Surgical Approaches to Chronic Limb Ischemia

Although endovascular advances provide a new array of options in appropriately selected patients, surgical techniques also continue to see innovation.

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The treatment of critical limb ischemia (CLI) has changed dramatically because of the explosion of catheter-based interventions. However, surgical bypass techniques continue to evolve in response to increasingly complex scenarios such as failed endovascular procedures, lack of conduit, and severe, extensive disease. Stimulated by these challenges, innovative approaches to surgical bypass continue to develop. These innovations include advances in vein bypass, improved prosthetic graft performance, and better knowledge of procedure selection through choice of the proper target artery or choice of bypass, as opposed to endovascular revascularization.

INNOVATIONS IN VEIN BYPASS

The autogenous vein remains the ideal conduit for lower extremity bypass. The greater saphenous vein results in durable reconstruction no matter which configuration is favored by the surgeon: in situ, reversed, or translocated. However, lack of saphenous vein is becoming a common clinical scenario because of previous bypass, coronary surgery, thrombophlebitis, or poor vein quality. As many as 30% of patients in need of bypass lack a suitable saphenous vein. This number increases to 50% in patients requiring a secondary bypass procedure[1] and has led to innovative approaches to alternate autogenous conduit.

Alternative autogenous conduits include the lesser saphenous vein, arm vein, composite veins, umbilical vein, and cryopreserved vein. These alternative conduits can result in acceptable, although not equivalent, results. Because arm and lesser saphenous segments may not be long enough to reach a distal tibial artery, composite vein configurations can be fashioned from several segments in order to achieve adequate length for the bypass.[2,3] Cryopreserved vein and human umbilical vein are other alternative conduits that are biologic in their properties and, therefore, have an intrinsic appeal for distal reconstruction. However, these conduits have shown limited success when used for tibial bypass.[4,5] This limited success arises from the need to splice vein segments together for adequate length and the poor quality of secondary venous conduit. The use of cryopreserved vein should be limited to bypasses that must traverse infected fields in the absence of other autogenous conduits.[6] The initial use of human umbilical vein grafts was impeded by aneurysmal degeneration of the graft material. This complication has been addressed in recent modifications of the graft design. Arm vein and lesser saphenous segments remain the best alternative choice for autogenous reconstructions when saphenous vein is not available.

INNOVATIONS IN PROSTHETIC BYPASS

Prosthetic grafts have not performed well for distal revascularization.[7,8] Past results were discouraging enough to consider primary amputation in certain patient subgroups.[9] Since then, innovative techniques have been described to improve the performance of prosthetic grafts for bypass. These innovations include improvements in graft biology, such as the interposition of venous tissue at the distal anastomosis and heparin lining the inner surface of the graft. Additional innovations address improvements in graft hemodynamics through optimization of graft geometry at the anastomosis.

Vein Interposition at the Distal Anastomosis

The interposition of venous tissue between a prosthetic graft and the recipient artery attempts to improve graft performance in several ways. The venous tissue may reduce the hyperplastic response and improve graft patency by creating a biologic buffer zone in the endothelium of the venous segment. It is easier to suture the vein to small, diseased

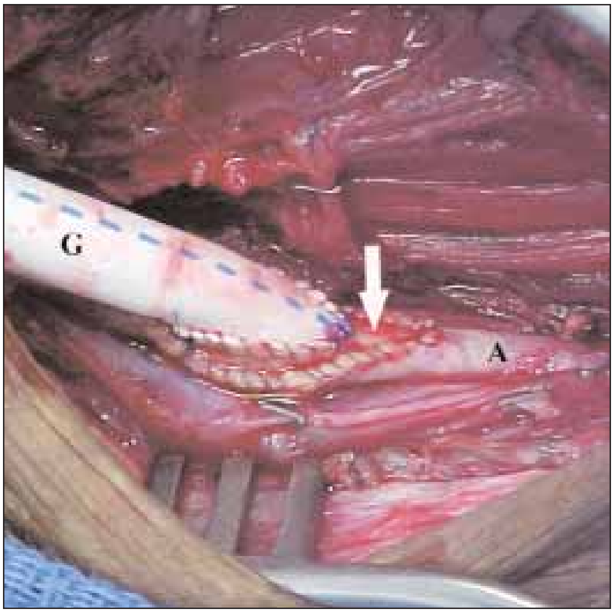

Figure 1. Anastomosis using the distal vein patch technique: PTFE graft (G), tibial artery (A), and vein path (arrow).

tibial arteries and then suture the prosthetic to the vein; this technique, although technically less demanding, may take more procedure time. There may be an effect on thrombogenicity at the interface between the high-resistance outflow artery and the prosthetic material.[10]

Vein Cuffs and Patches

In 1984, Miller et al described a vein cuff that would improve prosthetic graft patency.[11] The Miller technique involved construction of an oval venous cuff sutured to the recipient artery. The prosthetic graft was then sutured directly to the vein cuff. Miller reported on 114 bypasses with a 72% patency rate at 18 months but only had 21 distal bypasses in the series. Hobson reported a benefit for using the Miller vein cuff technique for tibial bypass with 54% patency with the cuff versus 12% patency for prosthetic alone at 24 months.[12] However, several disadvantages have been recognized with the Miller cuff, including turbulence noted at the anastomotic reservoir and difficulty achieving a proper angle between the graft and recipient artery. These hemodynamic factors may help to explain the immediate and early graft failures reported in Miller's initial series. Additionally, the oval formation of the Miller cuff is difficult to maintain in the tight anatomic spaces involved in distal bypasses, which is especially problematic in the diabetic population in which pedal bypass may be required.

Taylor et al described a vein interposition technique in an effort to address these concerns.[13] Taylor's technique required a vein patch four to five times the diameter of the prosthetic conduit. A U-shaped slit was made on the underside of the graft with minimal angulation to ensure that the graft lay parallel to the artery. The heel of the graft was then sutured directly to the artery with vein used to close the anterior elliptical defect. Taylor reported on 256 grafts with 1-, 3-, and 5-year patency rates of 74%, 58%, and 54%, respectively. Taylor hypothesized that improved graft patency was due to a reduction in the compliance mismatch between the graft material and the arterial wall, or to the inherent properties of the venous endothelium located at the anastomosis. However, there continue to be theoretical and practical disadvantages to the Taylor

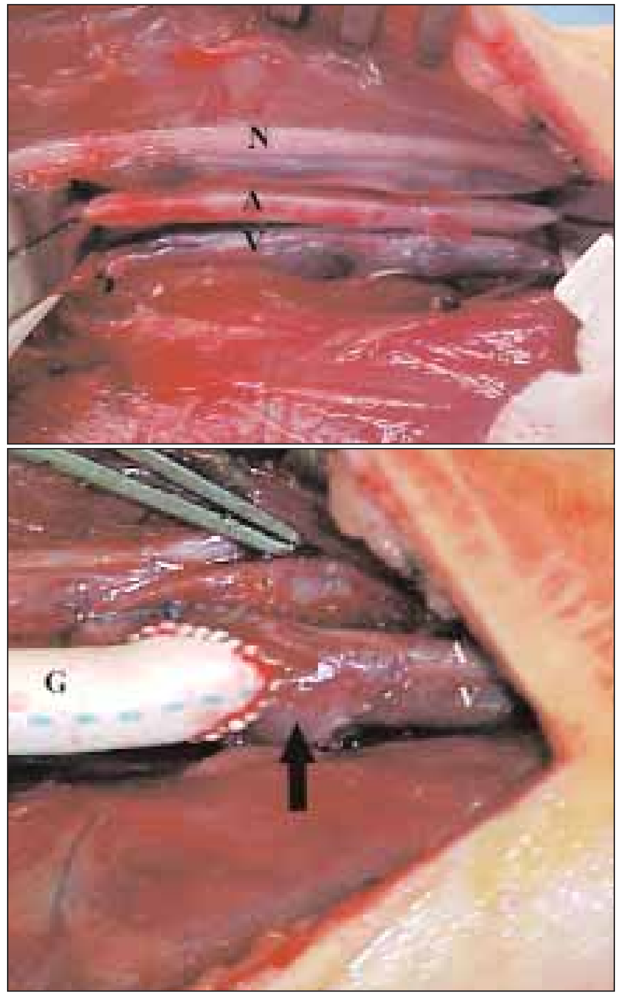

Figure 2. The distal vein patch technique with the addition of an arteriovenous fistula at the anastomosis. Tibial neurovascular bundle before anastomosis: nerve (N), artery (A), and vein (V) (top); graft (G), artery (A), vein (V), and patch over fistula (black arrow) (bottom).

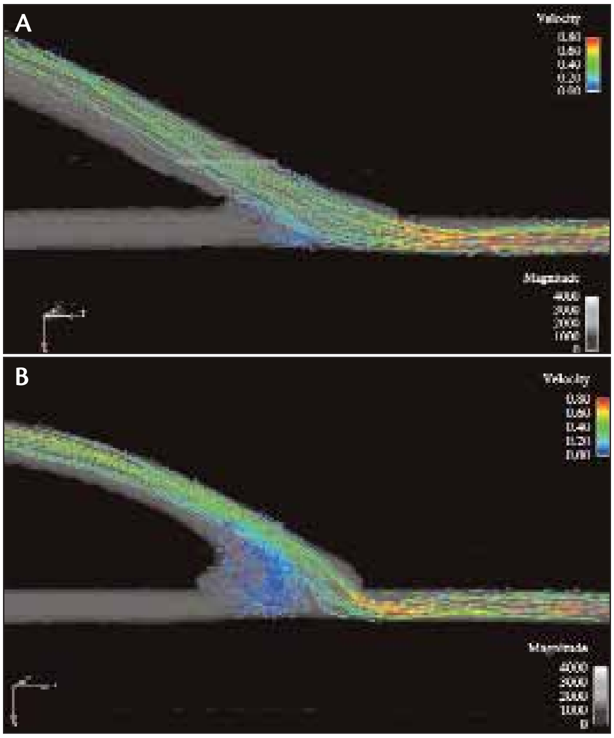

Figure 3. Magnetic resonance velocimetry images of anastomotic geometry. Straight end-to-side anastomosis (A) and precuffed end-to-side anastomosis (B).

patch technique. The arterial intima is directly exposed to graft material for the proximal half of the anastomosis, thereby losing the advantage of the venous endothelium for half of the anastomosis. There is also a point of anastomotic constriction where three suture lines converge among the artery, graft, and vein patch. Finally, a significant length of vein must be available to accomplish the anastomosis using the Taylor patch technique.

Distal Vein Patch

The distal vein patch (DVP) technique uses a technique familiar to vascular surgeons and requires a shorter arteriotomy, thereby decreasing the amount of venous tissue required for the procedure.[14] A 2- to 3-cm segment of tissue is suitable and can include saphenous vein remnants, arm vein harvested under local anesthesia, or superficial femoral vein. After the patch is sewn in place, a longitudinal cut is made in the proximal two-thirds of the patch, and the graft is sutured to the patch. The anastomosis is constructed to maintain a rim of venous tissue interposed between the graft and the entire circumference of the arterial wall (Figure 1). Because the venotomy is made in the proximal two-thirds of the patch, more venous tissue is left interposed at the toe of the anastomosis, which is a problem area for future hyperplasia.

The initial data for this DVP technique included 79 patients with no autogenous vein available as a conduit for bypass.[15] Eighty bypasses were performed in the 79 patients, with follow-up ranging from 30 days to 4 years. During this time interval, the DVP group represented 16% of the total tibial bypass experience. The indication for revascularization was limb-threatening ischemia in all patients with rest pain in 49% and gangrene or nonhealing ulceration in 51%. Reasons for the lack of adequate saphenous vein included previous failed lower extremity bypass, previous coronary bypass, unsuitable vein quality, and absence of vein due to varicose vein stripping. A high percentage of grafts originated from the external iliac artery (43%) to avoid hostile, scarred groins from previous bypass attempts. Primary graft patency was 82% at 12 months and 62% at 48 months. Subsequently, the DVP technique has been used in 249 cases.

Distal Arteriovenous Fistula

This technique is used for a subset of patients with critical ischemia and severely compromised arterial outflow as the only target for revascularization, such as isolated paramalleolar tibial segments or diseased pedal arteries. These patients are not often candidates for endovascular therapy due to the extent of the disease or previous endovascular failure. Standard bypass techniques offer a poor chance of success. An arteriovenous fistula (AVF) at the distal anastomosis has been hypothesized to benefit lower extremity revascularization in these challenging cases in two ways: it decreases outflow resistance to improve patency and carries arterial blood to the capillary bed in a retrograde fashion.[16,17] The venous circulation accepts flow overload in the high-resistance arterial circuit, thereby increasing graft flow above the critical thrombotic threshold in a disadvantaged runoff situation.

The DVP technique can be readily combined with a common ostium AVF between the recipient tibial artery and the corresponding tibial vein (Figure 2A).[18] The vein patch is sewn in place by performing patch angioplasty over the common ostium. The graft is then anastomosed to the common ostium patch as previously described for the DVP bypass (Figure 2B). An initial 30 cases have been performed with encouraging results. All patients had CLI and were considering primary amputation if additional revascularization was not possible. In each case, the recipient artery was an isolated paramalleolar tibial segment or a diseased pedal vessel not deemed optimal for bypass as assessed by preoperative angiography. Postoperative venous hypertension due to the AVF in the bypassed limb was noted in each patient to a moderate degree. This technique resulted in more than 70% primary patency at 1 year with comparable limb salvage. This innovative technique may be considered if an aggressive attempt at limb salvage is warranted.

Anastomotic Geometry

Attempts have been made to improve prosthetic graft performance by reproducing the geometry of the vein cuff with preformed prosthetic material (Distaflo, Bard Peripheral Vascular, Tempe, AZ). Theoretically, the precuffed graft would optimize hemodynamic flow patterns without the need to suture venous tissue at the distal anastomosis. Several investigators have reported their initial experience with the precuffed grafts. Jordan et al reported 43% patency for 35 precuffed grafts over a range of 1 to 30 months.[19] There has been a randomized trial comparing precuffed grafts and grafts with a vein cuff. This series randomized 47 precuffed bypasses and 44 bypasses with a vein cuff. Patency rates at 1 year were 52% for the precuffed grafts and 62% for the vein cuff bypasses. At 2 years, the patency rates were 49% and 44%, respectively.[20] A more recent analysis comparing precuffed grafts with the DVP was reported by Bellosta et al.[21] The investigators reported secondary patency at 48 months to be 31% using precuffed grafts and 62% for grafts with a DVP.

The precuffed grafts attempt to optimize hemodynamic forces at the distal anastomosis; however, the relationship between hemodynamics and intimal hyperplasia is an area of active research. Magnetic resonance velocimetry is a new method to study graft hemodynamics. This noninvasive modality uses magnetic resonance imaging technology to measure time-specific anatomic and blood flow data in a user-defined volume area. Processing magnetic resonance velocimetry data produces three-dimensional quantitative data that can be used to analyze hemodynamics of different anastomotic geometries (Figure 3).[22] Early experimental work suggests that anastomotic geometry affects hemodynamics, and the beneficial effect of the patch configuration may be due to improved hemodynamic flow patterns at the distal anastomosis. Ongoing work attempts to identify optimal anastomotic geometry.

Heparin-Bonded Grafts

Another innovative strategy to improve prosthetic graft performance involves heparin bonding on the inner surface of the graft to reduce graft thrombosis and the development of myointimal hyperplasia. Drug-immobilized surfaces may allow the prolonged activity

Figure 4. Angiosomes of the posterior tibial artery defined by cadaveric injection using different colored materials.

of chosen pharmaceutical effects and extend the desired effect on the device. Heparin-bonded grafts (Propaten, W. L. Gore & Associates, Flagstaff, AZ) use end-point covalent bonding of heparin to the luminal surface of the graft.[23] The proprietary Carmeda bonding mechanism uses a unique, single end-point covalent bond between the heparin molecule and the ePTFE that maintains the bioactivity of the heparin molecule. This process reduces platelet adherence, acute thrombus formation, and anastomotic myointimal hyperplasia in canine and primate models.[24,25]

Initial clinical experience with this bioactive graft has been encouraging. Walluschek obtained 80% 1-year patency for below-knee bypasses.[26] Bosiers et al reported primary and secondary 1-year patency rates of 82% and 97%, respectively, with little difference between popliteal (81%) and tibial (74%) bypasses. The limb salvage rate in patients with CLI (n = 41) was 87%.[27] Our initial patient cohort, combining the heparin-bonded graft with a distal vein patch in 70 patients, has resulted in primary patency rates of 87% and 72% at 6 months and 1 year, respectively. The addition of anticoagulant bonding at the graft surface is a promising adjunct to improving prosthetic graft performance for distal bypass. However, more work is required to confirm long-term results.

INNOVATIONS IN PROCEDURE SELECTION

Selecting the Proper Angiosome

Ischemic lower extremity wounds can fail to heal despite successful revascularization. Gooden et al reported that 25% of patients with heel ulcers ultimately succumbed to a major lower extremity amputation despite a palpable pedal pulse.[28] Bypass to the

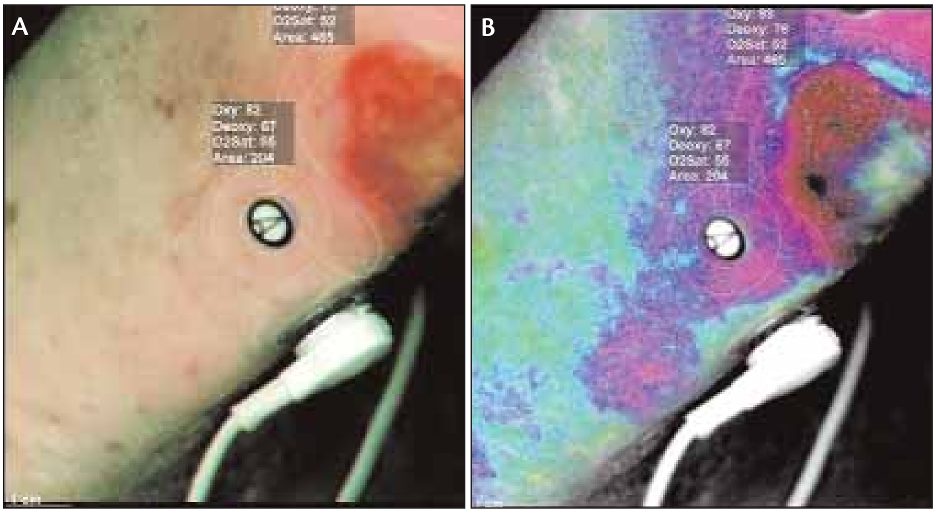

Figure 5. Hyperspectral imaging of a foot with lateral plantar wound. Probe in place near the wound (A). A hyperspectral image with corresponding values of oxyhemoglobin, deoxyhemoglobin, and oxygen saturation (B).

dorsalis pedis artery for heel ulceration has led to 85% healing; however, there remains a 15% failure rate.[29] Healing and limb salvage for ischemic wounds may be improved by direct revascularization of the involved area of the foot. In 1987, Taylor and Palmer introduced the angiosome concept that divides the body into three-dimensional vascular territories supplied by specific source arteries and drained by specific veins.[30] The foot and ankle area itself has six distinct angiosomes arising from the posterior tibial artery (3), the anterior tibial artery (1), and the peroneal artery (2).[31] The posterior tibial artery gives rise to a calcaneal branch that supplies the medial ankle and plantar heel, a medial plantar branch that feeds the medial plantar instep, and a lateral plantar branch that supplies the lateral forefoot, plantar midfoot, and entire plantar forefoot. The anterior tibial artery continues on to the dorsum of the foot as the dorsalis pedis. The peroneal artery supplies the lateral ankle and plantar heel by the calcaneal branch and the anterior upper ankle by an anterior branch (Figure 4).

A retrospective analysis was performed for 52 nonhealing lower extremity wounds requiring tibial bypass over a 2-year period.[32] Preoperative arteriograms were reviewed to determine arterial anatomy relative to each wound's specific angiosome and bypass anatomy. Patients were divided into two groups: direct revascularization (bypass to the artery directly feeding the ischemic angiosome) or indirect revascularization (bypass unrelated to the ischemic angiosome). In the direct revascularization group, there was 91% healing with a 9% amputation rate. In the indirect group, there was 62% healing with a 38% amputation rate ($P = .03$). In the wounds that healed, total healing time was not significantly different. Direct revascularization of the angiosome specific to the anatomy of the wound seemed to lead to a higher rate of healing and limb salvage. Although many factors must be considered in choosing the target artery for revascularization, consideration should be given to revascularization of the artery directly feeding the ischemic angiosome.

Selecting the Proper Means of Revascularization

Choosing the appropriate procedure to achieve a functional result in terms of limb salvage goes beyond reporting patency or target lesion revascularization. To date, treatment of chronic limb ischemia has been associated with poorer outcomes with endovascular intervention. We initiated a study of patients undergoing revascularization for chronic limb ischemia by surgical and endovascular means, conducting a retrospective evaluation to determine functional tissue outcome.[33]

A total of 113 patients were included in the study, and there were no significant differences in comorbidity between the two groups. All bypass procedures were performed to a tibial artery, and endovascular therapy included some combination of angioplasty, stent deployment, cryoplasty, and atherectomy. These endovascular techniques were used to treat superficial femoral, popliteal, and tibial arteries with an average of 1.8 lesions treated per patient. Surgical bypass resulted in greater wound healing in wounds > 2 cm in largest diameter (71% healing rate with bypass, 25% healing rate with endovascular therapy). Complete wound healing occurred in 81% of the bypass group versus 35% of the endovascular group, with bypass patients also demonstrating a shorter time for total healing.

Hyperspectral Imaging

One innovative diagnostic methodology to assess the functional result of either form of revascularization involves hyperspectral imaging. Hyperspectral imaging can determine levels of two major optical signals in biological tissue: oxyhemoglobin and deoxyhemoglobin. These signals provide a measure of local oxygen delivery and extraction in the tissue microvasculature over a specified field of view, thereby allowing assessment of the spatial distribution that can vary with location.[34] Hyperspectral imaging produces a two-dimensional image of the state of tissue oxygenation, including its spatial variation, which could accurately assess the microcirculatory response to revascularization (Figure 5). This technology shows promise in that regard, and it may be useful in determining the need for revascularization and the success of different modes of revascularization beyond that of patency data, but definitive information is not yet available.

CONCLUSION

The treatment of chronic limb ischemia now involves both endovascular and open surgical techniques in order to obtain optimal results. Appropriate patient selection for intervention is multifactorial and depends on clinical indication, arterial anatomy, and patient risk. The explosion in endovascular device development has been accompanied by innovation in techniques and grafts for surgical revascularization. Choosing the proper target artery with the best modality to achieve the optimal functional result are concepts requiring continued innovation and study. ■

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1. Brewster DC. Composite grafts. In: Rutherford RB, ed. Vascular Surgery. Philadelphia, PA: W. B. Saunders Company;1989:481-486.
2. Calligaro KD, Syrek JR, Dougherty MJ, et al. Use of arm and lesser saphenous vein compared with prosthetic grafts for infrapopliteal arterial bypass: are they worth the effort? J Vasc Surg. 1997;26:919-924; discussion 925-927.
3. Holzenbien TJ, Pomposelli FB Jr, Miller A, et al. Results of a policy with arm veins used as the first alternative to an unavailable ipsilateral greater saphenous vein for infrainguinal bypass. J Vasc Surg. 1996;23:130-140.
4. Anderson LI, Nielsen OM, Buchardt Hansen HJ. Umbilical vein bypass in patients with severe lower limb ischemia: a report of 121 consecutive cases. Surgery. 1985;97:294-299.
5. Bannazadeh M, Sarac TP, Bena J, et al. Reoperative lower extremity revascularization with cadaver vein for limb salvage. Ann Vasc Surg. 2009;23:24-31.
6. Castier Y, Francis F, Cerceau P, et al. Cryopreserved arterial allograft reconstruction for peripheral graft infection. J Vasc Surg. 2005;41:30-37.
7. Bergan JJ, Veith FJ, Bernhard VM, et al. Randomization of autogenous vein and polytetrafluoroethylene grafts in femoro-distal reconstruction. Surgery. 1982;92:921-930.
8. Veith FJ, Gupta SK, Ascer E, et al. Six-year prospective multicenter randomized comparison of autologous saphenous vein and expanded polytetrafluoroethylene grafts in infrainguinal arterial reconstructions. J Vasc Surg. 1986;3:104-114.
9. Bell PR. Are distal vascular procedures worthwhile? Br J Surg. 1985;72:335.
10. Wolfe J, Tyrell M. Venous patches, collars, and boots improve the patency rates of polytetrafluoroethylene grafts. Adv Vasc Surg. 1995;3:134-143.
11. Miller JH, Foreman RK, Ferguson L, et al. Interposition vein cuff for anastomosis of prostheses to small arteries. Aust N Z J Surg. 1984;54:283-285.
12. Kansal N, Pappas PJ, Gwertzman GA, et al. Patency and limb salvage for polytetrafluoroethylene bypasses with vein interposition cuffs. Ann Vasc Surg. 1999;13:386-392.
13. Taylor RS, Loh A, McFarland RJ, et al. Improved technique for polytetrafluoroethylene bypass grafting: long-term results using anastomotic vein patches. Br J Surg .1992;79:348-354.
14. Neville RF, Attinger C, Sidway AN. Prosthetic bypass with a distal vein patch for limb salvage. Am J Surg. 1997;174:173-176.
15. Neville RF, Tempesta B, Sidway AN. Tibial bypass for limb salvage using polytetrafluoroethylene and a distal vein patch. J Vasc Surg. 2001;33:266-271; discussion 271–272.
16. Horsley JS. Reversal of the circulation in the lower extremity. Ann Surg. 1916;63:277-279.
17. Dean RE, Read RC. The influence of increased blood flow on thrombosis in prosthetic grafts. Surgery. 1964;55:581-584.
18. Neville RF, Dy B, King W, et al. The "Patchula" bypass is a viable option for the patient without autogenous conduit and severe distal occlusive disease. Presented at Southern Association for Vascular Surgery; January 17, 2008; Naples, Florida.
19. Alcocer F, Jordan WD Jr, Wirthlin DJ, et al. Early results of lower extremity infrageniculate revascularization with a new polytetrafluoroethylene graft. Vascular. 2004;12:318-324.
20. Panneton JM, Hollier LH, Hofer JM. Multicenter prospective randomized trial comparing pre-cuffed polytetrafluoroethylene graft to a vein cuffed polytetrafluoroethylene graft for infragenicular arterial bypass. Ann Vasc Surg. 2004;18:199-206.
21. Bellosta R, Luzzani L, Carugati C, et al. Which distal anastomosis should be used in PTFE femoro-tibial bypass? J Cardiovasc Surg. 2005;46:499-503.
22. Neville RF, Elkins CJ, Marcus AT, et al. A hemodynamic comparison of straight vs precuffed ePTFE grafts using MRV technology. Presented at: 35th Annual Symposium of the Society for Clinical Vascular Surgery; March 21-24, 2007; Orlando, Florida.
23. Heyligers JM, Verhagen HJ, Rotmans JI, et al. Heparin immobilization reduces thrombogenicity of small-caliber expanded polytetrafluoroethylene grafts. J Vasc Surg. 2006;43:587-591.
24. Lin PH, Bush RL, Yao Q, et al. Evaluation of platelet deposition and neointimal hyperplasia of heparin-coated small-caliber ePTFE grafts in a canine femoral artery bypass model. J Surg Res. 2004;118:45-52.
25. Lin PH, Chen C, Bush RL, et al. Small-caliber heparin-coated ePTFE grafts reduce platelet deposition and neointimal hyperplasia in a baboon model. J Vasc Surg. 2004:39:1322-1328.
26. Walluscheck KP. Heparin-bonded expanded polytetrafluoroethylene vascular graft for occlusive vascular disease of the lower extremity. Ital J Vasc & Endovasc Surg. 2006;13:137-147.
27. Peeters P, Verbist J, Deloose K, Bosiers M. Will heparin-bonded PTFE replace autologous venous conduits in infrapopliteal bypass? Ital J Vasc Endovasc Surg. 2008;15:143-148.
28. Gooden MA, Gentile AT, Mills JL, et al. Free tissue transfer to extend the limits of limb salvage for lower extremity tissue loss. Am J Surg. 1997;174: 644-648; discussion 648-649.
29. Berceli SA, Chan AK, Pomposelli FB Jr, et al. Efficacy of dorsal pedal artery bypass in limb salvage for ischemic heel ulcers. J Vasc Surg. 1999;30:499-508.
30. Taylor GI, Palmer JH. The vascular territories (angiosomes) of the body: experimental study and clinical applications. Br J Plast Surg. 1987;40:113-141.
31. Taylor GI, Pan WR. Angiosomes of the leg: anatomic study and clinical implications. Plast Reconstr Surg. 1998;102:599-616; discussion 617-618.
32. Neville RF, Ducic I, Attinger CE. Revascularization of a specific angiosome for limb salvage: does the target artery matter? Ann Vasc Surg. In press.
33. Neville RF, Singh N, Jamil T, et al. Revascularization for wound healing: are endovascular techniques as good as open bypass? Presented at: 35th Annual Society for Clinical Vascular Surgery; March 23, 2007. Orlando, Florida.
34. Khaodhiar L, Dinh T, Schomacker KT, et al. The use of medical hyperspectral technology to evaluate microcirculatory changes in diabetic foot ulcers and predict clinical outcomes. Diabetes Care. 2007;30:903-910.