.1 ± 360.21	0.42
Beta blocker (postoperative), mean ± SD	165.0 ± 371.92	439.4 ± 530.38	0.005
HMG-CoA inhibitor (preoperative), mean ± SD	234.3 ± 494.40	287.6 ± 418.71	0.58
HMG-CoA inhibitor (postoperative), mean ± SD	226.7 ± 524.32	298.2 ± 375.62	0.46

Difference in PWV with and without each variable is listed.

Ca: calcium; HMG-CoA: 3-hydroxy-3-methylglutaryl-coenzyme A reductase; PWV: pulse wave velocity; SD: standard deviation.

Table 3: Univariate analysis for difference in preoperative and postoperative pulse wave velocity for continuous variables

	r	95% CI	*P*-value
Age	0.20	−0.0124 to 0.389	0.07
Left ventricular ejection fraction	−0.01	−0.213 to 0.203	0.96
Treatment length	0.41	0.22 to 0.57	<0.001
Difference in sBP	0.03	−0.175 to 0.241	0.75

CI: confidence interval; sBP: systolic blood pressure.

drugs, advanced glycation end product cross-links breakers, and lipid-lowering drugs have been listed as potential drugs to reduce PWV [25]. Our study has shown that using beta blockers after surgery may attenuate the effect of aortic surgery on PWV. Although weaker than other vasodilatory drugs, beta blockers can reduce PWV by reducing the heart rate. Reduction in heart rate influences the viscoelastic properties of the arterial wall and reduces pulse pressure amplification [25]. Although further study is needed, using beta blockers may be considered in patients undergoing surgery requiring longer treatment length.

Another approach for reducing the effect on PWV may be to develop a better device that could mimic the compliance of the native aorta. A previous study that compared expanded polytetrafluoroethylene and Dacron grafts on PWV has shown that the expanded polytetrafluoroethylene graft had less effect on the changes in PWV after surgery [26]. Further, a previous study from our group showed that an endoskeleton stent graft had a reduced effect on PWV compared to an exoskeleton stent graft, which showed a significant increase in PWV [3, 15]. Frozenix, a frozen elephant trunk device used in the present study, is also an endoskeleton type device. Although the sample size was small, a subanalysis of the patients receiving the Frozenix device showed a positive correlation in treatment length and an increase in PWV. Interestingly, this difference was due to the length of the graft portion ($r = 0.457$, 95% CI 0.044–0.737, $P = 0.032$) and not the stented portion ($r = 0.196$, 95% CI −0.246 to 0.571, $P = 0.38$). Further study of graft selection and type of endoprosthesis may provide more information for a better device design.

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Limitations

Our study has several limitations. First, it is a retrospective study with a relatively small sample size. However, evaluation of changes in PWV for the whole group with a sample size of 89 provides statistical power of 0.99 with $\alpha = 0.05$. Further, evaluation of changes in PWV with a sample size of 51 provides a statistical power of 0.66 for patients undergoing graft replacement; a sample size of 22 for the frozen elephant trunk technique provides a statistical power of 0.82; and a sample size of 16 for hybrid surgery provides a statistical power of 0.99, all of which are acceptable. Second, although there were no major changes in

Table 4: Multivariate analysis for change in preoperative and postoperative pulse wave velocity

Variable	Coefficient	95% CI	*P*-value
Age	5.00	−3.557 to 13.558	0.25
Frozen elephant trunk procedure[a]	−57.35	−400.428 to 285.719	0.74
Hybrid surgery[a]	−194.30	−789.562 to 400.972	0.52
Treatment length	3.31	0.056 to 6.562	0.046
Beta blocker	−220.08	−401.972 to −38.183	0.018
Difference in sBP	3.26	−4.381 to 10.893	0.4

R^2 = 0.25; residual = median = −54.72, Q1–Q3 = −233.77 to 162.18.

sBP: systolic blood pressure.

[a]Compared to graft replacement.

anaesthesia, critical care, outpatient management and surgical strategy during the study period, the selection of surgery type may have changed from 2016 with the introduction of the frozen elephant trunk technique. Although this technique may have an effect on long-term surgical outcomes, it does not affect the result of this study, which evaluated changes in PWV for each surgical strategy. Third, there are different kinds of devices for the frozen elephant trunk procedure and the stent graft, which itself can have different effects on PWV. We have used the Frozenix device for the frozen elephant trunk procedure and the J-graft, Hemashield or Triplex for graft replacement. Further study should be performed to confirm the effects of other devices on PWV. Further, with longer follow-up on these patients, the effect of increased PWV on long-term outcome should also be evaluated. Previous reports have shown a negative effect of increased PWV on long-term outcomes [3, 5–8, 14, 21]. Although further study is needed, this study provides suggestions on feasible modifications to the surgical approach and perioperative care, the goal being to minimize the effect of surgery on PWV.

Clinical implications

Based on our findings, placement of the frozen elephant trunk device and the stent graft during the hybrid operation should be performed with the understanding that an extension of the treatment length is associated with an increase in PWV postoperatively.

CONCLUSION

Although prevention of aneurysmal rupture is the primary goal, changes in physiological changes should also be considered. In the era of hybrid surgery, treatment for more extensive disease was associated with increased PWV. The goal should be to reduce the risk of spinal cord injury and to reduce the length of treatment to reduce the effect on PWV. Further, improvements in devices that mimic the native aorta and the use of medication such as a beta blocker may reduce the risk for increased PWV and its accommodated risk factors after surgery.

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Author contributions

Daijiro Hori: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Validation; Writing—original draft. **Sho Kusadokoro:** Conceptualization; Data curation; Writing—original draft. **Makiko Naka Mieno**: Formal analysis; Methodology; Writing—review & editing. **Tomonari Fujimori:** Data curation; Writing—original draft. **Toshikazu Shimizu:** Data curation; Writing—original draft. **Naoyuki Kimura:** Formal analysis; Writing—review & editing. **Atsushi Yamaguchi:** Formal analysis; Writing—review & editing.

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