

Theoretical mechanism of temporary renal function improvement after abdominal aortic aneurysm surgery

Applications for clinical imaging and laboratory data

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Abstract

We evaluated the effects of changes in blood flow due to abdominal aortic aneurysm (AAA) surgery by using a simple zero-dimension model and applied theoretical values to clinical data.

The zero-dimension electronic circuit model and diagram of blood flow distribution were created by setting the resistance of the aorta, bilateral iliac arteries, renal arteries, and aneurysm. Resistance of the aneurysm and resistance of the aorta before surgery were compared with that of the aorta after surgery. We set the radius length of each anatomical parameter to calculate theoretical values.

Renal flow increased 13.4% after surgery. Next, we analyzed contrast-enhanced computed tomography data of 59 patients who underwent AAA surgery. A total of 19 patients were treated with a Y graft and 7 patients were treated with a straight graft during open surgery. However, 33 patients were treated with a bifurcated stent graft. A significant linear relationship between the increased estimated glomerular filtration rate (eGFR) ratio and the decreased aneurysm ratio was found only for the straight graft group.

Using a circuit model, renal blood flow theoretically increased after AAA surgery. Clinically, there was a correlation between volume regression and eGFR improvement only in the limited AAA group.

Abbreviations: AAA = abdominal aortic aneurysm, CT = computed tomography, eGFR = estimated glomerular filtration rate, EVAR = endovascular aneurysm repair, OS = open surgery, POD = postoperative day, SD = standard deviation.

Keywords: abdominal aortic aneurysm, electric model, improvement, renal function, simulation

1. Introduction

Renal function is a concern after abdominal aortic aneurysm (AAA) surgery. Recent studies have demonstrated that postoperative renal deterioration is associated with poor survival.^[1–3] Intraoperative burden on the kidney such as temporary ischemia due to vessel clamping during pararenal AAA surgery and angiography with contrast medium during endovascular aneurysm repair (EVAR) could cause acute renal failure.^[4–6] Some reports have speculated on the mechanism of the kidney during

cardiac surgery via simulation.^[7] The vascular clamp, decreased renal blood flow, and consequent renal hypoxia were assumed to be important pathways to acute renal failure.^[7,8] In addition, in the case of shaggy aorta, a procedure-related shower embolism could lead to renal dysfunction.^[9] In contrast, some studies have shown temporary (several days) improvement of renal function.^[10,11] We have found this unique phenomenon in some cases of AAA surgery and assumed that postoperative hydration was the cause. However, we retrospectively encountered some AAA patients whose renal function improved dramatically and found that the aneurysmal diameters were relatively larger (>70 mm). Therefore, we hypothesized that decreased postoperative infrarenal blood flow volume could cause increased renal artery flow and subsequent renal improvement. The purpose of this study was to evaluate the effects of blood flow “revision” due to AAA surgery by using a simple zero-dimension model and applying theoretical values to clinical data.

2. Methods

2.1. Model

The zero-dimension electronic model was created as shown in Fig. 1. The diagram of blood flow distribution was created by setting the resistance of the aorta (R_a), resistance of the bilateral iliac arteries, resistance of the renal arteries, and resistance of the aneurysm (R_{aa}). R_{aa} and R_a before surgery were compared with R_a after surgery. We set the radius length of each anatomical parameter to calculate theoretical values.

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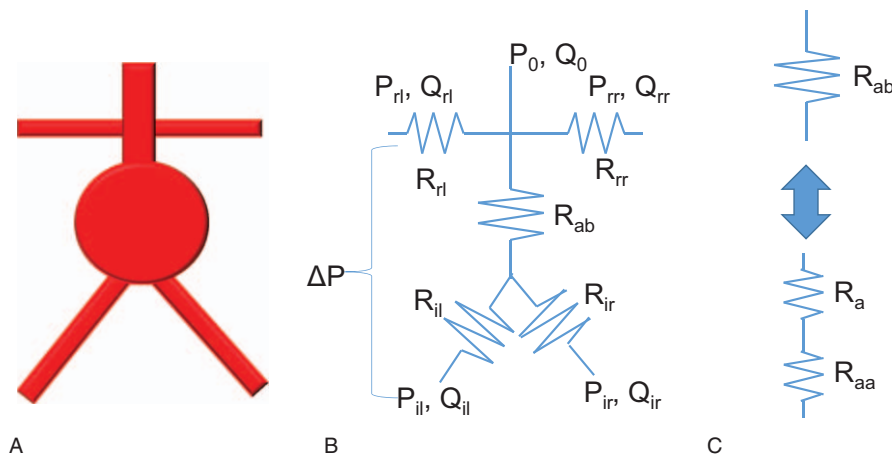


Figure 1. (A) Zero-dimension electronic model. (B) Diagram of the blood flow distribution was created by setting the resistance of the aorta, bilateral iliac arteries, renal arteries, and aneurysm. (C) Resistance of the aneurysm (R_{aa}) and resistance of the aorta (R_a) preoperatively were compared with R_a postoperatively. R_a = resistance of the aorta, R_{aa} = resistance of the aneurysm.

2.2. Patients

This retrospective cohort study was performed according to the guidelines of the research ethics committee of the University of Tokyo Hospital (approval number: 3316(2)). All patients provided informed consent for participation. Among the patients who underwent open surgery (OS) or EVAR for infrarenal AAA at the University of Tokyo Hospital between January 2006 and August 2014, 59 who had undergone CT imaging before and after surgery were selected. Patients with ruptured AAA, hemodialysis, renal artery reconstruction, and AAA diameter less than 50 mm were excluded.

OS was performed in 26 patients: straight graft replacement was performed in 7 patients and a bifurcated (Y) graft was used in 19 patients. EVAR with a bifurcated stent graft was performed in 33 patients. We obtained the estimated glomerular filtration rate (eGFR: mL/min/1.73 m²) and compared the preoperative value to the maximal value within 7 days postoperatively.

2.3. Volume measurement

Using CT images obtained before and after surgery, we compared the ranges of the aorta and aneurysm to the range of the replaced site with the artificial graft or stent graft. We used the Aquarius iNtuition software (TeraRecon, San Mateo, CA) to measure volume. Because the aneurysm volume includes the intrasac thrombus, and because the software sometimes cannot recognize the aneurysm outline, especially near the thick thrombus, we performed semi-automatic measurements.

We defined the increased eGFR rate as (preoperative eGFR – postoperative maximal eGFR)/preoperative eGFR × 100 (%). In addition, the decreased aneurysm rate was defined as (preoperative volume – postoperative volume)/preoperative volume × 100 (%).

Statistics. Data were described as the mean ± SD for continuous variables. The correlation between the increased eGFR ratio and the decreased aneurysm ratio was evaluated using the Pearson correlation coefficient. All analyses were conducted using MS Excel software. Significance was set at $P < .05$.

3. Results

3.1. Electric circuit model

The distribution of the infrarenal blood flow was estimated using a zero-dimension model based on viscous resistance of the flow.

The zero-dimension model was defined as shown in Fig. 1. The aneurysm was represented by a sphere and other arteries were represented by a cylinder. The electrocircuit consisted of viscous resistance of the flow in the abdominal aorta (R_{ab}), the left and right renal arteries (R_{rl} and R_{rr}), and the left and right iliac arteries (R_{il} and R_{ir}). The inflow pressure and flow rate (P_0 and Q_0) as well as the pressure and flow rate at each junction of the arteries were also included.

Blood pressure and the inner diameter of the arteries were assumed to be the same before and after aneurysm surgery. Considering Ohm's law ($R = V/I$), the flow resistance (R) of the cylinder was determined as follows:

$$R = \frac{\Delta p}{Q} = \frac{8\mu l}{\pi r^4} \quad (1)$$

Here, the pressure gradient was Δp , the blood flow was Q , the viscosity coefficient of the flow was μ , and the cylinder radius was r_0 .

According to Ohm's law, the preoperative pressure gradient was expressed as follows:

$$\Delta P_{\text{pre}} = Q_{ab(\text{pre})} \left(R_{ab(\text{pre})} + \frac{R_{ir}R_{il}}{R_{ir} + R_{il}} \right)$$

Assuming that the resistance of the right iliac artery (R_{ir}) and left iliac artery (R_{il}) are the same (R_i):

$$\Delta P_{\text{pre}} = Q_{ab(\text{pre})} \left(R_{ab(\text{pre})} + \frac{1}{2}R_i \right)$$

Similarly, the postoperative pressure gradient ΔP_{post} is determined by

$$\Delta P_{\text{post}} = Q_{ab(\text{post})} \left(R_{ab(\text{post})} + \frac{1}{2}R_i \right)$$

Assuming that the pressure gradient between the abdominal aorta and iliac arteries before and after surgery are the same:

$$\Delta P_{\text{pre}} = \Delta P_{\text{post}}$$

$$Q_{ab(\text{pre})} \left(R_{ab(\text{pre})} + \frac{1}{2}R_i \right) = Q_{ab(\text{post})} \left(R_{ab(\text{post})} + \frac{1}{2}R_i \right)$$

$$Q_{ab(\text{post})} = Q_{ab(\text{pre})} \frac{R_{ab(\text{pre})} + \frac{1}{2}R_i}{R_{ab(\text{post})} + \frac{1}{2}R_i} \quad (2)$$

This equation shows that $Q_{ab(post)}$ decreases postoperatively if the resistance increases after surgery ($R_{ab(pre)} < R_{ab(post)}$).

Next, by applying the law of conservation of mass, the preoperative aortic blood flow at the orifice of the renal arteries is expressed as the following formula:

$$Q_{0(pre)} = Q_{rr(pre)} + q_{rl(pre)} + Q_{ab(pre)}$$

Assuming that the blood flow of the right renal artery (Q_{rr}) and left renal artery (Q_{rl}) are the same (Q_r):

$$Q_{0(pre)} = 2Q_r(pre) + Q_{ab(pre)}$$

Postoperative blood flow ($Q_{0(post)}$) at the renal orifice is calculated as follows:

$$Q_{0(post)} = 2Q_r(post) + Q_{ab(post)}$$

Let us assume that aortic flow before surgery and aortic flow after surgery are the same:

$$Q_{0(pre)} = Q_{0(post)}$$

$$2Q_r(pre) + Q_{ab(pre)} = 2Q_r(post) + Q_{ab(post)}$$

$$Q_r(post) = Q_r(pre) + \frac{1}{2}(Q_{ab(pre)} - Q_{ab(post)})$$

Then, when we substitute Eq. 2, the postoperative renal artery flow ($Q_{r(post)}$) should be

$$Q_{r(post)} = Q_r(pre) + \frac{1}{2}Q_{ab(pre)} \frac{R_{ab(post)} - R_{ab(pre)}}{R_{ab(post)} + \frac{1}{2}R_i} \quad (3)$$

Because the resistance (R_{ab}) represents 1 circuit of the abdominal aorta and aneurysm, it should be expressed by Eq. 1:

$$R_{ab} = R_a + R_{aa} = \frac{8\mu}{\pi} \cdot \left(\frac{l_a}{r_a^4} + \frac{l_{aa}}{r_{aa}^4} \right)$$

3.2. Theoretical value of the renal flow

We applied the following values of some clinical data to the $R_{ab(pre)}$ and $R_{ab(post)}$ equations: the length of the aneurysmal neck ($l_a = 15$ mm), the radius of the abdominal aorta ($r_a = 10$ mm), the longitudinal length of the aneurysm ($l_{aa} = 85$ mm), the aneurysmal radius ($r_{aa(pre)} = 25$ mm), and the postoperative aortic radius ($r_{aa(post)} = 10$ mm).

$$R_{ab(pre)} = \frac{8\mu}{\pi} 1.718 \times 10^6$$

$$R_{ab(post)} = \frac{8\mu}{\pi} 10^7$$

Assuming that the length of the iliac artery is 20 mm (l_i), and that the radius is 5 mm (r_i), the resistance of the iliac artery should be

$$R_i = \frac{8\mu}{\pi} \cdot 2.266 \times 10^8$$

The result was substituted into Eq. 3; therefore, the renal arterial flow ($Q_{r(post)}$) should be

$$Q_{r(post)} = Q_r(pre) + Q_{ab(pre)} \times 6.718 \times 10^{-2}$$

Renal flow was found to increase 6.7% of the aortic flow postoperatively. Assuming that the preoperative renal flow

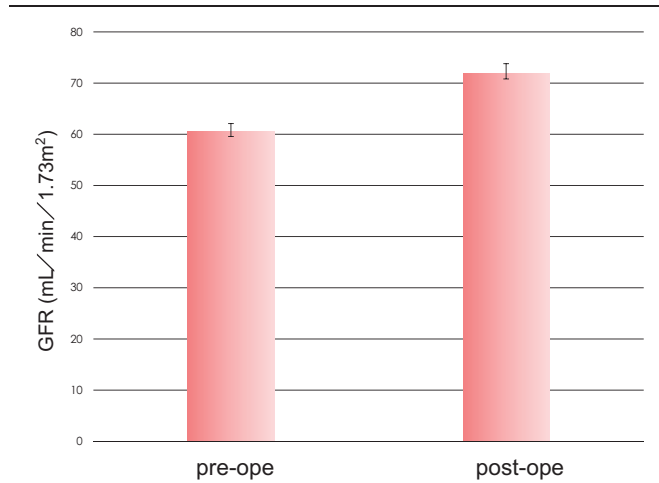


Figure 2. The postoperative estimated glomerular filtration rate (eGFR) was larger after surgery than before surgery. eGFR = estimated glomerular filtration rate.

($Q_{r(pre)}$) is approximately half of the aortic flow ($Q_{ab(pre)}$), the renal flow increases 13.4% after surgery.

3.3. Clinical application

Postoperative eGFR was larger after surgery (71.8 ± 1.9 mL/min/1.73 m²) than before surgery (60.5 ± 1.5 mL/min/1.73 m²) (Fig. 2). The correlation between the increased eGFR ratio and the decreased aneurysm ratio was evaluated for all patients (n = 59), for the Y graft group including EVAR (n = 52), and for the straight graft group (n = 7). A significant linear relationship was found only in the straight graft group (n = 7) (Fig. 3).

4. Discussion

Using the zero-dimension electric circuit model, we revealed an increase of 13.4% in renal flow after AAA surgery. Some surgeons who have encountered temporary renal improvement after surgery might agree with this result; however, it is only a theoretical value. This study had critical limitations. During clinical application of data, we found linear regression between the renal function and sac size in the straight graft replacement group; however, the number of cases was small. Perioperative hydration should strongly affect renal function. Using the data of 125 patients who underwent OS in our department, we discovered the following intravenous infusion values (average ± SD): 6.48 ± 6.67 mg/kg/h during surgery; 1649 ± 683 mL on postoperative day (POD) 0; 3258 ± 752 mL on POD 1; 2495 ± 556 mL on POD 2; and 2125 ± 541 mL on POD 3. It is reasonable that large infusion amounts administered for days would contribute strongly to renal function.

Few reports have focused on temporary renal improvement after AAA surgery.^[10,11] Most studies determined the outcome of renal function after a longer postoperative period^[1-6] because there are many confounding factors affecting renal function immediately after surgery. Our study is the first to report the theoretical value of renal flow improvement after AAA surgery, and we hope that it will help determine postoperative care strategies at other institutes.

The vasculature of the kidney is so complicated that there are many analyses using mathematical modeling^[12]. Renal function was regulated by several factors such as glomerular filtration, myogenic response, and tubuloglomerular feedback. Because we focused on the inflow of the kidney, we set these details in the “black box.”

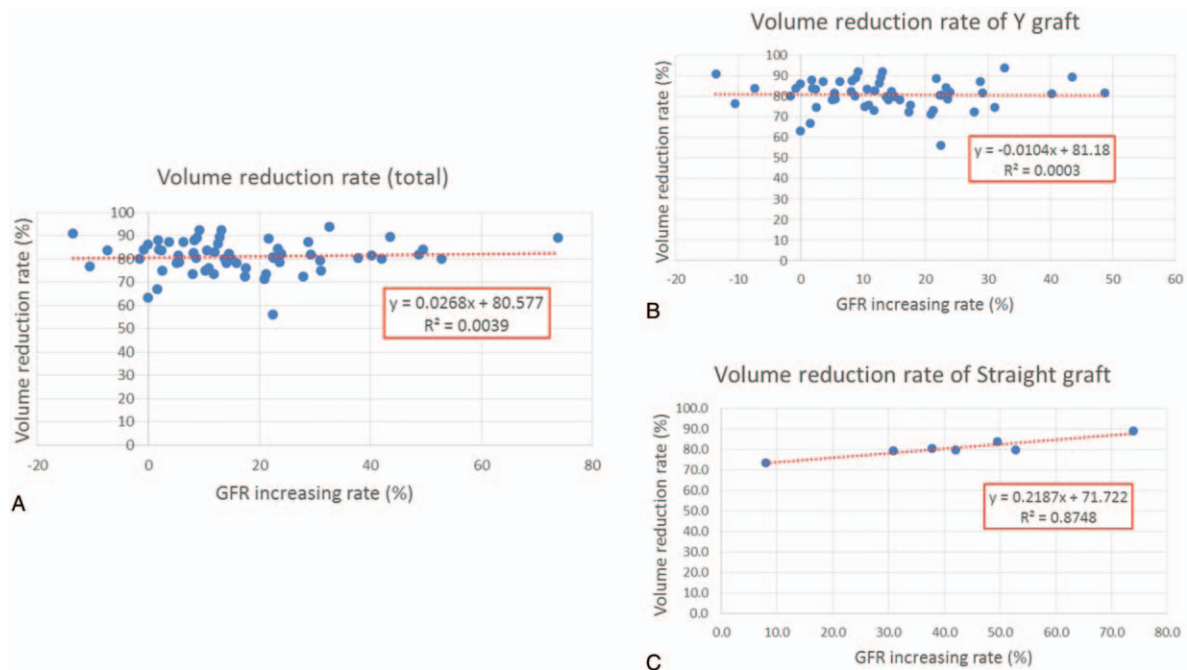


Figure 3. The correlation between the increased estimated glomerular filtration rate (eGFR) ratio and the decreased aneurysm ratio was evaluated for all patients (A), for the Y graft group including endovascular aneurysm repair (EVAR) (B), and for the straight graft group (C). A significant linear relationship was found only in the straight graft group (C). eGFR = estimated glomerular filtration rate, EVAR = endovascular aneurysm repair.

The idea of the zero-dimension model was created through discussions with others working in the fields of medicine and engineering. Some engineers have reported that the electric circuit model mimics blood circulation^[13,14]; however, their theory was too complicated to apply clinically. No clinical report has utilized such theories for peri-operative strategies. When creating the model for our study, we focused on clinical applications and made the model as simple as possible.

5. Conclusion

Using the zero-dimension electric circuit model, renal blood flow theoretically increased after AAA surgery. Clinically, there was a correlation between volume regression and eGFR improvement only in the limited AAA group. However, other factors such as perioperative infusion volume could contribute to renal improvement.

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