# 124 Extra-Anatomic Bypass in the Management of the Peripheral Artery Disease

Ed Aboian and Atul S. Rao

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E. Aboian
Mills-Peninsula Division, Palo Alto Medical Foundation, Burlingame, CA, USA
e-mail: edaboian@yahoo.com

A.S. Rao (✉)
Division of Vascular and Endovascular Surgery, Maimonides Medical Center, Brooklyn, NY, USA
e-mail: arao@maimonidesmed.org


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**Abstract**

The so-called extra-anatomic bypasses are surgical arterial or venous bypass procedures that circumvent the "normal" anatomic pathways. While such procedures can be performed in any vascular bed, the term most frequently is used to describe those bypasses that reroute blood to the lower extremities, avoiding intracavitary procedures. Initially promulgated as alternative revascularization methods in the treatment of peripheral arterial occlusive disease and as techniques for bringing blood back to the lower extremities in "clean fields" in the face of prosthetic infections, their role has expanded in recent years. The advent of complex endovascular technologies to treat a myriad of aortic pathologies has resurged these bypasses as adjunctive procedures in aortic endografting. In this chapter, we discuss the indications and techniques of the more commonly used extra-anatomic bypass and also touch on more complex indications and uses in the endovascular era. Much of our discussion will focus on the more common lower extremity bypasses – femorofemoral bypass and axillofemoral bypass. We will also discuss aortic arch vessel cervical extra-anatomic bypasses. Indications, techniques, and unique complications will all be covered.

**Glossary of Terms**

**Endarterectomy** Removal of atheromatous plaque from inside of the artery.

**Femorofemoral bypass** Bypass from one common femoral, superficial femoral or profunda femoral artery to a contralateral femoral artery.

**Graft 'Hooded' on** The hood of the graft sutured onto the target artery over the vessel bifurcation.

**Tissue loss** Evidence of ulceration or gangrene in the extremity.

**Abbreviations**

| | |
|---|---|
| CT angiography | Computerized tomographic angiography |
| ePTFE graft | Extended Polytetrafluoroethylene graft |
| SFA | Superficial femoral artery |
| TASC | TransAtlantic Inter-Society Consensus |
| TIA | Transient ischemic attack |

## Introduction

The extra-anatomic bypass refers to any bypass graft that is placed outside of the normal anatomic vascular pathway. These procedures are an important tool in vascular surgical armamentarium. They were developed as alternatives to traditional in-line reconstructions to overcome anatomic or physiologic constraints. Traditionally, these procedures have been used to provide inflow to the lower extremities while circumventing hostile operative fields (infection, prior surgical sites, etc.), or providing less invasive techniques that avoid the risks associated with intracavitary large artery exposures. With the advent of endovascular therapies, the necessity for extra-anatomic bypasses as primary means of revascularization in high-risk patients has diminished. However, in the modern era they have evolved a new role, as rapid advances in endovascular techniques have expanded the use of these procedures to comprise a component of a "hybrid" therapy for vascular reconstructions, most commonly for aortic aneurysms and dissections.

In this chapter we will provide an overview of extra-anatomic procedures and their basis. We will focus most of our discussion on those utilized in the treatment of lower extremity peripheral arterial occlusive disease, namely, the aortoiliac and femoral arterial systems. We will also discuss the use of adjunctive extra-anatomic vascular reconstructions utilized in the treatment of aortic aneurysms and other aortic pathologies.

## History

Freeman and Leeds described the first femorofemoral bypass with autogenous superficial femoral artery in 1952 (Freeman and

Leeds 1952). In that report aneurysmal thrombosis of right common iliac artery resulted in severe right lower extremity ischemia. The right lower extremity was revascularized by cross-femoral transposition of endarterectomized left superficial femoral artery. The first comprehensive description of prosthetic femorofemoral bypass in a series of patients was provided by Vetto in 1962 (Vetto 1962). The technique described in the report is similar to that used today. Later, Blaisdell and Hall along with Louw proposed axillofemoral bypass in 1963 (Blaisdell and Hall 1963; Louw 1963). Blaisdell and Hall's initial description was that of bilateral axillofemoral bypasses following the excision of an infected aortic graft. The first description of bypass from the descending thoracic aorta to the femoral arteries was by Stevenson et al. who performed a bypass between the descending thoracic aorta and the femoral arteries in a patient with a history of disabling intermittent claudication and thrombosed aortoiliac graft (Stevenson et al. 1961).

## Hemodynamics

An important consideration in the creation of extra-anatomic bypasses is that the new construct must provide adequate flow to the recipient limb, without significant compromise of blood flow to the donor limb. Intuitively it would follow that rerouting a portion of blood from a particular vascular bed may result in compromise to that donor vascular bed. However, from a physiologic perspective, blood flow is maintained in a parallel resistance fashion, thereby not significantly reducing the overall resistance of the system as a whole. To support this contention, studies have confirmed minimal, if any, significant arterial steal. Shin et al. demonstrated in a dog model increased flow through the "donor" artery proximal to a crossover bypass graft takeoff, and no steal observed even in the presence of hypotension (Shin and Chaudhry 1979). This concept had similarly been described by Ehrenfeld et al. nearly two decades prior (Ehrenfeld et al. 1968). Both models involved the creation of arteriovenous fistula in the "recipient" artery, serving to increase the demand of blood flow needed for that extremity. And both studies demonstrated similar results that the increased demand of flow was met by an increase flow into the "donor" artery. In fact, Shin et al. demonstrated increased blood flow even in the suprarenal aorta.

Other studies have demonstrated a slight decrease in the mean resting ankle pressure on the donor artery side following femorofemoral bypass (Flanigan et al. 1978; Nicholson et al. 1988). However, in the presence of patent inflow and outflow ipsilateral to the donor artery, this phenomenon is of no clinical significance.

Certain physiologic principles can affect the overall patency of extra-anatomic bypass grafts relative to native anatomic or in-line vascular reconstructions. According to Poiseuille's Law, the derivation of resistance is directly proportional to the length of the tube and inversely proportional to the fourth power of the radius of the tube (Pfitzner 1976). Therefore, shorter, larger diameter bypass grafts have diminished resistance, which may confer improved patency. However, extra-anatomic bypasses often provide flow through circuitous routes, thereby increasing the "L" in the equation for resistance; similarly because of the donor and recipient vessel sizes, smaller diameter grafts are used compared to the native arteries that are being bypassed (i.e., the aorta). This results in decreasing the radius in the resistance equation and thereby increasing the resistance of these grafts.

When evaluating a patient for possible creation of an extra-anatomic arterial reconstruction, several hemodynamic factors must be carefully considered. First, the inflow to the donor vessel must be free of disease. A hemodynamically significant inflow lesion may place the bypass graft in jeopardy of failure. It also can contribute to the development of "steal" syndrome in the donor limb (Shin and Chaudhry 1979; Ehrenfeld et al. 1968; Trimble et al. 1972). In their canine model of extra-anatomic bypass, Shin et al. showed "steal" phenomenon only in "critical" inflow restriction (Shin and Chaudhry 1979). Second the outflow of both donor and recipient vessels must be fully ascertained. Significant outflow lesions in the recipient vessel may also increase resistance and place the graft in jeopardy of failure. In the lower extremity, this concept is illustrated by the frequent need for outflow bypass procedures to aid patency of the inflow graft. Alternatively, the grafts can be "hooded" onto the profunda femoris artery, which generally provides a low resistance outflow bed.

## Indications for Extra-Anatomic Bypass

### Atherosclerotic Aortoiliac Occlusive Disease

Femorofemoral and axillofemoral bypasses are appropriate for patients with aortoiliac occlusive disease requiring revascularization for palliation of symptoms or for limb salvage, who are not candidates for endovascular therapy and are at high risk for open in-line revascularization. Patients that would be considered poor candidates for endovascular intervention based on the TASC II classification are those with type D lesions (Norgren et al. 2007) or those that had failed prior endovascular interventions.

### Active Infection

The presence of an active infection in the vicinity of a native artery that would preclude safe placement of an in-line reconstruction represents one of the most common applications of an extra-anatomic bypass. This includes infections of the aorta, mycotic aortic aneurysms, infected aortic prostheses, and aortoenteric fistulas. In the lower extremity, the groins are frequent sites of such infections, stemming from contiguous spread of primary groin infections or from infected prostheses that originate in the groin. Such infections necessitate a graft originating from a remote inflow source and traveling such that it circumvents the infected site. In the case of abdominal aortic infections, the most common extra-anatomic bypasses include axillofemoral or axillobifemoral bypasses, thoracofemoral bypasses, and cross-femoral (femorofemoral) bypasses. In the case of groin infections, extra-anatomic bypasses include axillofemoral and obturator bypasses. The distal target site of such reconstructions in these circumstances is distal to the groin, often involving the SFA or profunda artery directly. Cases of extra-anatomic bypasses performed for infected descending thoracic aortic prosthetic grafts have also been described, with a graft tunneled via a median sternotomy from ascending aorta through the diaphragm to supraceliac aorta (Riesenman and Farber 2010).

### Hostile Anatomy

A prior history of abdominal operations and/or abdominal wall stomas makes aortofemoral bypass technically more challenging. This includes any history of retroperitoneal procedures, involving the kidneys, ureters, or bladder. In addition, a history of retroperitoneal inflammatory processes or neoplasms may complicate iliac artery exposures and tunneling of grafts in this plane. Similarly, in the chest, history of prior sternotomy may render in-line anatomic procedures to be more risky. In these scenarios extra-anatomic bypasses are reasonable alternatives.

### High-Risk Patients

Patients with significant cardiac and/or pulmonary comorbidities, who have prohibitive risk for cavitary procedures, could be candidates for extra-anatomic revascularization. Complete preoperative evaluations of patients requiring revascularizations must be undertaken, including baseline cardiac and pulmonary assessments. This may include diagnostic tests such as cardiac stress tests and pulmonary function tests. In addition, consultation with specialists may be of value to help generate risk profiles. Based on these risk profiles, decisions can then be made as to the optimal revascularization route.

### Dissection

While a complete discussion of aortic dissections is beyond the scope of this chapter, they should be considered as a potential indication for extra-anatomic bypasses. In this potentially labile patient population, such bypasses provide an expeditious method of restoring normal perfusion to distal sites, circumventing dissected aortic tissue. In addition to the use of axillobifemoral or femorofemoral bypasses to restore perfusion to malperfused lower extremities, visceral extra-anatomic bypasses can be performed, i.e., retrograde iliac–mesenteric or celiac artery bypasses.

### Component of a Hybrid Therapy

With the advent of advanced endovascular techniques, hybrid procedures have emerged as less invasive methods of treating aneurysmal or occlusive arterial disease compared to traditional open surgical therapy in patients in whom purely endovascular solutions are not feasible. Hybrid procedures combine a less invasive open surgical technique with an endovascular solution (Leon et al. 2007). As such, extra-anatomic bypasses are often utilized as less invasive surgical modalities to complement other endovascular procedures. An example is the use of a femorofemoral bypass as an adjunct in the management of infrarenal aortic aneurysms, when an aorto-uniiliac device is used (Chuter et al. 1999). Similarly, carotid to carotid artery or carotid to subclavian artery bypasses and transpositions can be used as adjuncts in the management of arch and descending thoracic aortic aneurysms and dissections.

## Lower Extremity Extra-Anatomic Bypasses

### Technique and Graft Configuration for Lower Extremity Revascularization

#### Preoperative Considerations

The preoperative workup for extra-anatomic bypasses is similar to the general evaluation and preparation prior to other major vascular procedures, with some minor differences. Thorough patient vascular histories are obtained, with attention to risk factors and symptoms of claudication and rest pain/tissue loss in both extremities. Careful physical examination is performed with thorough pulse examination in all extremities. In the case of preoperative evaluation for possible axillofemoral bypass, bilateral upper extremity blood pressure assessment is of major importance to assess for possible inflow disease that may compromise subsequent graft patency. A blood pressure differential of 15 mm of mercury or greater should warrant further investigation. Noninvasive imaging should be obtained of the target sites to serve as a baseline and help guide other imaging modalities as necessary. For the lower extremity, we routinely obtain arterial noninvasive physiologic tests such as ankle brachial indices and pulse volume recordings. We also obtain full arterial duplex of the lower extremity that we are aiming to revascularize. In addition, in the case of extra-anatomic bypasses, the donor artery status must be clarified. As such, for femorofemoral bypasses, we obtain full noninvasive physiologic testing of the donor side, as well as arterial duplex of the intended donor artery. For axillofemoral bypasses, any discrepant or abnormal upper extremity blood pressures or pulse exams warrant upper extremity duplex assessment or other imaging.

In the modern era, many extra-anatomic bypasses are performed in cases of endovascular failure, so preoperative angiographic imaging is routinely performed beforehand. However, if not done prior, we recommend good contrast-enhanced imaging of target sites in order to be familiar with the anatomy and runoff. For limited suprainguinal disease (aortoiliac occlusive disease), we advocate the use of CT angiography, but for infrainguinal disease, we routinely perform digital subtraction angiography.

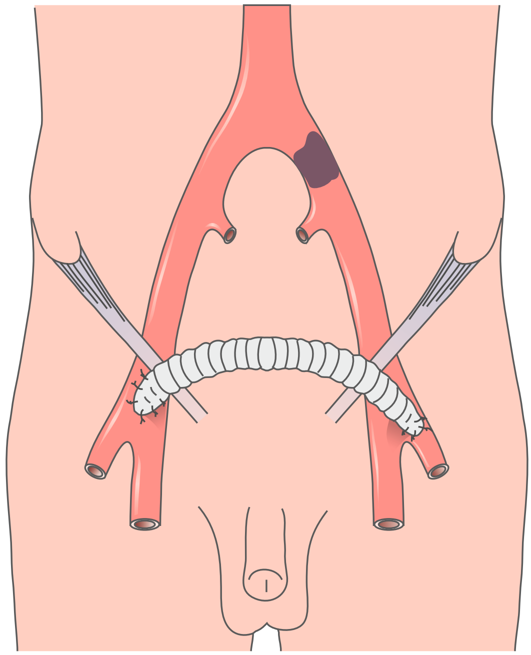
While the choice of anesthesia can vary, we generally favor general anesthesia for these procedures as they involve several sites of operation. However, based on the anesthesiologists' experience, regional blocks can provide a safer alternative for procedures such as femorofemoral bypasses. Finally, some of these procedures can be done under minimal anesthesia with local infiltration and sedation alone, but given the multiple operative sites, this often becomes difficult.

Finally, the importance of maintenance of sterility during these procedures cannot be underemphasized. These procedures can involve multiple sites of surgery and often involve redo dissections. These factors alone increase the risk of infection. Added to that, however, is the fact that many of these procedures are performed due to infected prostheses in the first place. Therefore, careful sterile technique is paramount. In cases involving extra-anatomic bypasses in conjunction with debridement or removal of infected tissue/prosthetics, the clean revascularization part is ideally performed first in clean planes, and it is performed with isolation of the infective processes with the aid of sterile adhesive antimicrobial drapes or covers. Once the clean bypass procedure is completed, dressings are applied to isolate the clean fields prior to debridement of the infections. In the case of axillobifemoral graft placement for aortoenteric fistulas with hemodynamic instability, the abdominal/infected portion must of course be immediately addressed, and care is taken to perform the revascularization in clean planes once the bleeding and infection are controlled. This includes taking measures to change gowns, gloves, drapes, and instruments prior to beginning the clean revascularization.

## Femorofemoral Bypass

Femorofemoral procedures involve bypassing from one common femoral, superficial femoral (SFA), or profunda femoral artery to a contralateral femoral artery. These are most typically performed due to unilateral iliac or proximal common femoral artery occlusion. They can also be performed adjunctively with axillofemoral bypasses, thoracofemoral bypasses, and aorto-uniiliac endografting. The major advantage is the relative ease of exposure of the target arteries and the avoidance of the intra-abdominal cavity (Sketch 1).

The procedure is performed with the patient in the supine position. We prefer spinal or general anesthesia, although local infiltration anesthesia also can be used in acute settings in critically ill



**Sketch 1** Schematic of femorofemoral bypass

patients. The abdomen is prepped along with the groins and anterior thighs to allow access to the abdomen in case of need for more proximal arterial control. Bilateral longitudinal incisions are used to expose the femoral arteries from inguinal ligament to femoral bifurcation. As an alternative, oblique groin incisions (parallel to the groin creases) can be used, but they provide somewhat limited exposure beyond the femoral artery bifurcation. The presence of significant calcification or stenoses in the femoral vessels may predispose one to a longitudinal incision, anticipating the need for a thorough endarterectomy. Dissection and control of the common femoral artery, SFA, and profunda is undertaken. The graft is tunneled subcutaneously from one groin incision to the other within the abdominal wall superior and anterior to the pubis to form a C-shape configuration. We favor bluntly dissecting the subcutaneous plane superior to the fascia with fingers from either side until our fingers connect. A gentle "C" curve is attained, and we find that anastomosing to the distal common femoral artery aids in the creation of such a curve. Alternatively, the graft can be tunneled in the extraperitoneal retropubic space in cases of prior abdominal midline surgical scars. The conduit for femorofemoral bypass could be a native vein, an endarterectomized arterial conduit, or a prosthetic material. However, we generally prefer to use externally supported ePTFE grafts. Dacron and ePTFE grafts confer similar patencies and hemodynamic performance (Johnson and Lee 1999).

In regard to graft diameter comparing 6–8 mm grafts, studies have confirmed that there is no significant patency advantage to one size over the other (Schneider et al. 1992; Ricco and Probst 2008). Therefore, we prefer 8 mm externally supported ePTFE grafts, although this determination ultimately depends on the size of the native femoral artery.

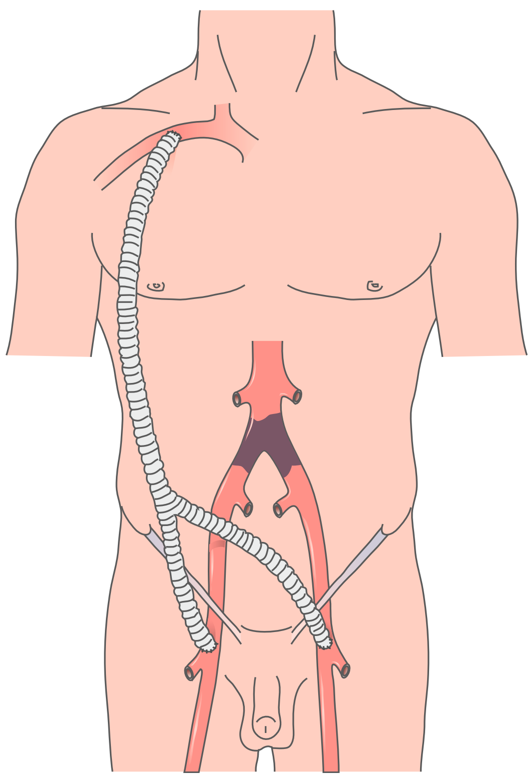
Once we have completed dissection, have secured control of the femoral artery branches in both groins, and tunneled our graft, the patient is systemically heparinized. An arteriotomy is created on the donor common femoral artery. The graft is beveled such that the toe faces distally, and an end-to-side anastomosis is fashioned between graft and artery. In the recipient artery, we configure our anastomoses in end-to-side fashion with the hood of the graft overlying the origin of deep femoral artery in order to take advantage of the low resistance outflow of the profunda femoris to maximize graft patency. This is especially important in patients with significant femoropopliteal occlusive disease. If an endarterectomy has been performed, we usually use the hood of the graft to act as a patch or alternatively sew a patch angioplasty into place, followed by anastomosis of the hood of the graft into the patch. We hood our graft such that there is a gentle C-type curve onto the recipient artery. Excessive angulation can result in kinking or turbulence that can compromise graft patency.

If the bypass is performed for common iliac artery occlusive disease with undiseased external and internal iliac arteries or in the case of femorofemoral bypass used in the treatment of aortic aneurysm with aorto-uniiliac devices, endarterectomy of the more proximal common femoral artery may be necessary in order to ensure adequate retrograde perfusion to the recipient internal iliac artery.

## Axillofemoral Bypass

Axillofemoral bypasses provide a means of bringing inflow to the femoral artery system with one of the axillary arteries serving as the donor source. They are typically performed in the setting of abdominal aortic/iliac artery occlusive disease in high-risk patients or in the setting of hostile abdomen requiring restoration of inflow to the femoral arteries. The major advantage is the lack of intracavitary exposure needed and thereby the relative ease of exposure of proximal and distal target sites (Sketch 2).

The procedure is performed under general anesthesia with the arms either tucked or with the right arm abducted at 90°. Our preference is to tuck the arm to the side, but when performing the bypass as such, care must be taken to provide some laxity to the anastomosis to avoid significant tension upon arm abduction. While there have been descriptions of the procedure having been performed under local anesthesia in patients with lower extremity ischemia and in tenuous



**Sketch 2** Schematic of axillofemoral bypass

physiologic states (Al-Wahbi 2010), tunneling of the axillofemoral graft segment can prove difficult under these circumstances. A wide surgical preparation is necessary, involving the ipsilateral neck, chest wall, shoulder, lateral chest and abdominal walls, and bilateral groins.

Either axillary artery can be an appropriate donor unless there is disease in the more proximal subclavian or axillary arteries. Preoperative evaluation by history, bilateral upper extremity blood pressure and pulse examination, and noninvasive imaging must be performed prior to the procedure to avoid the situation of inadequate inflow from the donor artery. If there is no significant disease in either subclavian artery, the right axillary artery is preferred, as the innominate and right subclavian arteries are less prone to atherosclerotic changes (Alexander and Selby 1980), and left-sided grafts may complicate a future left-sided thoracotomy for an aortic procedure.

A transverse infraclavicular incision is made and carried through the clavipectoral fascia, exposing the pectoralis major muscle. The pectoralis major muscle fibers are split with the retractor, exposing the deep fascia and deep to that the fat containing the axillary vein, artery, and brachial plexus elements. The axillary vein is usually encountered first, and branches may have to be ligated to allow sufficient exposure. The axillary artery is exposed from the clavicle medially to the pectoralis minor muscle laterally, often requiring the ligation of crossing veins or small arterial branches.

Simultaneous groin incisions are made as described earlier to expose the recipient femoral vessels. We then tunnel the vertical limb of the graft deep to the tendon of the pectoralis major muscle in a lateral direction to the chest wall and then subcutaneously along the midaxillary line to the ipsilateral femoral artery. Frequently, a counterincision is required along the abdominal or chest wall to facilitate tunneling secondary to the distance the graft must travel. The graft should be tunneled medially to the anterior superior iliac spine to avoid potential mechanical compression of the graft against the bone when the patient lies in the right lateral decubitus position. Similarly, care must be taken to ensure some redundancy in the axilla to avoid tension on the axillary artery anastomosis. Once the patient is fully heparinized and the arteries are clamped, the proximal anastomosis is performed to the first portion of axillary artery medial to pectoralis minor muscle in end-to-side fashion. Placement of the anastomosis in that location avoids tension and decreases the chance of axillary artery anastomotic disruption (Blaisdell 1985, 1988). If needed, the pectoralis minor muscle can be divided, and the thoracoacromial trunk ligated to allow enhanced exposure. Care must be taken to avoid injury to the brachial plexus structures and nerve branches. The vertical limb is anastomosed to the ipsilateral femoral artery in end-to-side fashion. The same principles of femoral anastomosis are applied as discussed earlier.

Our preferred graft material is externally supported 8 mm diameter ePTFE. We prefer to use a preformed axillofemoral graft to expedite the procedure. When we use this, the vertical limb must be passed through our tunnel site in a cephalad direction. However, if a premade bifurcated axillofemoral graft is unavailable, the creation of a cross-femoral bypass is necessary. This involves creating an end-to-side anastomosis to the distal vertical limb of the axillofemoral graft and tunneling to the contralateral groin as described earlier. Alternatively, Blaisdell describes an end-to-end anastomosis to the proximal common femoral artery (Blaisdell 2010). In order to do so, He performs the ipsilateral axillofemoral anastomosis of the vertical limb to the distal common femoral artery; then the proximal common femoral artery is dissected back to the inguinal ligament and the artery is transected with oversewing of the proximal stump. An end-to-end anastomosis to the common femoral artery is then created with the crossover graft. The use of preformed graft can expedite the performance of the operation by decreasing the number of anastomosis from four to three. It is very important to confirm enhancement of blood flow in the recipient vessels using continuous wave Doppler after the anastomoses are completed and all clamps are removed. It is also essential to ensure adequate blood flow in the donor arm beyond the axillary anastomosis by confirming a good radial pulse or satisfactory oxygen saturation in the hand with both the axillofemoral graft and axillary outflow vessels unclamped.

### Obturator Bypass

Though it is relatively infrequently performed, the obturator bypass provides an additional tool in the vascular surgeon's armamentarium in revascularizing the lower extremity in the face of hostile groin anatomy. This bypass is typically performed in the settings of active infection in the groin, but also has been described in the settings of extensive neoplasm resection when there is no soft tissue to cover the reconstruction (Donahoe et al. 1967); it is also described in the settings of therapeutic radiation to the groin, or extensive scarring. The major drawbacks are that it requires more extensive exposure than some of the other extra-anatomic bypasses and that many surgeons are less familiar with the anatomy.

The operation is performed with the patient under general anesthesia. The patient is placed supine, and the entire abdomen and lower extremity are prepped. Infected wounds are excluded from the sterile field to the extent possible. Utilizing a standard curvilinear lower quadrant incision, the muscles of the anterior abdominal wall are divided through the transversalis fascia. The extraperitoneal fat and peritoneal sac are identified and swept off the transversalis fascia, and the peritoneum is retracted medially. The retroperitoneal space and psoas muscles are identified, and the peritoneum is further swept medially until the iliac vessels are identified. Great care is taken to avoid any injury to the ureter (which we prefer to keep anteriorly attached to the posterior peritoneal lining). The common or external iliac artery can serve as the donor artery. The obturator foramen is approached more medially in the operative field. The obturator foramen is palpated under the superior ramus of the pubic bone. The obturator artery and nerve perforate this membrane superolaterally, so it is safest to avoid these structures by passing the graft through the superomedial aspect of the obturator foramen. The caudad portion of the obturator canal is reached by incising the endopelvic fascia and bluntly separating a portion of the underlying obturator internus and levator ani muscle fibers. The membrane is extremely strong and must be incised sharply or with an electrocautery. The obturator foramen passes through the obturator externus muscle and the pectineus muscle more anteriorly. The adductor muscles attach to the bony margins around the obturator foramen. We prefer a long tunneling device to be passed from below and directed upward. The graft can then be tunneled to any of the femoral vessels or even the popliteal artery. The superficial femoral artery and popliteal artery are reached by tunneling just anterior to the adductor magnus between the adductor longus and adductor brevis. If tunneling is done to the deep femoral artery, the tunnel must extend through the adductor brevis to reach the profunda artery. After administration of intravenous heparin, the proximal and distal anastomoses are then completed using standard techniques, usually end to side to both donor and target arteries. Once the reconstruction has been completed, the surgical incisions are closed and excluded before the groin is explored to remove any infected prosthetic or native material and ligate vessels as necessary to prevent hemorrhage. It is critical to debride sufficient artery to permit oversewing of grossly noninfected segments of the femoral arteries proximally and distally. Ideally, continuity of the SFA and profunda is sought in order to allow retrograde flow through the distally perfused artery into the other (i.e., if distal target is the distal SFA, by maintaining continuity of the two vessels, blood can retrograde perfuse the profunda). If this is not feasible and the origins of these vessels need to be ligated, they can be reimplanted upon one another or alternatively mobilized and syndactylized. Autologous venous bypass conduit is preferred to prosthetic as this operation is performed in the settings of active infection in the groin (Shaw and Baue 1963).

### Thoracofemoral Bypass

This procedure serves as an alternative inflow procedure, generally performed in the setting of inability to perform in situ aortoiliac bypass due to prior failure, surgery, radiation, or infection. This procedure requires a thoracotomy and therefore is suitable only to patients with good physiologic reserve. Patients at high risk with poor pulmonary reserve are better served with an axillofemoral bypass. One of the major advantages is the relatively atherosclerotic disease-free inflow source of the descending thoracic aorta (Frazier et al. 1987; Passman et al. 1999).

Our technique is very similar to that described by Criado (1997). After the induction of anesthesia with a double lumen endotracheal tube, the patient is placed in a modified lateral 60° right lateral decubitus position, with the hips rotated as flat as possible. To facilitate positioning, we usually use a "beanbag" to stabilize the patient's position and reduce the risk to any dependent pressure points during surgery. The left arm is positioned anteriorly and supported. We make our groin incisions first to limit the time of open cavitary space. The left groin incision is extended cephalad, and the abdominal muscles are divided above the inguinal ligament to expose the retroperitoneal space. A retroperitoneal tunnel is created anterior to the bladder to the right groin incision to allow future tunneling of the right limb of the graft.

A left posterolateral thoracotomy is performed through the seventh, eighth, or ninth intercostal space. Single lung ventilation is begun, and the inferior pulmonary ligament is divided to allow improved mobilization of the lung. The descending thoracic aorta is dissected, and a disease-free segment is located for the proximal anastomosis. A segment of the aorta is circumferentially dissected, and an umbilical tape passed around it. Caution must be exercised to avoid avulsion of posterior intercostal arteries. At the time of fashioning the proximal anastomosis, we prefer using the umbilical tape to anteriorly elevate the aorta and facilitate placement of a side-biting aortic clamp. We tend to use bifurcated Dacron grafts, similar to those used for aortobifemoral bypass grafts. The graft limbs are tunneled from the chest into the extraperitoneal abdominal space through a small opening on the periphery of the diaphragm. We pass our hands from the left retroperitoneum cephalad, posterior to the kidney, and caudad from the chest incision through the retroperitoneum until our hands meet. Distal anastomoses are typically made to the femoral arteries; however, they may be made to the iliac arteries, as dictated by the anatomy (Fig. 1).

## Results

### Femorofemoral Bypass

#### Patency

The results of femorofemoral bypass grafting have been shown to vary widely among the different published series (Ricco and Probst 2008). This difference is likely related to patient selection and indication for bypass. Some authors use femorofemoral bypass exclusively for high-risk patients with limb-threatening ischemia while others extending indications to low-risk patient with claudication. Ricco and Probst reported a multicenter, randomized prospective comparison of femorofemoral bypass to direct (aortofemoral or iliofemoral) bypass (Ricco and Probst 2008). In their treatise, they tabulated the results of any previously published studies of femorofemoral bypass that included at least 40 patients, follow-up of at least 5 years, and life-table estimates of graft patency at 5 years. Their summary of prior published reports is listed in Table 1.

The cause of failure of the extra-anatomic bypass grafts is most likely related to progression of disease in both inflow and outflow arteries. Studies, however, have shown conflicting data regarding endovascular treatment of the inflow arteries in regard to graft patency. Porter et al. reported some degree of contralateral iliac artery disease in patients with extensive unilateral disease and advocated use of the donor iliac artery angioplasty in combination with crossover bypass (Porter et al. 1973). Perler et al. concluded that patency of the crossover bypass in patients who underwent preliminary stenting of the donor artery was comparable to that in patients whose donor artery was normal (Perler and Williams 1996). In another report by Aburahma et al., the combined use of iliac balloon angioplasty and stenting with femorofemoral bypass grafting was effective and durable, if the donor iliac stenosis length was less than 5 cm (Aburahma et al. 2001).

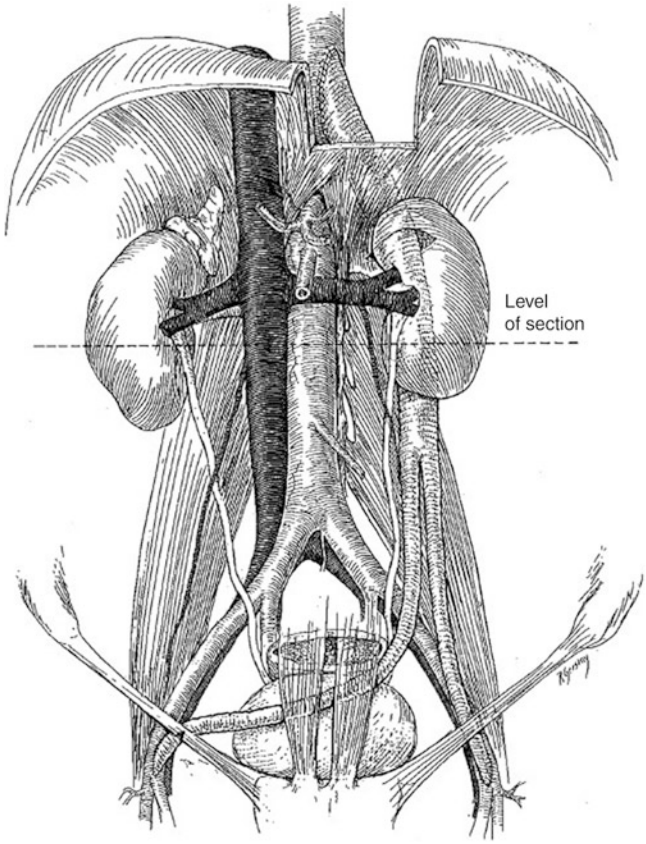



**Fig. 1** Thoracofemoral bypass (Reprinted from Enrique Criado (1997) Descending thoracic aorta to femoral artery bypass. Surgical technique Annals of Vascular Surgery 11 (2):206–215, with permission from Elsevier)

For longer lesions, percutaneous transluminal angioplasty failed to support femorofemoral bypass grafting. Another study, however, found inflow donor iliac artery stenting to be an independent predictor of decreased primary and assisted primary crossover bypass patency (Huded et al. 2012).

Another reported cause of crossover bypass failure is progression of outflow arterial disease in the recipient limb (Rutherford et al. 1987; Dick et al. 1980). The striking effect of SFA occlusion on the primary patency of crossover bypass was described by Rutherford et al., who report a drop in primary patency from 79 % to 53 % when comparing patients with patent SFAs to those with SFA occlusions (Rutherford et al. 1987). In the randomized study by Ricco and Probst, crossover femorofemoral bypass patency rates in patients with SFA stenosis >50 % or occlusion resulted in patency rates of 62.5 % and 42.3 % at 5 and 10 years versus 71.9 % and 64.3 % at 5 and 10 years in those with stenoses <50 % in the SFA. Interestingly SFA stenosis/occlusion made no difference in regard to 10-year patency in the arm of patients randomized to undergo direct bypass (aortofemoral or iliofemoral) (Ricco and Probst 2008). Conversely, there is data to suggest that the patency of the SFA does not influence the patency of the bypass graft (Ascer et al. 1985; El-Massry et al. 1993). Proponents of this notion support that patency of at least one healthy artery – either the superficial femoral artery or the deep femoral artery – appears to provide adequate outflow to support patency (Schneider et al. 1992).

Certain patient characteristics may also play a role in graft patency. In patients with histories of prior aortic grafting with subsequent aortobifemoral graft limb occlusion, femorofemoral bypass has been noted to portend inferior results compared with patients undergoing primary femorofemoral bypass (Schneider

**Table 1** Outcomes in femorofemoral bypass grafting (Reprinted from Jean-Baptiste Ricco and Herve Probst (2008) Long-term results of a multicenter randomized study on direct versus crossover bypass for unilateral iliac artery occlusive disease. Journal of Vascular Surgery 47(1): 45–54.e1, with permission from Elsevier)

| | | | Primary patency at 5-year[a] | |
|---|---|---|---|---|
| First author | Year of publication | Number of bypasses | % | Bypasses at risk at 5-year |
| Mannick[34 b] | 1978 | 53 | 80 | Na |
| Flanigan[14] | 1978 | 80 | 74 | Na |
| Sheiner[35] | 1979 | 73 | 73 | Na |
| Dick[30] | 1980 | 133 | 73 | Na |
| Devolfe[36] | 1983 | 99 | 71 | Na |
| Plecha[37] | 1984 | 119 | 72 | 39 (33 %) |
| Lamerton[38] | 1985 | 54 | 60 | 12 (22 %) |
| Rutherford[4] | 1987 | 60 | 62 | 5 (8 %) |
| Piotrowski[18] | 1988 | 47 | 55 | 5 (11 %) |
| Farber[39] | 1990 | 71 | 82 | 21 (30 %) |
| Perler[40] | 1991 | 50 | 57 | 2 (4 %) |
| Harrington[41] | 1992 | 162 | 64 | 31 (19 %) |
| Criado[26] | 1993 | 110 | 60 | 21 (19 %) |
| Brener[29] | 1993 | 228 | 55 | 54 (24 %) |
| Johnson[9] | 1999 | 340 | 49 | 51 (15 %) |
| Mingoli[33] | 2000 | 228 | 70 | 89 (39 %) |
| Purcell[42] | 2005 | 144 | 74 | 20 (14 %) |
| Kim[43] | 2005 | 192 | 65 | Na |
| This study | 2007 | 74 | 72 | 51 (69 %) |

*Na* Data not available in the study
[a]Cumulative patency at 5 years according to life-table analysis
[b]Denotes references number

et al. 1992; Rutherford et al. 1987; Brener et al. 1993). Most patients who experience thrombosis of an aortobifemoral graft limb are symptomatic and require urgent intervention. Femorofemoral bypass is an option to expeditiously restore lower extremity circulation; however, it may be at the cost of inferior long-term patency. Schneider et al. also noted a trend toward younger patient age conferring worsened graft patency for femorofemoral bypass (Schneider et al. 1992). However, there was a similar trend after aortobifemoral bypass, and the result may represent the effect of more aggressive atherosclerosis in patients who require intervention at a younger age.

### Limb Salvage

The true determination of limb salvage rates based on the available literature is difficult to adequately ascertain as many of the reported studies focus on claudicants or groups with mixed indications. Schneider et al. documented a 3-year limb salvage rate of 88 % among patients undergoing femorofemoral bypass (Schneider et al. 1992) for acute ischemia, claudication, rest pain, or tissue loss. Mingoli et al. demonstrated a 5-year limb salvage rate of 78 % following femorofemoral bypass (Mingoli et al. 2001) in their cohort of patients, of whom 82.5 % were treated for limb-threatening ischemia. Interestingly, in the reported series of iliac angioplasty/stenting in conjunction with femorofemoral bypass, the diminished patencies seen in iliac angioplasty/stenting of inflow did not portend decreased limb salvage rates (Aburahma et al. 2001; Huded et al. 2012).

### Mortality

The perioperative mortality associated with femorofemoral bypass is highly dependent on patient selection but should be well under 5 % in elective operations (Flanigan et al. 1978; Brief et al. 1975). The overall survival is also highly variable and is related to the indication for operation. Many of the case series seen in the literature report on mixed indications for surgery, with higher-risk patients frequently undergoing extra-anatomic bypasses. Thus, actual mortality rates as a result only of the procedure itself cannot be accurately interpreted. Ricco and Probst report one mortality in the direct reconstruction arm versus zero mortalities in the crossover bypass arm in their randomized prospective trial (Ricco and Probst 2008). They also cite well-matched baseline cardiovascular risk factors in both groups.

## Axillofemoral Bypass

### Patency

As with femorofemoral bypass, the reported results of axillofemoral bypass vary broadly in the literature. This is again most likely related to patient selection and indication for procedure. Early reports were focused on occlusive disease and reported 3-year patency in the range of 39–85 % (Schneider and Golan 1994). Subsequently, the indication for the extra-anatomic bypass was extended to include patients with claudication, who would tend to have more favorable patency. The other group of patients that has favorable outcome following this procedure is that of patients undergoing axillofemoral bypass as part of the treatment for infection of the aorta or an aortic prosthesis or for aortoenteric fistula. The long-term survivors in this category are likely to have better patency than those with chronic severe arterial occlusive disease (Bacourt and Koskas 1992; Seeger et al. 2000). A more recent report by Passman and associates reported a 5-year estimated primary patency rate of 74 % (Passman et al. 1996). This was found to be comparable with aortofemoral bypass patency in the same cohort with a 5-year patency rate of 80 % (not a statistically significant difference).

Thus, it becomes clear that outcomes in patients with arterial occlusive disease must be distinguished from patients in whom the procedure was performed for aneurysmal disease. In addition, as Passman and colleagues point out, earlier series of axillofemoral grafting were small sized and externally supported grafts were not used in many of these (Passman et al. 1996).

Emergent axillobifemoral bypass confers less favorable outcome compare to elective group (Savrin et al. 1986; Agee et al. 1991). Results after primary operations, including axillofemoral bypass, can be expected to be superior to those for procedures performed as a secondary procedure (history of failed reconstruction) (Rutherford et al. 1987).

The configuration of the graft also may have bearing on the patency. While it remains a controversial subject, many authors cite axillobifemoral configuration as conferring better patency rates than axillounifemoral configuration (Rutherford et al. 1987; Hepp et al. 1988; LoGerfo et al. 1977; Kalman et al. 1987). LoGerfo et al. attribute this phenomenon to higher blood flow through the vertical limb of the graft proximal to the origin of the crossover limb (LoGerfo et al. 1977). They measured average flow by electromagnetic flow meter to be 273 mL/min in axillounifemoral grafts and 621 mL/min in axillobifemoral grafts. In their series, they report 74 % versus 34 % patency rates at 5 years for axillobifemoral versus axillounifemoral configurations, respectively. Other groups report similarly discrepant patency rates for the two configurations. Rutherford et al. cited a 62 % versus 19 % patency at 5 years for axillobifemoral versus axillounifemoral grafts (Rutherford et al. 1987), and Hepp et al. report 5-year patency rates of 79.9 % and 45.7 %, respectively (Hepp et al. 1988).

However, other series report comparable patency rates and limb salvage rates in axillounifemoral and axillobifemoral configurations (Ascer et al. 1985; Mohan et al. 1995). Mohan et al. report impressive primary patency rates of 80 % at 3 years in both graft configurations and secondary patency rates of 91 % in axillobifemoral grafts and 85 % in axillounifemoral grafts at 2 years (Mohan et al. 1995).

### Mortality

Despite the varied indications and mixed patient demographics/risk profiles reported for axillary to femoral arterial reconstructions, perioperative mortality rates have been relatively consistent, ranging from about 4.9–13 %, with the majority reporting 8–9 % mortalities (Schneider et al. 1992; Rutherford et al. 1987; El-Massry et al. 1993; Hepp et al. 1988; LoGerfo et al. 1977; Kalman et al. 1987; Harrington et al. 1992; Burrell et al. 1982). The 5-year mortality following axillofemoral bypass ranges from 23 % to 79 % in published series. Such variability is in part related to patient selection. Patients with claudication usually have better survival than patients with critical limb ischemia. There is also significant variability in comorbidities and lack of uniform definition of high-risk patient among published series. A recent summary of published reports on outcomes of axillounifemoral and axillobifemoral bypass grafts by Ruggiero et al. is provided in Table 2 (Ruggiero and Jaff 2011).

### Obturator Bypass

As with all extra-anatomic bypasses, there is a great variability in the literature. Sautner et al. reported their experience achieving secondary patency rates of 75 % and 55 % at 1 and 5 years, respectively, and a limb salvage rate of 77 % at 5 years (Sautner et al. 1994). In addition, they report similar cumulative data when they combined their results with cases reported in the literature, citing overall patency rates of 72.7 % and 56.9 % at 1 and 5 years, respectively. However, Nevelsteen et al. report less robust outcomes, with a 5-year patency rate of 37 % with a perioperative mortality rate of 9 % in their series of 55 obturator bypasses (Nevelsteen et al. 1987). Patency rates varied based on distal target site in their analysis, with 71 % above knee versus 45 % below knee patencies at 3 years. Despite its technical demands and the relative difficulty of creating the tunnel, transobturator grafts appear to provide good hemodynamic performance and seem relatively insensitive to hip movement. The main advantage of this procedure is in cases of severe groin infections precluding other safe means of establishing inflow.

### Thoracofemoral Bypass

Thoracofemoral bypasses have generally demonstrated good durability in limited long-term data. Passman et al. reported a primary patency of 79 % at 5 years with an overall survival of 67 % in their series of 50 patients over 15 years (Passman et al. 1999). Their secondary patency in that series was 84 % at 5 years, and their limb salvage rate was 93 %. They noted a trend toward improved patency in patients treated for claudication versus limb-threatening ischemia. Interestingly, they reported no difference in patency rates whether the procedure was performed as a primary revascularization or secondarily. This same group of authors had earlier published their data along with a meta-analysis at the time comprising 146 patients (Criado and Keagy 1994). In it they noted very similar results with 5-year primary and secondary patency results of 73 % and 83 %, respectively. McCarthy et al. report a patency rate of 100 % at 4 years in their series of 21 patients over 10 years (McCarthy et al. 1993). Large series of descending thoracic aortic to femoral artery bypasses are lacking, however, and long-term follow-up is also limited. Thus, thoracofemoral bypasses serve as a highly durable alternative extra-anatomic bypass in good risk candidates.

## Supra-aortic Trunk and Upper Extremity Extra-Anatomic Bypasses

We include upper extremity bypasses in our discussion of extra-anatomic bypass. While our discussion has focused mainly on bypasses in lower extremity disease, we will briefly discuss upper extremity/supra-aortic trunk revascularizations as forms of extra-anatomic bypasses. These extrathoracic, extra-anatomic bypasses have proven to be quite a durable alternative to riskier anatomic procedures. Berguer et al. report a low perioperative mortality of 0.5 % (one patient) in their series of 182 cervical revascularizations, which included carotid–subclavian artery bypasses and transpositions, carotid–carotid bypasses, and subclavian–subclavian bypasses (Berguer et al. 1999). They also cite good long-term patency with 91 % and 82 % primary and secondary patency at 10 years, respectively.

**Table 2** Outcomes in axillofemoral bypass grafting (Reprinted from Nicholas J. Ruggiero and Michael R. Jaff (2013) The current management of aortic, common iliac, and external iliac artery disease: Basic data underlying clinical decision making. Annals of Vascular Surgery 251(7):990–1003, with permission from Elsevier)

| Author | Year | Patient number | Reasons | 30-day mortality (%) | 5-year mortality (%) | Graft type | Graft number | 1-year patency (%) | 5-year patency (%) |
|---|---|---|---|---|---|---|---|---|---|
| Moore el al.[122] | 1971 | 52 | A | 8 | 70 | AF(F)[a] | 52 | 62 | 9 |
| Eugene et al.[123] | 1977 | 59 | A | 8 | 73 | AF | 35 | 62 | 30 |
| | | | | | | AFF | 24 | 62 | 30 |
| Lo Gerfo et al.[124] | 1977 | 130 | A | 8 | 23 | AF | 64 | 64 | 37 |
| | | | | | | AF | 66 | 89 | 74 |
| Johnson et al.[135] | 1977 | 56 | A | 2 | 37 | AFF | 56 | 82 | 76 |
| Sheiner[126] | 1979 | 45 | A | 2 | 32 | AF | 25 | 60 | 51 |
| Ray et al.[127] | 1979 | 84 | A | 3.7 | 32 | AF | 33 | 75 | 67 |
| | | | | | | AFF | 21 | 90 | 77 |
| Kenney et al.[128] | 1982 | 92 | A | NA | NA | AF | 58 | 85 | 66 |
| Courbier and Bergeron[129] | 1982 | 220 | A | 3.6 | 24 | AF | 220 | 57 | 64 |
| Asceretal.[130] | 1985 | 56 | A | 5.3 | 57 | AF | 34 | 68 | 44 |
| Allison et al.[131] | 1985 | 109 | A | 6.4 | 44 | AF | 87 | 48 | 16 |
| | | | | | | AFF | 25 | 58 | 45 |
| Chang[132] | 1986 | 88 | A | 2 | 47 | AF | 47 | NA | 33 |
| Christenson et al.[133] | 1986 | 85 | A | 3.6 | 45 | AF(F) | 85 | 74 | 68 |
| Foster et al.[134] | 1986 | 52 | A | 12 | 60 | AF(F) | 52 | 60 | 32 |
| Donaldson et al.[135] | 1986 | 100 | A | 8 | 31 | AF(F) | 72 | 78 | 48 |
| Savrin et al.[136] | 1986 | 33 | A | 18 | 59 | AF(F) | 96 | 91 | 75 |
| Schulz et al.[137] | 1986 | 41 | A | NA | NA | AF(?)[b] | 11 | 95 | 80 |
| Rutherford et al.[138] | 1987 | 42 | A | 12 | 50 | AF | 15 | 48 | 19 |
| | | | | | | AFF | 27 | 78 | 62 |
| Pietri el al.[139] | 1987 | 167 | A | 7.2 | NA | AF(F) | 167 | NA | 35 |
| Hepp et al.[140] | 1988 | 124 | A | 4.9 | 40 | AF | 102 | 60 | 46 |
| | | | | | | AFF | 22 | 83 | 80 |
| Mason et al.[90] | 1989 | 37 | A | 2.8 | NA | AF(F) | 37 | NA | 80 |
| Naylor et al.[95] | 1989 | 38 | A | 11 | 56 | AF | 21 | NA | 50 |
| | | | | | | AFF | 17 | NA | 80 |
| Harris et al.[83] | 1985 | 76 | A | 4.5 | NA | AFF | 76 | 93 | 85[d] |
| Dé and Hepp[141] | 1991 | 131 | A | 5.3 | NA | AF | 107 | NA | 44 |
| | | | | | | AFF | 24 | NA | 73 |
| Bacourt et al.[142] | 1992 | 98 | 5 | 24 | 55 | AFF | 98 | NA | 65 |
| Wittens et al.[143] | 1992 | 117 | A | 12 | NA | AFF[c] | 58 | 38[e] | NA |
| | | | | | | AFF[d] | 59 | 84[c] | NA |
| El Massry et al.[144] | 1993 | 79 | A | 5 | 79 | AF | 50 | NA | 79 |
| | | | | | | AFF | 29 | NA | 76 |
| Taylor et al.[145] | 1994 | 184 | A | 5 | 48 | AF(F) | 184 | NA | 71 |
| Overall | | | | 6.9 | 44 | | | 75 | 85 |
| Axillounifemoral | | | | | | | | 71 | 49 |
| Axillobifemoral | | | | | | | | 83 | 68 |

*A* atherosclerotic, *S* septic, *AF* axillounifemoral graft, *AFF* axillounifemoral graft, *NA* no data

[a]AF(F), combined AF and AFF

[b]AF(?), AF or AFF not specified

[c]3-year (%) graft patency

[d]4-year (%) graft patency

[e]Femorofemoral limb at 90° angle from axillofemoral graft

## Carotid–Subclavian Revascularizations

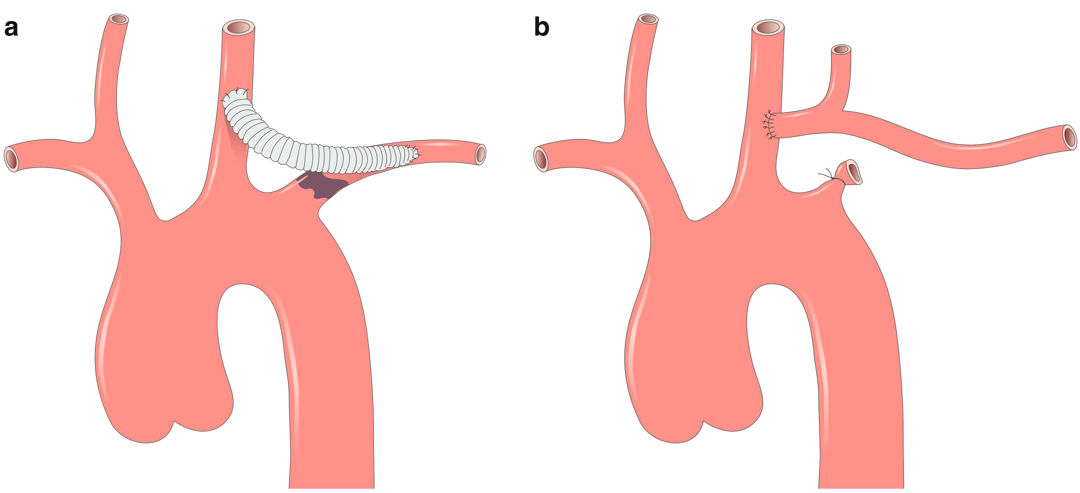
Patients with subclavian artery stenosis or occlusion may require surgical intervention for symptoms of vertebrobasilar insufficiency due to subclavian steal or for symptoms of upper extremity ischemia such as claudication or distal embolization. In addition, patients with prior history of internal mammary artery coronary bypass grafts with subsequent proximal subclavian artery stenoses may require revascularization of the subclavian artery for graft salvage. Those with stenoses or occlusion of the common carotid artery most frequently require revascularization for TIAs, stroke, or syncopal episodes. As was mentioned earlier, these procedures can also be used as a component of hybrid therapy for aortic arch aneurysms.

### Carotid–Subclavian Bypass and Transposition

#### Technique

The carotid–subclavian artery bypass or transposition allows the bypass of an occluded proximal arch vessel (common carotid artery or subclavian artery) by providing inflow from the other vessel (Sketch 3). Both procedures share the advantage of being performed through limited cervical incision, with avoidance of a median sternotomy or thoracotomy. The advantage of transposition over the bypass is avoidance of prosthetic material and one anastomosis versus two anastomoses. The primary disadvantage of transposition, however, is the need for more extensive dissection of the proximal subclavian artery. Transposition is contraindicated in patients with an early origin of the vertebral artery and in patients with patent internal mammary–coronary artery bypass grafts.

For subclavian artery to carotid artery transposition, a transverse supraclavicular incision approximately 2 fingerbreadths superior to the clavicle is made. The clavicular head of the sternocleidomastoid muscle is divided. The omohyoid muscle is divided medially, and the common carotid artery is circumferentially dissected and mobilized medially. The internal jugular vein is retracted anteromedially. The subclavian artery is exposed by dividing the scalene fat pad and then the inferior insertion of the anterior scalene muscle (on the first rib). The phrenic nerve should be identified coursing on the anterior scalene from lateral to medial as it descends inferiorly. On the left side, the thoracic duct should also be ligated with ties to avoid a postoperative duct leak. The subclavian artery is mobilized sufficiently proximally and distally; proximally the internal mammary and vertebral




**Sketch 3** (**a**) Schematic of carotid–subclavian artery bypass. (**b**) Schematic of carotid–subclavian artery transposition

branches are carefully controlled. After heparinization, the proximal subclavian artery is transected. The stump of the subclavian artery is oversewn with two layers of running Prolene suture. Once the subclavian artery is mobilized sufficiently, the common carotid artery is then clamped and an end-to-side anastomosis is performed with 6-0 Prolene suture.

The exposure for a carotid–subclavian bypass is similar; however, less extensive dissection and mobilization of the subclavian artery are required. End-to-side graft to artery anastomoses are created to the subclavian artery and carotid artery. The graft is tunneled posterior to the internal jugular vein, and care is taken to avoid injury to the vagus nerve. Prosthetic grafts are generally favored over autogenous tissue as they confer improved patency (Ziomek et al. 1986; Law et al. 1995). Our preferred graft choice is Dacron, although PTFE is also suitable.

## Results

Excellent short- and long-term results have been reported in the literature for both carotid transposition and carotid–subclavian bypass. Mortality reports in more recent series have been very low between 0 % and 0.8 %, and patency figures in these reports have confirmed good durability ranging from 83 % to 100 % at 5 years (Law et al. 1995; AbuRahma et al. 2000; Perler and Williams 1990; Salam and Lumsden 1994; Vitti et al. 1994). In a systematic review of all published series, Cina et al. identified 516 procedures with a mean follow-up of 58 months with a primary patency of 84 % for carotid–subclavian bypass (Cina et al. 2002). As discussed earlier, prosthetic appears to confer better patency than autogenous vein, and this was seen by Cina et al. in their systematic review as well, with 86 % patency (at a mean follow-up of 58 months) versus 74 % patency (at a mean follow-up of 49 months) in prosthetic and vein, respectively. However, transpositions appear to confer the best patency. Law et al. report 100 % patency of transpositions at 5 years, and similarly Cina et al. cite a 99 % patency at a mean follow-up of 61 months (Law et al. 1995; Cina et al. 2002).

The perioperative stroke rates reported have been relatively low for these procedures, ranging from 0 % to 6.6 % (Law et al. 1995; Vitti et al. 1994; Cina et al. 2002). However, Scali et al. reevaluated the stroke risk in a very recent series and found it to be higher than prior reported (Scali et al. 2013). They reported a perioperative stroke rate of 8.9 % in patients undergoing open cervical subclavian revascularization for thoracic aortic endovascular aneurysm repair (TEVAR) versus 15.8 % for those undergoing revascularization for occlusive disease.

### Carotid–Carotid and Axillo-axillary Bypass

The carotid–carotid artery bypass provides an extrathoracic arterial inflow source and can be useful in the setting of occlusive disease in the other arch vessels. In these situations the contralateral carotid artery can provide inflow for either carotid or subclavian revascularization. Manart et al. described the virtues of the bypass in that it provides a clean source of inflow via a short graft with high flow rates (Manart and Kempczinski 1980). Bilateral common carotid artery exposure with retropharyngeal tunneling of the graft has been described by Berguer and Gonzalez (Berguer and Gonzalez 1994). This avoids a subcutaneous graft and potential transection with any midline neck procedure. Alternatively the grafts can be tunneled to the contralateral internal carotid artery or subclavian artery (Berguer and Gonzalez 1994).

Carotid–carotid artery crossover bypass surgery has been reported to be a safe and durable procedure. Ozvath et al. described their series of 24 patients over 5 years, with an 88 % primary and 92 % secondary patency at 3 years (Ozvath et al. 2003). Stroke-free survival was 94 % at 4 years.

Axillo-axillary graft can similarly provide an extrathoracic revascularization source for arch vessel occlusive disease (Mozersky et al. 1973). The exposure of the axillary artery is discussed earlier in the chapter. Once bilateral axillary arteries have been exposed, the graft is passed subcutaneously over the chest wall and bilateral end-side anastomoses are fashioned. The major disadvantage of this procedure is the risk of graft transection with future sternotomy procedures. Results, although limited, have been favorable with primary patencies in the order of 88 % at 10 years (Chang et al. 1997).

## Complications

While the majority of potential complications seen in extra-anatomic bypasses are common to all bypass procedures and grafts, there are certain potential situations specific to these grafts of which the clinician must be aware. Complications specific to axillofemoral bypass include brachial plexus injuries, axillary anastomotic disruption, and thromboembolism to the donor arm and recipient legs following thrombosis of the graft. Disruption of the axillary anastomosis of axillary-femoral grafts was originally described in a Dacron graft by Daar and Finch (Daar and Finch 1978). They described a case in which sutures were pulled through the artery 3 weeks following bypass. Taylor et al. described their large series of 200 PTFE axillofemoral grafts over 10 years, in which they report a 5 % incidence (10 patients) of axillary disruption (Taylor et al. 1994). They cite that the disruption ultimately results from excessive tension along the axis of the graft, and this creates an excessive force on the heel of the graft. They recommend certain precautionary measures to minimize the incidence: placing the anastomosis on the first part of the axillary artery, prepping the entire arm to allow movement to assess the anastomosis under stress, and leaving redundancy in the graft and tunneling it parallel to artery outward to chest wall before curving it downward toward groins. In addition, they state the manufacturers' recommendation to minimize excessive arm abrupt movements and abduction greater than 90° for 6–8 weeks.

Treatment of axillary disruption involves expeditiously getting the patient to the OR and obtaining proximal control of the subclavian artery using supraclavicular approach or balloon occlusion. After obtaining proximal control, the infraclavicular incision is reopened and the repair should be performed by placing interposition graft. Simple repair of anastomotic disruption has been shown to result in secondary disruption (White et al. 1990). Interestingly, at the time of their publication, Taylor et al. cite 23 other reported such cases, and a total of 67 cases of which they were "informed" about using "Freedom of Information Act authority." As they point out, all prior reported cases involved PTFE, except the initial description by Daar and Finch. In addition, they note the incidence of graft disruption, even after the adherence to the aforementioned recommendations. And in some of those disruptions, the graft was torn in the body of the graft with intact artery. They hypothesize that perhaps a weakness induced by needles in the PTFE graft disrupts the polymeric integrity.

Non-anastomotic disruption of axillofemoral bypass grafts has also been described in PTFE grafts (Onoe et al. 1994; Grochow and Raffetto 2008; Shibutani et al. 2012). One such case was purported to be due to mechanical stress placed on the graft by the iliac bone (Onoe et al. 1994).

Thrombotic complications related to axillofemoral bypass are rare. Axillary artery thrombosis is a possible complication of axillofemoral bypass graft and is related to excessive downward traction on the donor artery, leading to a sharp angulation or "Y" elongation of the artery with proliferative changes in the intima (Khalil and Hoballah 1991; Kempczinski and Penn 1978).

Distal embolization is an extremely rare complication and primarily occurs after graft thrombosis. The incidence of embolic events in one series was reported to be 2.7 % of all patients with axillofemoral bypass and 25 % of those patients with occluded grafts (McLafferty et al. 1995). The source of the embolus is presumed to be the blind stump of the proximal portion of the graft limb that remains patent after graft occlusion (Bandyk et al. 1981). The

**Fig. 2** Status post revision of original axillobifemoral bypass graft with resection of infected portion of vertical limb, left limb, and crossover limb. Re-anastomosis of clean bifurcated graft in clean tissue planes (Note, left common femoral artery oversewn and syndactylized superficial femoral artery and profunda femoris artery to allow retrograde flow through both branches)

treatment of this complication varies from embolectomy to prophylactic detachment of the proximal graft and patch angioplasty of the axillary artery. In addition, Kallakuri et al. describe the endovascular treatment of this "graft stump syndrome," by using a stent graft to cover the embolic source (Kallakuri et al. 2003).

Specific complications to cervical extra-anatomic bypasses include stroke, cranial nerve injury, and thoracic duct leak. The incidence of stroke was discussed earlier. In Berguer's series of 173 patients, he reported a 4 % incidence of perioperative stroke (Berguer et al. 1999). In addition, he reported five cases of transient Horner's syndrome and four cases of recurrent laryngeal nerve injury.

While it is beyond the scope of this chapter to discuss graft infections, we make note that infection of axillofemoral or femorofemoral bypass grafts poses a unique problem because these patients have often been treated for failure of prior reconstructions; often have multiple comorbidities, making them extremely poor candidates for additional reconstructive surgery to deal with this problem; and have extremely limited anatomic options for revascularization. They frequently require another alternative extra-anatomic bypass if revascularization is needed (Fig. 2).

## Extra-Anatomic Bypass in the Endovascular Era

With the advent of complex endovascular aortic procedures, a new role has emerged for the extra-anatomic bypass – as an adjunctive part of a hybrid procedure. Femorofemoral crossover grafts were routinely used adjunctively during the treatment of abdominal aortic aneurysms with aorto-uniiliac devices. While the use of these devices has diminished significantly in favor of bifurcated, modular devices, crossover bypasses may still be required to in cases of unilateral iliac severe occlusive disease or to treat complications such as endograft limb occlusion. The durability of femorofemoral bypasses in this setting is quite good – Hinchliffe et al. report patency rates of 91 % at 3 years and 83 % at 5 years in their series of aneurysms treated with aorto-uniiliac devices coupled with adjunct femorofemoral crossover bypasses (Hinchliffe et al. 2003).

Endovascular treatment of descending thoracic aortic aneurysms has evolved as a primary treatment choice in this group of patients. With the FDA approval of several thoracic aortic stent grafts, including the Gore TAG (W.L. Gore & Associates, Flagstaff, AZ), Zenith TX2 (Cook Medical Inc, Bloomington, IN), and Medtronic Talent (Medtronic Inc, Santa Rosa, CA), endovascular stent graft exclusion of descending thoracic aortic aneurysms has become a mainstay of treatment. These devices require proximal seal

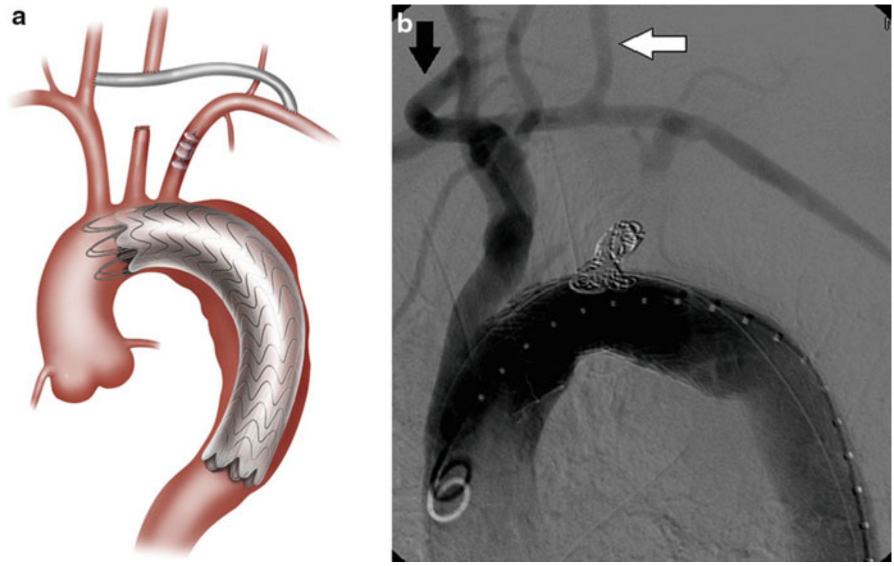



**Fig. 3** (**a**) Schematic depicting thoracic aortic endovascular aneurysm repair (TEVAR) with coverage of left subclavian artery and left common carotid artery. Cervical extra-anatomic right carotid to left common carotid artery and left subclavian artery bypasses performed to revascularize covered arch vessels (Reprinted from Nicholas D. Andersen et al. (2013) Results with an algorithmic approach to hybrid repair of the aortic arch. Journal of Vascular Surgery 57(3):655–667, with permission from Elsevier). (**b**) Intraoperative arch aortography upon completion of procedure depicted in (**a**). *Solid black arrow* depicts graft originating from *right* common carotid artery. *Solid white arrow* depicts *left* common carotid artery

zones in normal aorta distal to the arch vessels but proximal to the origin of the aneurysms. Therefore, in order to extend the proximal seal zone to allow endovascular treatment of a broader group of patients, hybrid approaches have emerged that involve some degree of coverage of the arch vessels with the stent graft combined with cervical revascularization (Fig. 3; Melissano et al. 2007; Ishimaru 2004).

The subclavian artery is the most frequently covered with endografts, and based on increased risk of neurologic injury (Buth et al. 2007), consensus guidelines recommend revascularization of the artery when intentional endograft coverage is performed (Matsumura and Rizvi 2010). Extra-anatomic subclavian artery revascularizations as components of these hybrid procedures seem to have equivalent durability to those performed for occlusive disease alone (Scali et al. 2013). Carotid–carotid artery bypasses are also performed in order to extend the proximal landing zone even further proximally.

In addition to the management of aneurysms, other aortic pathologies are treated with endovascular graft coverage, including dissections, transections, and pseudoaneurysms (Murphy et al. 2012). Extra-anatomic bypass combined with endograft aortic coverage has also become more commonplace in the management of Kommerell's diverticuli (Knepper and Criado 2013), which often requires bilateral carotid–subclavian bypasses due to the presence of aberrant right subclavian arteries.

## Conclusions

Extra-anatomic bypass grafts have traditionally provided a safer, less risky alternative to standard anatomic vascular reconstructions. However, their durability has been challenged as compared to the standard, anatomic revascularization techniques. This along with the explosion of minimally invasive endovascular technologies has led to the diminution in the use of these techniques as primary revascularization methods, and instead they are mainly utilized in the face of hostile factors such as infection or prior surgical scars (Angle et al. 2002). However, their use even in treating graft infections has evolved, as some authors favor in situ reconstructions of abdominal aortic graft/endograft infections over axillofemoral reconstructions (Oderich et al. 2006; Fatima et al. 2013). While the use of extra-anatomic revascularizations perhaps has diminished in the management of lower extremity arterial occlusive disease and in the management of aortic graft infections, their use has risen in the management of complex aortic pathologies. In order to extend seal zones of aortic stent grafts, extra-anatomic bypasses are used more frequently as adjunctive techniques. Thus, an intimate understanding of the indications and workings of extra-anatomic bypasses is a vital piece of knowledge for all vascular specialists.

## Summary

The extra-anatomic bypass refers to any bypass graft that is placed outside of the normal anatomic vascular pathway. It provides a safer, less risky alternative to a standard in-line revascularization. The durability and patency of the extra-anatomic reconstruction is inferior to the standard anatomic revascularization. Minimally invasive endovascular technology has decreased utilization of this technique as primary revascularization method for the treatment of atherosclerotic occlusive disease. However, the development of endovascular technology in the management of complex aortic pathology, has increased utilization of extra-anatomic reconstruction as adjunct procedure. In the future, the development of branch and fenestrated technology in the treatment of complex aortic pathology, may result in revised utilization of these procedures.

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