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Hemodynamic Interpretation of Various Extraanatomical Bypasses: Clinical & Engineering Views

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Abstract

Axillo-bifemoral (Ax-Fem) bypass are now well accepted for bilateral iliac artery occlusion as the second best option. This extra-anatomical (unnatural) bypasses, however, have various hemodynamic liabilities affecting the patency. Hemodynamic conditions of each different type of Ax-Fem bypass were assessed with computer simulation model to determine the hemodynamically more sound type. Simulation models of five different types of Ax-Fem bypass were constructed. Our investigation based on the computer simulation models have shown distinct differences between two most popular Lazy-S type and Inverted-C type on the distribution of flow volume, shear stress and recirculation zone, etc., though both types have shown similar clinical results. Lazy-S type has shown better hemodyanmic status than inverted-C type. The theoretical advantage of "Lazy-S" type has never been adequately proved for its superiority clinically over the inverted-C type. Inverted-C type is now in more favor with clinically better results in spite of many hemodynamic liabilities including retrograde flow to the branching graft. The improvement of over-all long-term patency rate of various extra-anatomical bypasses is still warranted through proper correction of the hemodynamic liability. Even though clinical outcome of the extra-anatomical bypass has been equal regardless of the type of crossover femoral graft configuration, there are distinct differences on the hemodynamic characteristics among various types of configuration. Further hemodynamic study in the pulsatile flow status is warranted to correct hemodynamic defects with proper modification of various hemodynamic factors of each model.

Key words: Extraanatomical Bypasses, Hemodynamic Interpretation, Computer Simulation

Introduction:

Once the nature can no longer compensate the shortage of arterial blood supply to the lower extremity due to the blockage of the arterial vessel lumen mostly as the result of atherosclerosis, the distal tissue of which the viability shall depend on this arterial circulation, will go through series of ischemic condition with equivalent symptoms (e.g. claudication to rest pain) and signs to reach the end point of tissue gangrene[1-6]. The aim of the bypass surgery in this condition is to relieve this ischemic outcome of the arterial occlusion to the tissue artificially by the establishment of detour route to continue to supply arterial blood to the distal tissue with various conduits (e.g. artificial vessel or autogenous vessel) successfully bypassing the blocked vessel[7-10]. Among various methods, bypass graft has shown much better results on the longer segment of artery blockage in particular in comparison to the cleaning the blocked vessel lumen to relieve obstruction known as endarterectomy[11-15]. There is still significant disagreement over the superiority

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of different mode of anastomosis (e.g. end-to-end versus end-to-side) of the bypass graft to the proximal inflow artery as well as to the distal outflow artery especially in hemodynamic-advantage point of view[16-19]. But the blockage at the distal aorta and iliac artery (two major branches splitting out of aorta trunk to supply both lower extremities) for example, can be ideally handled by both methods of anastomosis for the "aortofemoral bypass", that is, the replacement of the blocked aorto-iliac arteries with bypass graft in situ as normal anatomical fashion to parallel the original course of the aorto-iliac vessels to keep the normal anatomo-physiologic as well as hemo-dynamic status like the nature[9,10,15,20-22].

But various conditions (e.g. old age, cancer, and heart ailment, etc.) to increase surgical risks deter this ideal solution of aorto-iliac blockage with more physiologic aorto-bifemoral bypass (Ao-Fem) to follow the natural course of the vessels as the gold standard. Axillo-bifemoral (Ax-Fem) bypass for bilateral iliac artery occlusion or femoro- femoral (Fem-Fem) bypass for unilateral occlusion has been well accepted instead as the best second option[23-28]. However, these two different extra-anatomical(unnatural) bypasses have various hemo-dynamic liability each system inherently carries affecting the patency rate significantly[29-33] and therefore, various types of configuration for the construction of Ax-Fem bypass were proposed to improve its patency rate (Figure 1-5). But their clinical results have been mixed and the superiority of one type to the another has not been clearly proven yet. Hence, further hemodynamic study of these various models of Ax-Fem bypass has been warranted for the proper selection of hemodynamically more advantageous type.

It is right time for us to go back to the drawing board to see how we can improve their patency rates by the correction, if not, modification of their hemo-dynamic defects through further intimate communication among the surgeon and engineer involved in this particular issue.

Purpose:

In order to determine the hemodynamically more sound type of configuration among various types of Ax-Fem bypass, hemodynamic conditions of each different type of Ax-Fem bypass with different configuration were assessed first and their results were compared with their clinical assessment results, based on the retrospective analysis of clinical cases of Ax-Fem bypass.

Materials & Methods (Clinical study):

Ao-Fem bypass was implemented as the first option with ideal hemodynamic structure for the bilateral (aorto) iliac artery occlusive disease among the patients at Sungkyunkwan University (SKU) and Kyungpook National University (KNU), whenever the local and/or systemic condition should allow. Ax-Fem bypass has been used as the second best option when the patients should belong to the high risk group for the Ao-Fem bypass. Single Fem-Fem bypass for unilateral iliac artery occlusion has not been included in this review. Selection of the mode of the bypass, Ax-Fem vs Ao-Fem as well as the indication has been based on the clinical and laboratory (e.g. hemodynamic) assessment including aortography. Hemodynamic assessment for the pre- & postoperative evaluation has been relied on the duplex sonography with additional implementation of the conventional arteriography, CT-contrast angiography, and/or MR-angiography as the options.

Ao-Fem bypass was done in the synthetic, either textile (e.g. dacron) or non-textile (e.g. PTFE) graft. PTFE (polytetrafluoroethylene) synthetic non-textile graft with the size of 6mm to 8mm of inner diameter were used for all the Ax-Fem bypass in end-to-side fashion to make direct anastomosis of the graft to the natural vessels (inflow & outflow). Ax-Fem bypass was done either in Lazy-S or Inverted-C configuration at SKU, while all the Ax-Fem bypass at KNU was done in Inverted-C configuration. Routine follow up assessment of the graft patency were done with the duplex sonography in addition to the clinical assessment on regular interval to detect the early failure sign with minimum 6 months interval for the proper disposition (e.g. revision; angioplasty, etc.) of impending graft occlusion. The cause of early and late graft failure was also assessed with additional study like arteriography and/or CT contrast study especially when the interventional procedure (e.g. thrombolytic therapy and/or surgical thrombectomy, etc.) should be required to acquire improved secondary patency rate.

The clinical results of two most popular types of Ax-Fem bypass (Inverted-C type and Lazy-S type) implemented to the AIOD at two independent hospitals of SKU and KNU were assessed for the primary patency rate through the first and second year by the retrospective review analysis of total 35 cases; 10 cases of SKU during the five year period of June, 1996 through May, 2001, and 25 cases of KNU during the ten year period of March, 1993 through February, 2002. Clinical outcome of Ao-Fem bypass has been used as the gold standard for the comparative study with those of Ax-Fem bypass.

Materials & Methods (Engineering study):

Simulation models of five different types of Ax-Fem bypass were constructed to keep the characteristics of limb graft configuration of each type (Figures 1-5). Figure 6 shows the computer simulation models. Hemodynamic assessment of the five different types of Ax-Fem bypass graft was made based on the values of the flow volume (velocity × area), velocity and pressure in the flow field of each vessel model with different configuration. The outlet boundary conditions were set to the pressure boundary conditions. Since pulsatile flow is very difficult to set the outlet boundary condition, we adopted "pressure" condition for the steady state simulation as the most appropriate one among several boundary conditions; Neumann, Pressure, and Convective. Pressure conditions are better for the hemodynamic studies because the Neumann or the Convective condition is extremely difficult to obtain the outlet boundary conditions, if not impossible, especially for the measurement of the velocity and/or pressure values at the outlets. Convective condition is also difficult to determine the C value so that we selected Pressure condition to define the outlet boundary condition where the outlet pressures are known. The mass flow rates at the outlets (steady or unsteady) depend on the pressure difference between the inlet and outlet. Therefore, the mass flow rates can be predicted when the pressure distributions are given to the viscous flow with multiple outlets (e.g. bifurcation).

We further verified the appropriateness of the boundary conditions through the comparison of our results with the in-vitro experiments and the results from the open literature. We confirmed good agreements between the numerical results using the pressure boundary and the results of the PIV experiment; the results of PDU and LDA measurements (except at the very near wall), and the results of the MRA images.

The velocity and pressure in the flow field of simulation model were calculated based on Navier-Stokes equation using FVM (Finite Volume Method). The viscosity variation within the model vessel was expressed using Carreau model. The simulation models of five different configuration was constructed with same condition of inflow and outflow status of steady flow as well as same graft diameter of 8.0 mm and same femoral artery diameter of 9.0 mm for the anastomotic sites. Various hemodynamic information obtained from each different model including distribution of the pressure, velocity and shear stress in addition to the flow volume distribution were compared with the clinical outcome of Ax-Fem bypass graft.

Results (Clinical study):

Primary patency rate of total 10 elective Ax-Fem (5 Lazy-S type & 5 Inverted-C type) patients of SKU has been 100% and 80% for the first year and second year respectively. Total 25 Ax-Fem (all Inverted-C type) patients of KNU have shown the patency rate at 77.7% and 51.8% for the first and second year respectively; 87.6% and 65.6% on elective 16 cases, and 62.5% and 31.3% on emergency 9 cases respectively. There has been no statistically significant differences between Lazy-S type and Inverted-C type on the preoperative clinical assessment results as well as the primary patency rate among SKU patients.

Results (Engineering study):

All five simulation models of different configuration of the branching graft, including two most popular type (Inverted-C & Lazy-S configuration) have shown significant reduction of the flow volume along the cross-over branching graft to the left lower extremity in the wide range of 6.6% to 40.8% of total inflow volume (Table 1). Inverted-C or its modification type (Model 2 & 4) has shown more drastic reduction of the flow volume along the cross over graft to the left femoral artery than Lazy-S or its modification type (Model 1 & 3).

Table 1 Flow volume distribution to both outflow anastomosis.

	Inflow ($\times 10^{-3}$kg/s)	Right outflow ($\times 10^{-3}$kg/s)	Left outflow ($\times 10^{-3}$kg/s)
Model 1	8.015 (100%)	5.642 (70.4%)	2.379 (29.6%)
Model 2	8.046 (100%)	6.684 (83.1%)	1.361 (16.9%)
Model 3	8.014 (100%)	4.788 (59.2%)	3.274 (40.8%)
Model 4	8.047 (100%)	7.517 (93.4%)	0.538 (6.6%)
Model 5	8.014 (100%)	6.234 (77.8%)	1.78(22.2%)

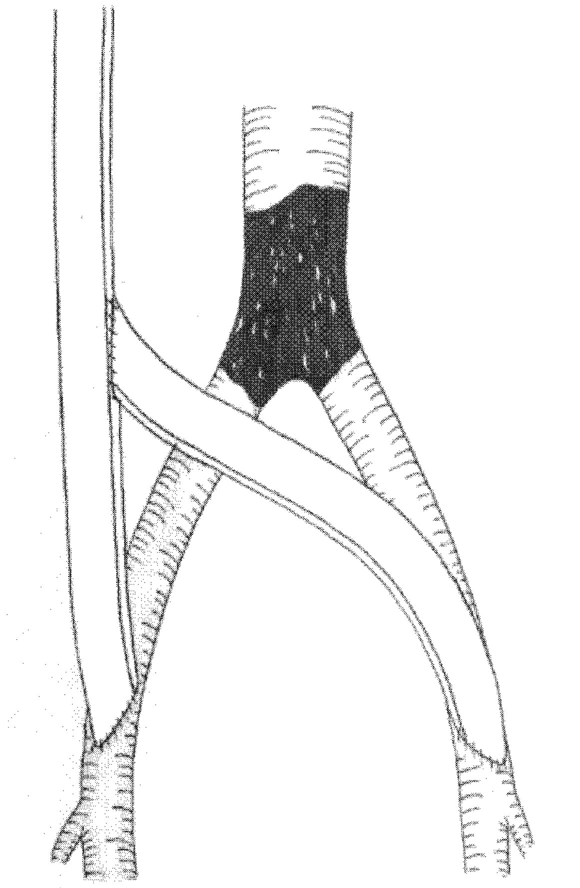

Figure 1 Model 1:Lazy-S type.
"Inverted-Y" fashioned bifurcation graft.
Anastomosis of left-sided branching limb to the right- sided main trunk in end-to-side fashion.
Antegrade flow through both limbs of the graft: Hemodynamically sound anastomoses.
One of two clinically most popular type of Ax-Fem bypass.

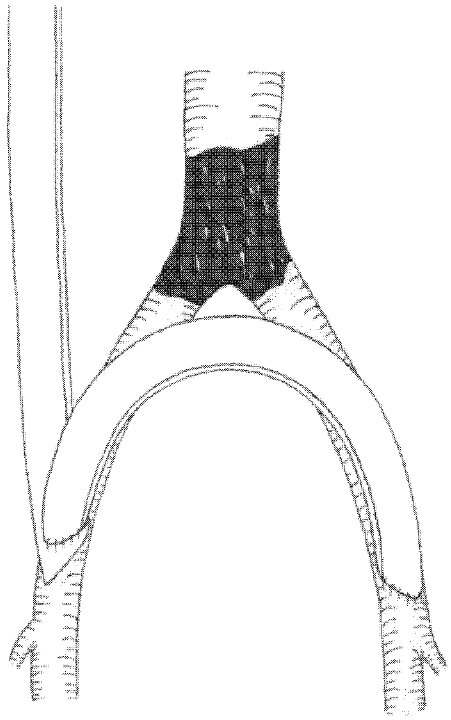

Figure 2 Model 2:Inverted-C type.
"L" shaped branching graft from the right-sided main trunk of the graft with the anastomosis of left-sided limb in end-to-side fashion.
Retrograde flow along the left-sided branching limb of the graft: hemodynamically unsound.
Antegrade flow along the right-sided main trunk of the graft.
One of two clinically most popular type of Ax-Fem bypass.

Model 1 with Lazy-S type configuration (Figure 1) has shown less reduction of outflow volume along the left limb anastomotic site of the graft than Model 2 with Inverted-C type (Figure 2); 29.6% vs 16.9%. Model 3 as the improved version of Model 1 with the modification of the branching graft from the main graft has shown much less reduction of the outflow volume (40.8%) at the left femoral anastomotic site, as the least reductio among five models (Figure 3).

Model 4 as the improved version of Model 2, has most severe reduction of the outflow volume at the left anastomotic site to 6.6% of the total inflow volume and it has failed to correct the

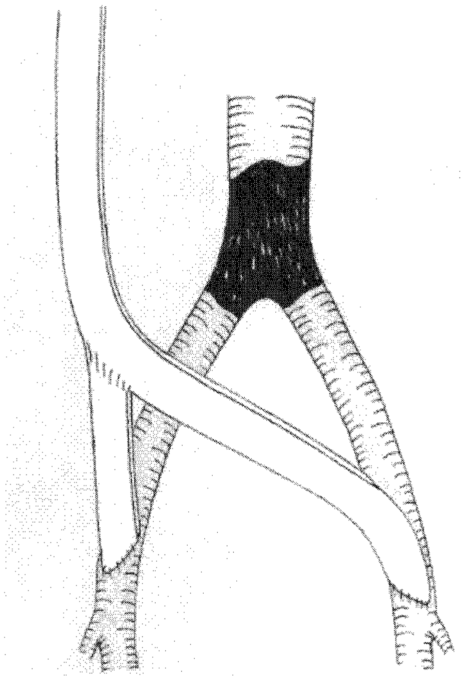

Figure 3 Model 3:Modified Lazy-S type.
Low cross-over main trunk of the bypass to maintain the main stream of inflow to the left and the graft interposition on the right side between the main graft trunk and right femoral artery with the anastomosis in end-to-side fashion.
Hemodynamically improved version of lazy-S configuration by the modification of the side-limb (branching) graft connection.

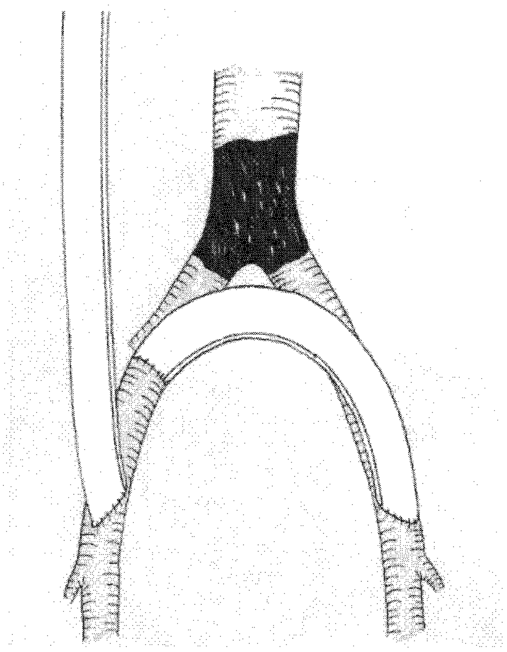

Figure 4 Model 4:Modified Inverted-C type.
* End-to-side anastomosis of the right-sided main trunk of the graft to the right femoral artery: same as the original version of inverted-C-type.
* End-to-end anastomosis of the distal stump of transected right (iliac-)femoral artery to the cross-over graft to the left.
* Modification of the conventional inverted-C type side limb (branching) connection: hemodynamically improved version to avoid double "piggy-bag" type of two anastomoses at the same site.

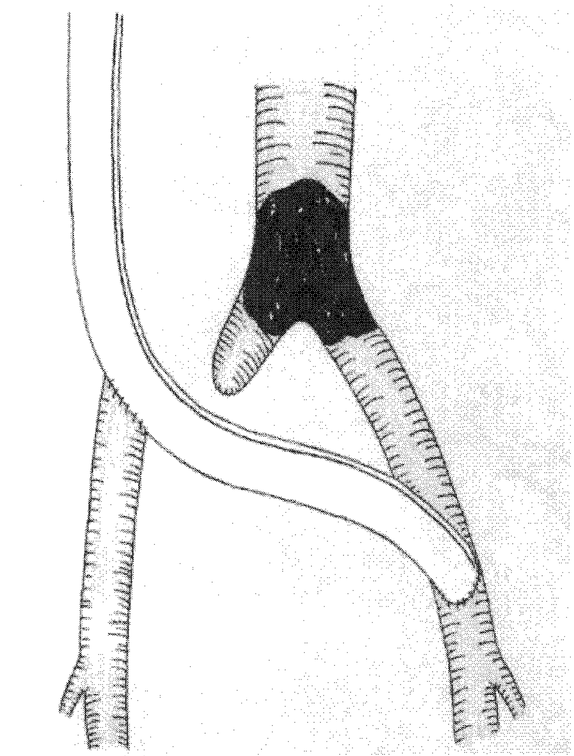

Figure 5 Model 5:Newly proposed upversion.
Most upversioned type of Ax-Fem bypass to combine the advantages from each four different configurations: eliminated the third anastomosis to reduce the number of anastomosis to two. Cross-over main trunk of the graft to the left femoral artery in end-to-side anastomosis.
End-to-side anastomosis of the distal stump of the transected right (iliac-)femoral artery, directly to the side of cross-over main trunk.

hemodynamic liability of Inverted-C type (Figure 4).

Model 5, designed to improve all the hemodynamic liability each model carries and also eliminate the third anastomosis by the direct anastomosis of the original right iliac-femoral artery stump (distal) to the side of the main cross-over graft trunk, has shown not much improvement of the flow shifting to the right and there has been persistent outflow volume reduction at the left anastomotic site to 22.2% of total inflow volume (Figure 5).

Accordingly, the tendency of the major flow volume shift to the right side anastomotic site was quite significant on all five models, including Model 5 (77.8%) which has been considered as the most ideal model among various types of the of Ax-fem bypass by many clinicians with improved hemodynamic risk involved. Model 2 and Model 4 have the worst risk of critical shifting of the flow to the right (Model 2-83% & Model 4-93.4%) and subsequent critical reduction of the outflow along the cross-over graft to the left.

Model 1 (Lazy-S type) has theoretically less risk of critical shifting of the flow by the reduction of the flow volume to the left, comparing to Model 2 (Inverted-C type); shifting of the inflow to the right side limb at 70.4% on Model 1 and 83.1% on Model 2. Model 3 (Improved version of Model 1) has least risk of critical shifting of the flow; right-59.2% & left-40.8%.

The degree of shear stress, therefore, has shown highest level among the Model 2, 4 & 5 along the right anastomotic site due to this major shifting of the inflow volume to the right side. Model 5, for example, has high degree of shear stress at the right anastomotic site between natural femoral artery to the side of cross-over graft, while it maintains low shear stress on the left side anastomotic site due to this shifted flow distribution. Model 1 and Model 3 both based on the same concept of Lazy-S type configuration, however, have shown even distribution of the shear stress along the both (left and right) anastomotic sites most probably due to the improved shifting of the outflow volume. Model 4 has shown naturally very low shear stress along the left anastomotic site due to the very low flow volume. Model 2 with Inverted-C type also has shown least recirculation zone on the left anastomotic site most probably due to the drastically reduced flow volume.

Discussion:

Patency analysis of various types of bypass graft for its risk factors has been made for decades to improve overall patency rate especially on the hemodynamic point of view which is relatively new concept to the clinicians only through the last two decades[24,31,32]. Most of the attention in this regard was given to the anatomical(in-situ) bypass to recognize its superiority to manage aortoiliac occlusive disease with substantial accumulation of new hemodynamic informations[23,34-37]. However, the extra-anatomical bypass has gained increasing favor rapidly in spite of many hemodynamic liability especially of the configuration of two limbs of Ax-Fem bypass graft[38-40]. Our investigation based on the computer simulation models have shown distinct differences between two most popular Lazy-S type and Inverted-C type configuration of Ax-Fem bypass graft on the distribution of flow volume, shear stress and recirculation zone, etc., though both types have shown similar clinical results of primary patency rate. Lazy-S type has shown better hemodyanmic status with lesser reduction of the outflow volume along the left anastomotic site with even distribution of the shear stress along both anastomoses, comparing to those of the Inverted-C type. Lazy-S type configuration is also able to keep the antegrade takeoff of the second limb of bifurcation graft as inverted-Y fashion and allow smooth laminar blood flow to both limbs of graft without formation of the turbulence (Figure 1)[41,42]. In contrast, inverted-C configuration of the second limb taking off from the end of main trunk of Ax-Fem graft near to the anastomotic site will induce the retrograde blood flow into the cross-over limb against the hemodynamic rule of the principle (Figure 2)[43]. However, the theoretical advantage of "Lazy-S" type configuration based on the hemodynamic advantage of the acute-angled branching parallel to the main trunk as side-arm fashioned takeoff has never been adequately proved for its superiority clinically over the inverted-C configuration except European Axillobifemoral Bypass Trial with twice better patency rate[44]. And these theoretical advantages of Lazy-S type over Inverted-C type even proved by the simulation model in our study were unable to help its initial leading role for the extra-anatomical bypass for AIOD through the last decade. It has been slowly replaced by the Inverted-C type even with better clinical results in general. Inverted-C type anastomosis of the second limb of Ax-Fem bypass is now in more favor with clinically better results of the patency in spite of many hemodynamic liabilities including retrograde flow to the branching graft. Lately further effort to bring the maximum inflow all the way to the distal end of the main graft by the application of double "piggyback" technique of the anastomosis of Fem-Fem limb of Ax-Fem bypass has been well accepted among clinicians as the method to minimize the potential risk of hemodynamically vulnerable segment by early branching as short as possible. Various efforts have also been made to compensate the hemodynamic disadvantage of each configuration of the takeoff branch from the main graft by the modification of these Lazy-S configuration as well as those of inverted-C configuration through the rearrangement of the connection between both limbs of the graft (Figure 3 & 4)[42]. More radical rearrangement was also proposed to improve many inherent hemodynamic defects of various types of Ax-Fem bypass, using main trunk of the graft as a single crossover graft to the contralateral femoral artery and end-to-side anastomosis of the transected proximal stump of ipsilateral right (iliac-)femoral artery to the side of main graft to allow antegrade blood flow to both limbs of Ax-Fem bypass and also eliminate the anastomosis[45] (Figure 5).

In spite of all these efforts to reduce the hemodynamic liability of various extraanatomical bypasses to improve its clinical results, clinical results of Ax-Fem bypass in general are known to be still poor comparing to those of single cross-over Fem-Fem bypass which is against the hemodynamic anticipation, because the hemodynamic advantage of Ax-biFem bypass over Fem-Fem bypass would be much higher with increased total blood volume and blood flow through the graft to supply both lower extremities.

The better clinical results of independent cross-over Fem-Fem bypass graft implemented to the unilateral iliac artery occlusive disease, have given further assurance to this hemodynamically more liable Inverted-C type configuration over the Lazy-S type of Ax-Fem bypass.

There are of course, many other hemodynamic factors, affecting the graft patency other than graft limbs configuration like graft length and diameter. But the ultimate results of graft patency will depend on total sum of all these various clinical as well as hemodynamic factors, especially of inflow and outflow status of the donor and recipient arteries.

As far as the inflow and outflow of the donor artery is equally normal without stenosis, the donor artery should be capable to respond to the lowered resistance of the recipient arteries by the increased blood flow without compromising its own circulation of donor artery system and there will not be a "steal" phenomenon.[29,46,47]. But if there is any outflow stenosis on the donor artery system, the increasing flow demand by the recipient artery system will result in a steal phenomenon on the donor side theoretically since the response by the donor artery is directly linked to the outflow resistance status, especially for the cross-over Fem-Fem bypass.

However, the improvement of over-all long term patency rate of various extra-anatomical bypasses is still warranted to match to the gold standard of Ao-Fem bypass through proper correction of the hemodynamic liability due to much reduced outflow volume at one of the two limbs of branched graft, that is left-sided cross-over graft anastomotic site by various methods including change of the diameter and length of the graft as well as modification of the arrangement of both anastomotic limbs of the graft. More scrutinizing investigation of these hemodynamic characteristics of each model has to be made in the pulsatile flow status as well.

Conclusion:

Eventhough clinical outcome of the extra-anatomical bypass for the aortoiliac occlusive disease has been equal regardless of the type of cross-over femoral graft configuration, there are distinct differences on the hemodynamic characteristics among various types of configuration of axillo-bifemoral bypass graft. In order to improve clinical results of this extra-anatomical bypass, further hemodynamic study with computer simulation models in the pulsatile flow status as well is warranted with the implementation of various modified graft conditions.

Proper modification of various hemodynamic factors of each model of Ax-Fem bypass graft including graft size (diameter), length, and the anastomosis method to correct these inherent hemodynamic defects of the presently available extra-anatomical bypass graft is urgently needed together with the improvement of man-made graft material for the better compliance to match the natural vessels. Further detailed evaluation of various hemodynamic issues on two clinically popular and well tested extra-anatomical bypasses in particular is also warranted through the joint efforts by the clinician and engineer in this particular field in order to improve the long-term patency rate of the graft.

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