COMPUTER SIMULATION OF THE SLIT ARTERIOTOMY TECHNIQUE FOR ARTERIAL END-TO-SIDE MICROANASTOMOSIS

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Abstract: This paper reports the use of computer simulation to study an improved method in microsurgery procedure on arteries. Factors that were hypothesized to be important for the success of this new surgical technique were analysed using finite element methods in order to provide helpful information /explanation of its efficacy.

Introduction

Arterial end-to-side microanastomosis is one of the techniques used to restore blood supply in severed limbs or to revascularize free flaps to the limbs. In this technique, an opening is created in the side of the recipient artery, and the end of the donor artery is stitched to the opening so as to allow blood to flow from the recipient artery to the donor artery (Figure 1). Traditionally, this technique involves the creation of a hole in the recipient artery to ensure a high patency rate.

A novel method of using slit arteriotomy was developed and tried with success on 50 patients [1]. The new procedure involves cutting a slit rather than a hole on the recipient artery as shown in Figure 1b.

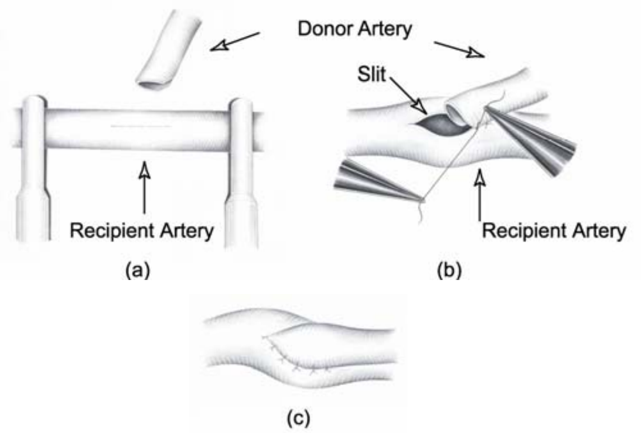

Figure 1: The slit arteriotomy for end-to-side arterial anastomoses. (a). Before anastomoses; (b). Stitching; (c). After anastomoses

Despite good results reported with arterial patency rate of 98% using this new method, elucidation of the mechanism in which the slit opens after microanastomosis, is necessary to convince other plastic/reconstructive surgeons of its efficacy.

In this instance, semi-quantitative study using non-linear finite element methods were employed to study the hypothesized factors contributing to non-closure of the slit; simulated by. These factors include residual stress, interaction between two blood vessels, blood pressure and thickness of donor artery.

Materials and Methods

Summary of Finite Element (FE) model: A general-purpose FEA (Finite Element Analysis) software ABAQUS/Standard is used for the computer simulation. As shown in Figure 2a, a 16 mm segment of the recipient artery and an 8 mm segment of the donor artery were modelled in ABAQUS with 4-node shell elements, S4R, which is an element type valid for both thin and thick shell and supporting large deformation analysis. The take-off angle of the donor artery is 45^{o}. The thickness of the recipient artery is fixed at 0.4mm while the thickness of donor artery is varied between 0.3 mm and 0.4 mm.

A slit, 3.2 mm in length and 0.42 mm in width, was created at the middle of the recipient artery in the initial configuration (Figure 2b) to take into account the effect of residual stresses discussed by Y.C. Fung [2]. For initial configuration, we referred to the state with no loading, deformation and stresses.

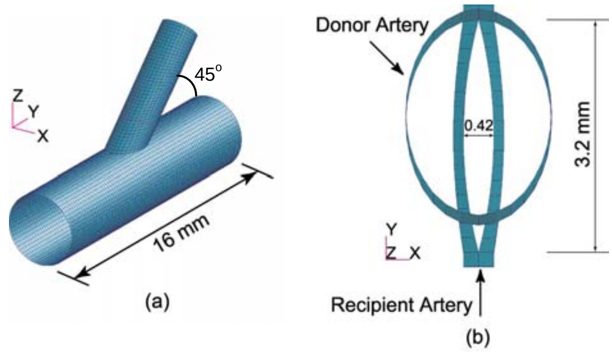

Figure 2: Summary of the FE model. (a). Overview of the model (b). Original dimensions of the slit

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The mesh of the respective donor and recipient artery has one shared note, node O (Figure 3a). All translational displacements were constrained at nodes of the two ends of the recipient artery, the upper end of the donor artery and also at the shared node O.

In present study, the arterial wall was considered as homogeneous, isotropic and was modeled as neo-Hookean hyperelastic model for the following reasons. Firstly, it is well accepted that macroscopically arterial wall can be considered as being made of a nonlinear elastic material [3,4]. Secondly, large strain is involved in the simulation, and hyperelastic model is suitable for this situation and can provide more accurate results than linear elastic model. Thirdly, neo-Hookean form is the simplest hyperelastic model and usually provides a sufficiently accurate representation for cases in which the strains are only moderately large (less than 1).

The strain-energy function for incompressible neo-Hookean material is as follows:

$$U = C_{10}/2\,(I_1 - 3) \quad (1)$$

In above equation, I_1 is the first strain invariant which is defined by

$$I_1 = trace\left(\overline{\mathbf{F}} \cdot \overline{\mathbf{F}}^T\right) \qquad (2)$$

where $\overline{\mathbf{F}} = \det(\mathbf{F})^{-1/3}\mathbf{F}$ and $\mathbf{F}$ is deformation gradient

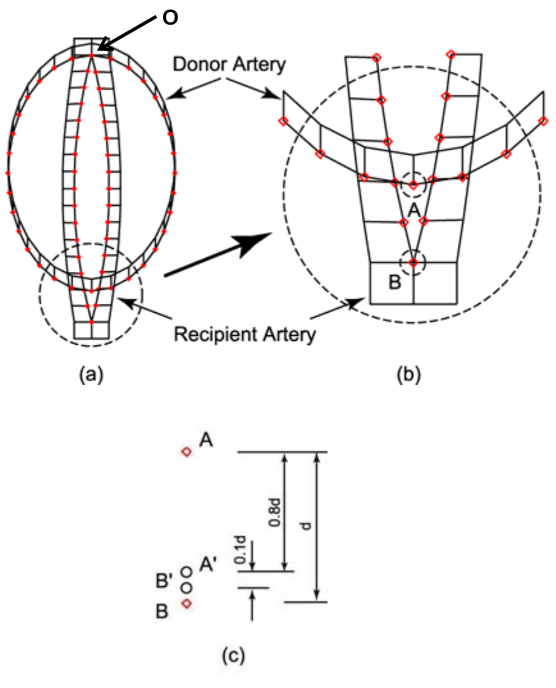

Figure 3: Illustration on applying prescribed displacements in the 1st step. (a). Elements at the end of donor artery and around the slit; (b). Enlarged view of a part of the mesh; (c). An example of applying prescribed displacements in the 1st step

C_{10} is a material constant. When the strain is infinitesimal, the incompressible neo-Hookean model behaves like a linear elastic model with Poisson's ratio $\gamma = 0.5$ and Young's modulus $E = 2(1+\gamma)C_{10}$. Therefore, we can determine C_{10} if we know the Young's modulus of the arterial material under infinitesimal strain condition. The linear elastic material used by Ballyk et al. [5] provides a reference with E = 0.455MPa. This corresponds to C_{10} = 0.152 MPa which would be used in all cases of our analysis.

Simulation Procedures: The simulation is divided into four steps. In the **first** step, prescribed displacements were assigned to nodes around the slit and the corresponding nodes around the lower end of the donor artery to fit them together.

In the **second** step, each pair of corresponding nodes was connected by a very rigid beam to couple their deformation together in the following steps. Next, these prescribed displacements were removed, allowing the system to deform freely without any external forces. An equilibrium configuration would thus be obtained giving insight to the interaction between the two blood vessels.

Based on the equilibrium state obtained at the end of the second step, blood pressure (100 mm Hg) is applied to the recipient artery in the **third** step. Similarly, the same pressure is added to the donor artery in the **fourth** step. The third and the fourth steps would provide an understanding on how mutual deformation forces in the two arteries and blood pressure affected slit opening.

It should be noted that the objective of the first step is to fit the slit to the circumferencial end of the donor artery. However, in the second step beam elements would be used to couple the corresponding nodes around the slit and the lower end of the donor artery (such as node A and B in Figure 3) and the length of beam element can not be zero. Therefore, in the first step, the slit and the end of donor artery is not perfectly fitted. There is still a gap between them, which is 10% of the initial gap. Figure 3c illustrates an example. The initial distance between the node A on the slit and the corresponding node B on the end of donor artery is d. At the end of the first step, A is moved to A' and B is moved to B', and the distance between A' and B is 0.1d.

Results

We simulate three cases defined in Table 1. The recipient artery, whose thickness and material constant C_{10} are 0.4 mm and 0.152 MPa respectively, is kept unchanged in all the cases. Different thickness values were used for donor artery to investigate its effect because the authors hypothesized that this parameter also had an effect on the opening state of the slit.

Table 1: Definition of cases

	Recipient Artery		Donor Artery	
	Thickness (mm)	C_{10} (MPa)	Thickness (mm)	C_{10} (MPa)
Case 1	0.4	0.152	0.3	0.152
Case 2	0.4	0.152	0.35	0.152
Case 3	0.4	0.152	0.4	0.152

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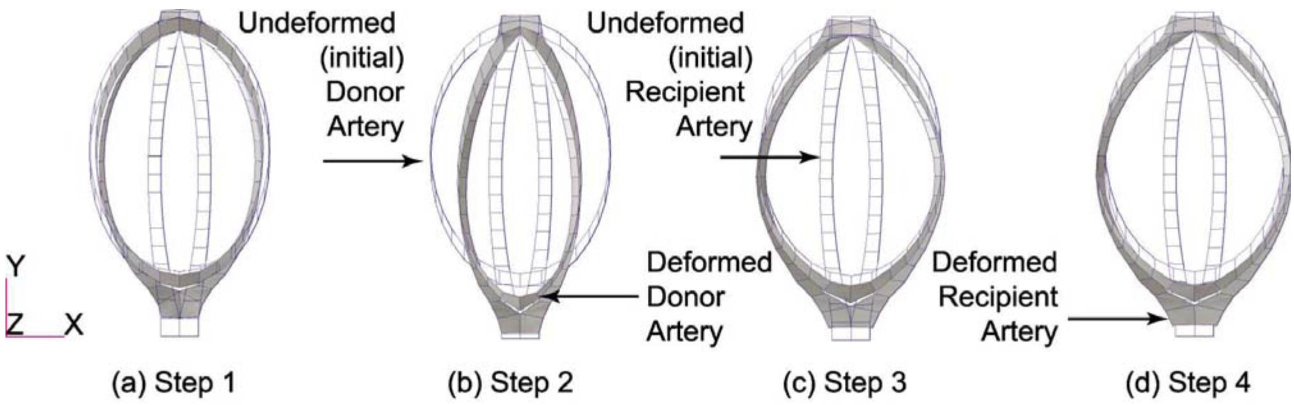

Figure 4: Configuration of the slit at the end of each of the four simulation steps. (The shaded elements represent the deformed configuration and the unshaded elements represent the initial configuration)

Discussion

Figure 4 gives clear illustration of the configuration of the slit at the end of the four simulation steps. The widths of the slit at different stages are also listed in Table 2. It can be observed from Figure 4 that after removing the prescribed displacements in the second step, the slit tends to spring back to recover its initial configuration. This is resisted by the donor artery due to its tendency to recover its initial configuration in the opposite direction. At the end of the second step, these two forces achieve an equilibrium state and the resulting configuration is between the initial configuration of the slit and the donor artery respectively. This can be clearly observed from Figure 4b or by comparing the width of the slit at the end of the second step, 1.21 mm, with the initial width, 0.42 mm in Table 2, Case 1. These results give an affirmation that the interaction between the recipient artery and the donor artery is one key reason that kept the slit open even without any other external forces.

At the end of the third step, the width of the slit is 2.31mm, which shows that blood pressure in the recipient artery bring about a significant enlargement in the opening of the slit. The blood pressure in the donor artery also enlarges the opening of the slit (Step 4) but this effect is relatively minor because of high stiffness of the shell (donor artery) under internal pressure.

Table 2: Simulation results

		Width (mm) of slit at the End of			
Case	Initial	Step 1	Step 2	Step 3	Step 4
1	0.42	1.686	1.218	2.310	2.440
2	0.42	1.686	1.294	2.282	2.394
3	0.42	1.686	1.350	2.256	2.358

Effects of Thickness of Donor Artery: Cases 1 to 3 study the effects of change in the thickness of the donor artery from 0.3 mm to 0.4 mm with an increment of 0.05 mm. The same simulation was performed for both models and the widths of the slit at the end of the four steps were compared in Table 2.

From Table 2, it can be seen that at the end of the second step, case 3 presents the widest slit while case 2 presents a wider slit when compared to case 1. Therefore, it can be concluded that increase in thickness of the donor artery increases the "interaction effect" between the two blood vessels. This is most likely due to the increase in recovery force of the donor artery when its thickness increases. However, the effect of the blood pressure is lowest in case 3 which is represented by the narrower slit at the end of the third and fourth steps as compared to case 2. Likewise, case 2 presents a narrower slit as compared top case 1 after the third and fourth steps. This is because the stiffness of the system increases when the thickness is increased and the deformation under the same external load (as used for case 1) will result in smaller deformation in case 2 and case 3 respectively.

Conclusions

We have proposed a finite element procedure applicable for the simulation of both the slit and hole arteriotomy for the end-to-side micro-anastomosis. The simulation leads to conclusions as follows. Firstly, the slit opens to a width sufficient for blood supply to flow after anastomosis. Secondly, there are two key underlying causes for the non-closure of the slit: the forces applied by the donor artery and the blood pressure. A thicker donor artery increases the width of the slit right after the stitching but may decrease the width at the end of the operation because it does not expand as much as the flaccid thin-walled artery with blood pressure. These results can provide guidance for selection of the donor artery in microsurgery.

Acknowledgements

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