A History of Surgery for Acute Leg Ischaemia.

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*Corresponding author. Gloucestershire Hospitals NHS FT, Gloucestershire, UK
E-mail address: jonothanearnshaw@gmail.com; Jonothan.earnshaw@nhs.net

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Introduction

Reconstructive surgery for acute arterial ischaemia has been available for less than a century and thus it is only relatively recently that the condition has been studied as a problem in its own right. Although acute limb ischaemia was probably less common than now because of the shorter average life span, peripheral arterial disease has affected man for thousands of years and yet the only treatment available until recently was limb amputation. Atherosclerosis has been found relatively frequently in Egyptian mummies. There is no doubt that prehistoric man performed surgical operations. It is known that trephining the skull for depressed fracture occurred in the Neolithic period (7000 BCE) and it can be imagined that the sharp flint instruments discovered from that era may well have been used for amputation of a damaged limb. Most amputations before the age of anaesthesia and antiseptic surgery followed trauma and were performed only for intolerable pain, or in life-threatening circumstances, because the mortality rate following surgery was so high. The ancient Greeks recognised senile gangrene, and Hippocrates (460 BC) described amputation for the condition, but only after a wait and see policy, if all else failed. He stated, ‘in extreme maladies, extreme and last remedies are fitting’, and advised amputation through devitalised tissue to prevent bleeding. In the second century A.D. Galen reported many surgical operations, including amputation, mostly for trauma.

The discovery of gunpowder in the 15th century almost certainly increased trauma surgery, in particular involving major limb arteries. One of the earliest treaties describing management of gunshot wounds was written by Hironymous Brunschwig in 1497. Other notable contributions on the subject came later from Theodor Bilroth (1859) and Heinrich von Pflössel und (1868). Advances were made in the technique of amputation at this time with the use of tourniquets by Guy de Chauliac (1546) and Leonardo Botallo (1565), and the use of a heated amputation knife which also acted as cautery. With this technique in 1614, Fabricius Hildanus performed one of the first successful above knee amputations. The use of the new screw tourniquet described by Petit (1718) was another advance.

The tourniquet produced pressure directly over the femoral artery and was therefore more secure. The immediate risk of limb amputation was bleeding, which was managed by cautery with red hot pokers. Therefore, when Amboise Pare described ligature of the limb vessels during amputation in 1564, this was regarded as a great humanitarian advance. (Figure 1). Ligation of blood vessels had in fact been practised before by Celsus in the first century AD, and Galen in the second. It is very surprising that this simple technique took so many years to become established.

Figure 1. Use of tourniquet for amputation
John Woodall (1639), the British naval surgeon advised that at amputation, all unhealthy tissue should be excised to encourage healing\textsuperscript{11}. He amputated through dead skin, which was painless, and then whittled away any remaining devitalised tissue.

Many military surgeons, including Baron Dominique de Larrey (\textbf{Figure 2}), a surgeon in Napoleon’s army, advised immediate amputation after fracture with vascular trauma due to gunshot (1797). De Larrey reported that he performed 200 amputations in 24 hours on the road to Moscow, at the Battle of Borodino\textsuperscript{12}. The time taken for amputation varied from 30 seconds to 3 minutes. However, Jean Faure, in his prize with winning lecture to the French Royal Academy of Surgery (1756) advised amputation only after gangrene was established and life threatened\textsuperscript{13}. Even in 1802, a common surgical aphorism was ‘\textit{when the brachial or femoral artery is wounded, though the patient should not perish by haemorrhgy, the limb must soon die for want of nourishment}’\textsuperscript{14}.

\textbf{Figure 2.} Baron Dominique de Larrey (1766-1842)

\textbf{Early clinical and experimental studies}

At the time of Galen, theories about the circulation of blood were very crude. It was believed that the liver contained the ‘power of life’, that blood originated there and then passed peripherally in the veins to supply the limbs. Air and blood were thought to mix in the heart through pores in the left ventricle (Siegal, 1968)\textsuperscript{15}. These ideas remained unchallenged for 1400 years until the time of Vesalius and William Harvey. Vesalius (1543) performed many brilliant anatomical dissections but was unable to find the pores in the heart, and challenged the theories of Galen\textsuperscript{16}. William Harvey (1628) completed \textit{De motu cordis} which described accurately the cardiovascular system and its physiology\textsuperscript{17}. He demonstrated that blood was pumped from the left heart via the arteries to the periphery and returned through the venous system. The description of the circulation...
was completed when Anthony Van Leeuwenhoek (1688) discovered capillaries\textsuperscript{18}.

John Hunter is known as the father of vascular surgery (Figure 3). In his treatise on the blood (1794) he wrote that it 'carries life to every part of the body, for wherever the whole or part is deprived of fresh blood, it very soon dies'\textsuperscript{19}. Hunter made many observations on arterial ischaemia. Although others had previously ligated the main limb arteries in animals, Hunter was among the first to put his experiments to clinical use. In July 1785, Hunter ligated the external carotid artery of a young stag in Richmond Park, mainly to see if this would retard the growth of the antler on that side. After ligation, he noticed that the hot velvet, or growing part, became cool.

![Figure 3. John Hunter (1728-1793)](image)

**Figure 3. John Hunter (1728-1793)**

In December 1785 a patient presented to Hunter with a popliteal aneurysm the size of a doll’s head (Home, 1786)\textsuperscript{21}. The treatment at the time was usually to await rupture of the aneurysm and then perform a proximal and distal ligation, with excision of the aneurysm. The alternative was primary leg amputation. Both of these operations carried a high mortality. Following the principle of his stag experiments, Hunter treated the popliteal aneurysm by ligation of the superficial femoral artery in the adductor (later Hunter’s) canal. This stopped the aneurysm pulsation and relieved the symptoms. The aneurysm thrombosed and disappeared. The patient, a Hackney coachman in whom popliteal aneurysms were relatively common (probably due to syphilis), recovered well, but died 15 months later after a fever.
At post-mortem the popliteal aneurysm had shrivelled to the size of a hen’s egg (Figure 4) (Qvist, 1981). Hunter’s experiments had great repercussions. When it was realised that the main artery of a limb could be ligated in some cases without gangrene, it became a popular procedure for aneurysm or trauma. John Abernethy (1809), a pupil of Hunter, reported that ligation and division of the artery was an improvement on ligation alone.

Figure 4. Popliteal artery aneurysm treated by John Hunter (from Hunterian museum at Royal College of Surgeons of England).

Astley Cooper was another surgeon whose experiments on animal ischaemia helped a greater understanding of therapeutic possibilities (Figure 5).

Cooper’s experiments on arterial ligation began when he was a student of medicine in 1786. He was aware of the importance of the collateral circulation after arterial occlusion. He sequentially ligated both carotids and both vertebral arteries in a dog, which survived to become his pet. After its death the collateral circulation was injected and can still be seen in the Royal College of Surgeons of England museum today. His work on the collateral circulation was presented to the Medico-chirurgical Society in 1811. Astley Cooper used this work in his clinical practice. In 1805 he ligated the common carotid artery for aneurysm in a 44-year-old woman, who died 21 days later from sepsis. On the same day in 1808 he ligated the external iliac artery in a 39-year-old man and the common carotid artery in a 50-year-old man, both of whom survived and lived for many years. In 1817 Astley Cooper was the first to ligate the aorta for a leaking aneurysm, though the patient died 48 hours later with ischaemic feet (Brock, 1952).
Another surgeon who performed many arterial ligations was Valentine Mott from the USA, whose list of successful ligations included the innominate artery in 1818, the common iliac artery in 1827 and the subclavian artery in 1833. George Norris (1847) analysed all reported ligations of major limb arteries between 1796 and 1842. After external iliac artery ligation, usually for aneurysm or trauma, only 28% of 118 patients died or required amputations. After common iliac artery ligation, 8/16 patients had amputations or died.

The method of arterial ligation used at the time was to pass a silk suture around the vessel on a long curve needle through the skin, and after ligation to leave the long ends dangling through the wound. The suture separated after a week or two and frequently produced haemorrhage. In 1817 Astley Cooper used cat gut to ligate a femoral aneurysm and then buried the ends, thus preventing separation (Brock, 1952). He was not the first to do this, as Galen probably also used the technique. However, burying sutures did not become common practice in till the time of Lister who described the use of sterilised cat gut (Godlee, 1917).

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The causes of gangrene

Though gangrene was well recognised and had been described for hundreds of years, it was not until the 18th century that its cause began to be understood. Fabricius Hildanus wrote of ‘hot’ and ‘cold’ gangrene (1603), and Ambroise Pare (1564)
stated that gangrene occurs when 'a part cannot receive the natural spirit proceeding from the liver, carried by the veins to give it nourishment'. He recognised different types of gangrene: 'warm as one sees in carbuncles and pestiferous anthrax; cold as one sees occur suddenly in a part without preceding pain, or swelling, or lividity, or other signs of gangrene'.

Francois Quesnay (1739) was among the first to point out that gangrene arose due to arterial obstruction. John Hunter had noticed thrombus in the vessels of a limb amputated for gangrene and this finding was reiterated by Hebreard in 1870 (Raynaud, 1888). Lariviere (1867) noted thrombus in the main arteries of the limb in a patient having an amputation for gangrene. Avisard (1819) argued that gangrene was due to ‘ossification and obliteration of the arteries’. Godin (1836) ascribed wet gangrene to venous obstruction and dry gangrene to arterial obstruction. However, arterial insufficiency as a cause of gangrene was relatively uncommon at that time. In a series of surgical lectures published in the Lancet, Astley Cooper (1823) stated that gangrene was usually due to infection or trauma, or occasionally an aneurysm. He stated that ‘less frequently cold gangrene occurred in old persons……from ossification of the arteries……combined with a debilitated action of the heart. The earthy matter (atheroma) sometimes is deposited in great quantities in the large vessels’. Descriptions of ALI were unusual before the 19th century, although Pare (1564) reported a case from Paris of a man who had been ‘making good cheer during the day, not complaining of any pain. However, during the night there came upon him gangrene and mortification of both legs without swelling or inflammation, but there was a colour in certain places tending to lividity, blackness, and greenness. In some other places the colour was almost natural. Still there was no feeling, and when one pricked it with the point of a lancet or with a pin, no blood came out of it, and there was no warmth to the sense of touch. On the contrary one felt rather coldness’.

Gould (1684) described the lodgement of a thrombus in a peripheral artery conducted there from the heart by the bloodstream ‘that all intercourse of spirits irrevocably be stopped’. In 1646 Marcus Severinus reported a spontaneous thrombosis of a popliteal aneurysm, with recovery of the limb (Bell, 1801). It was well recognised that if an aneurysm thrombosed without compromising the circulation to the limb it was no longer dangerous. Bell also gave details of a case of spontaneous thrombosis: ‘for some weeks the great aneurysm of the thigh increases with alarming and awful pulsation…… the man is exhausted with fever and pain. The pulsation ceases… the limb itself is paralytic cold, heavy, dead. The general swelling falls by slow degrees, yet half a year generally elapses before it is reduced to any seemly shape. When the limb recovers its natural heat, without any renewed pulsation in the aneurysm, it is a sign that the main artery is obliterated, the collaterals enlarged and the limb safe’. Therefore, the treatment recommended for aneurysm by many surgeons was compression, often for many months, to try to cause thrombosis.
Spontaneous arterial ischaemia was occasionally recorded in the literature (Bottomley, 1845\textsuperscript{34}; Meigs, 1869\textsuperscript{35}). The term embolus (Greek plug) was coined by Virchow (Figure 6) (1854)\textsuperscript{36}, and at about the same time the association between endocarditis and embolism was noted: ‘fibrinous concretions on the valves or the interior of the heart admit of being readily detached during life, and mingling with the circulating blood…..If detached and transmitted in large masses, they may suddenly block up a large artery, and so cut off the supply of blood to an important part’ (Kirkes, 1852)\textsuperscript{37}. With the discovery of anaesthesia in the mid-18th century, and the benefits of antiseptic surgery, elective operations could be countenanced. The beginning of vascular surgery, which previously had been swift, crude and destructive had arrived.

The dawn of vascular surgery

Just as it took surgeons along time to accept ligature instead of cautery for haemostasis, it took a long time for direct arterial surgery to become an established (Rob, 1972 Dale, 1974)\textsuperscript{38,39}. Hallowell (1761) is credited with the first arterial suture, when he united the lacerated edges of a brachial artery by running a pin through the edges of the artery and twisting a ligature in a figure of eight around the ends\textsuperscript{40}. It wasn’t until Alexander Jassinowsky of Odessa described arterial suture with fine silk (1889), achieving 22 patent end to end anastomoses from 24 attempts in animal carotid arteries\textsuperscript{41}, that other surgeons began to become aware of the possibilities.
Alexis Carrel was probably the most prestigious investigator in this field (Figure 7). His interest in vascular surgery was triggered by the failure of his surgical teachers to repair a portal vein injury in the President of the French Republic in 1894, which later proved fatal. Two years after qualifying as a doctor (1902) he described arterial suture using three stay sutures and completed with fine silk, avoiding the intima. He also described kidney autotransplantation in dogs.

In collaboration with Guthrie, Carrel later demonstrated that all layers of an artery could be sutured together without causing thrombosis, and he described an all coats, over and over suture technique that is still in use today. Carrel (1910) was also the first to experiment with arterial homografts, and in 1912 he was awarded the Nobel Prize in medicine.

Surgery for ALI really began when Severeanu of Bucharest (1894) recommended bougienage of the popliteal artery using an oiled catheter during amputation to remove any residual thrombus, in the hope of encouraging the skin flaps to heal. Though John Hunter had suggested in 1768 that removal of an obstructing thrombus might improve the condition of a limb, the first embolectomy for acute ischaemia was not performed until 1895 by Ssabanajeff (Figure 8). The operation was not successful. Several others reported attempted embolectomy in the next 15 years, including Sampson Handley (1907), but none was a success.

In 1910, two surgeons, Labey (Mosny, 1911) and Einar Key (Key, 1923) performed successful embolectomies, both for femoral emboli of less than six hours’ duration. However, apart from in Sweden, where the small size of the country enabled widespread awareness of the technique, general adoption of the operation did not come rapidly. The first successful case in Britain was not reported until 1925 by Jefferson, and by 1933 there were still only 129 cases reported in the literature. Einar Key reported 382 cases from Sweden, where the operation was, common, at a lecture to the Royal Postgraduate Medical School in 1936. In the two reported studies, overall, only one quarter of the patients survived with intact limbs. Key’s personal results were slightly better, with 40% of his 48 patients having limb salvage, but the overall mortality rate was very high. Key stated that the severity of the ischaemia depended on the following:

1. whether the obstruction was complete or partial
2. the development of collaterals
3. the formation of secondary thrombus
4. the state of the vessel wall
5. the action of the heart.

Key also declared that the duration of the ischaemia was the most important prognostic indicator. Danzis stated that urgent embolectomy was the only real treatment for this condition, despite the modest results, but noted that one quarter of successfully treated patients developed recurrent emboli, which were often fatal.
It had already been noticed that the outcome of patients with ALI due to an arterial thrombosis was not as good as those with embolism, whether treated surgically or conservatively. Some later authors deliberately excluded thromboses in their investigations, but some probably included them described as emboli with peripheral vascular disease. The distinction between thrombosis and embolism was regarded as often difficult and since no other surgical treatment was available, embolectomy was often attempted anyway.

Conservative treatment of acute leg ischaemia

It was widely believed in the 1930s and surgery for arterial ischaemia was merely interference. McKechnie (1936) reviewed 100 patients with acute leg ischaemia, including thromboses and emboli, which had been treated conservatively at the Mayo Clinic. Gangrene followed the arterial occlusion in 50% of cases and if gangrene ensued, the mortality rate was 75%. The outcome from conservative treatment was certainly no worse than that recorded for embolectomy. There was little difference in outcome between those with thromboses and those with emboli. The methods of conservative treatment were reviewed by McClure (1943) and included:

1. **Analgesia and bedrest.** Opiates were administered, with the patients resting in bed to optimise cardiac output. The leg was placed in a dependent position and great care was taken not to damage the fragile skin. Alcohol was also given orally as an analgesic and vasodilator.

2. **Vasodilators.** It was recognised that arterial spasm contributed to the severity of the ischaemia after a recent occlusion. Papaverine was used intravenously by Denk to produce vasodilatation after embolism in 10 patients, seven of whom responded well. After this, many surgeons used papaverine as primary treatment and also as an adjunct to embolectomy, as the intra-arterial route was found to produce superior results. Intravenous priscoline (tolazoline) was also investigated in 45 patients with both acute and chronic arterial ischaemia. The effects were most marked in patients with vasospastic disorders and claudication; those with ischaemic rest pain being little changed.

3. **Sympathectomy.** Claude Bernard (1851) described the sympathetic nervous system. It was believed that the sympathetic fibres ran alongside the arteries and therefore Jaboulay (1899) recommended periarterial sympathectomy to abolish arterial spasm. This misconception was continued when Leriche (1913) described his good results for this operation. It was later shown that the sympathetic nerves had a segmental distribution and that division of the lumbar sympathetic chain could benefit patients with peripheral arterial ischaemia. Lumbar surgical sympathectomy was first performed in a man with spastic paralysis of the leg (Royal, 1924). Adson (1932) described lumbar sympathectomy for vascular disease. His results in patients with Raynaud’s disease were excellent, but those in patients with peripheral arterial insufficiency were not as good. Of 89 patients, 76 legs were improved and only four required amputation. Less traumatic methods of interrupting the sympathetic supply included injection of local anaesthetic, procaine, which was only a temporary measure, and the use of spinal anaesthesia. A more permanent chemical sympathectomy using phenol was not employed until over 20 years later.

4. **Anticoagulants.** Heparin was discovered by Maclean, a medical student working in Howell’s laboratory in 1916. Heparin was extracted from calves’ liver, but it wasn’t until 1933 when the barium salt of heparin had been produced chemically that it was pure enough for use in patients. In experimental animals, heparin had been shown to prevent artificially induced venous thrombi, and thromboses on arterial suture lines and in vascular grafts. Heparin was initially used in patients with emboli to prevent secondary thrombosis, and rethrombosis after embolectomy. It was also used as a treatment for venous thrombosis, and phlebitis, and to prevent pulmonary embolism. The disadvantage of heparin was it was necessary to give it parenterally, but in 1941 dicoumarol (warfarin) became available, enabling long-term anticoagulation to be completed with an oral agent.

5. **Intermittent positive and negative pressure.** Hermann (1934) designed an airtight pressure chamber surrounding the limb which produced intermittent pressure changes between -20 mmHg and +80 mmHg to try to improve limb blood flow. Initial results were impressive, with 86% of patients treated having clinical benefit, including patients with ALI. In a later study of 29 patients with rest pain and ulceration, relief of rest pain was achieved in 20 patients, but the technique was shown to be best suited to chronic ischaemia.

6. **Intermittent venous occlusion.** In this technique, a cuff was placed around the thigh and inflated intermittently above venous pressure. This produced a reactive hyperaemic response in the limb, and in a study of 98 patients with a variety of peripheral vascular disorders, 61% of the 59 patients with gangrene were healed and rest pain was abolished in 72%.
The rationale for surgery

With a wide variety of conservative methods which had been introduced to treat acute leg ischaemia, it became important to establish whether surgical embolectomy was of benefit. Lund (1937) was one of the first to address this problem. Of a series of 27 embolectomies performed over six years, 37% left hospital with intact legs and 44% died, though some of the latter had restoration of the circulation by the operation. Lund noted that the limb salvage rates improved to 55% in the second half study and postulated that this was due to improved surgical technique. In a parallel group of patients who did not have surgery, only 8% had limb salvage and 85% died. Thus, Lund justified an active surgical approach to arterial emboli.

He also noted that to be successful, embolectomy was necessary within 24 hours of arterial occlusion and that the best results were obtained in young people with mitral valve disease. In 1950 both Andrus and Haimovic published large series of acute emboli managed without operation in an attempt to define the natural history. In 72 patients Andrus noted that those with aorto-iliac emboli fared worst and he stated that an embolus occurring in this region was an indication for surgery. It was stated that the good results of conservative treatment of emboli below the inguinal ligament meant that embolectomy was not justified unless the duration of ischaemia was less than 12 hours.

Haimovic studied 330 patients with emboli treated conservatively and 30 treated surgically. In the conservatively managed group, 13% of the patients died soon after admission, 22% required amputation, 43% recovered with limb salvage and the remainder had an undetermined outcome. Almost half the patients who left hospital with intact limbs had residual disabling ischaemic symptoms: claudication, neuritis or ischaemic contracture. In the select group of patients who had an embolectomy, the overall outcome was not different, however, if limb salvage was achieved there was a very low incidence of residual disability, and the functional outcome was excellent. For this reason, embolectomy was recommended. It was demonstrated in the same study that conservative treatment begun early had a beneficial effect. If vasodilators, sympathectomy and/or anticoagulants were used within 24 hours of the onset of ischaemia, the outcome was better than in patients treated in the same way who presented later. Thus, for patients presenting with ischaemia of less than 24 hours’ duration, a brief trial of conservative therapy was recommended before embolectomy. In places with good communication, such as Sweden, many patients arrived at hospital soon after the arterial occlusion, whereas DeTakats (1942) noted that in a series of 28 patients referred to him, only eight were of less than 24 hours’ duration and thus suitable for embolectomy.

The Swedish experience was that the long-term outcome after embolectomy was poor. It was found that 61 patients who had successful embolectomy with limb salvage, one quarter died in the first year after hospital discharge, one half within three years, two thirds within five years, and 90% within 10 years. Recurrent emboli occurred in 20%, and one third of the patients suffered strokes.

Improvements in surgical techniques

The earliest embolectomies were performed simply by direct removal of the clot through an arteriotomy at the site of the occlusion. Often the embolus itself was relatively simple to remove, but thrombus which formed distal to the occlusion could not be cleared. Retrograde massage of the limb along the length of the artery, or the use of an Esmarch-type tourniquet were aids to try to free distal thrombus. Occasionally it was necessary to perform an arteriotomy distally, to try to dislodge the thrombus (Danzis, 1933; Key, 1936). It was later suggested that retrograde flushing with saline via the distal arteriotomy could clear the segment between the arteriotomies. However, the free passage of saline did not guarantee subsequent patency of the arterial segment.

Emboli in the aorta and iliac arteries posed a greater problem because direct arteriotomy required a laparotomy, which was hazardous. Emboli at the aortic bifurcation could sometimes be dislodged by direct external pressure, or retrieved by
aspiration from below. If this failed, the aorta could be squeezed directly by a hand inserted through a retroperitoneal incision. Other devices used to remove distant thrombus, particularly from the region of the aortic bifurcation, included a vein stripper with an olive head (Oeconomous, 1961), and a corkscrew wire used to enmesh the clot (Shaw, 1960). An aggressive surgical approach to both thromboses and emboli was shown to yield good results in a small series.

After the discovery of anticoagulants, it was found that the heparin begun four hours after surgery and subsequently changed to long-term warfarin could greatly reduce rethrombosis and recurrent embolus. At this time two other surgical methods were described for treating acute ischaemia, but neither was to stand the test of time. In a Hunterian Oration, Makins (1917) described his surgical experiences from the Boer War where he observed that the incidence of gangrene after traumatic arteriovenous fistula was reduced if the artery and vein were ligated (25%) compared with ligation of the artery alone (40%). Ligation of the femoral vein for femoral and popliteal artery ALI was popularised by Brooks (1929) and was thought to ‘restore the balance of the circulation’ and thus lessen the risk of subsequent gangrene. The ideal indication was thought to be acute leg ischaemia. However, in a series of experiments in rabbits, Wilson (1932) showed simultaneous ligation of the main vein along with the artery of the hind limb further reduced blood flow, increasing the risk of gangrene. The concept was never widely adopted. In the second technique, the femoral artery was anastomosed to the femoral vein to create an arteriovenous fistula and ‘reverse the circulation in the limb’. In patients with severe ischaemia, this occasionally produced pulsation in the veins of the foot which usually ceased within a few days, and achieved only marginal benefit. It was soon abandoned.

Figure 9. Thomas Fogarty (born 1934)
The greatest advance in the surgical treatment of ALI and probably the most fundamental change in management, was the development of the balloon embolectomy catheter by Thomas Fogarty (1963) \((\text{Figure 9})^{66}\). The idea came to him whilst he was still a medical student. The principle was to advance a catheter beyond the embolus, to inflate the balloon at the distal tip, and to withdraw the catheter, thus retrieving the embolus.

The Fogarty catheter had the great advantage that in expert hands it caused little intimal damage and yet could retrieve secondary thrombus as well as the embolus. Also, embolectomy could be performed via an arteriotomy at a site distant from the embolic occlusion. Fogarty catheter embolectomy was widely adopted soon after it was described and resulted in a sea change in the outcomes after embolectomy \((\text{Figure 10})\).
Figure 10. Patent application for the Fogarty embolectomy catheter 1969.
Vascular reconstruction

Surgery for acute arterial thromboses did not really begin until the era of vascular reconstruction. Before then although it was widely recognised that arterial thromboses did not have as good a result from surgical removal as arterial emboli, many felt there was nothing to lose by an attempt\textsuperscript{80}. Thromboendarterectomy for chronic arterial occlusions was described by Jiannu (1912)\textsuperscript{87}, but was not often used until it was rediscovered by Dos Santos (1947)\textsuperscript{88}. Many surgeons reported excellent results using Dos Santos’ technique including Leriche (1947)\textsuperscript{89}. One of the first series was reported by Wiley (1952) and described thromboendarterectomy in 26 patients: five aortic, five iliac, 10 femoral and six combination occlusions, and included an acute iliac artery thrombosis. A total of 25 of the 26 arterial segments were patent after surgery, though three patients eventually died and three required amputations\textsuperscript{90}. The technique was still being advocated 20 years later when Cockett (1963) reported the St Thomas’ Hospital experience and stated that thromboendarterectomy was the optimal procedure for restoring flow in aortoiliac obstructions and that a ‘radical rebore’ also produced the best results for femoropopliteal occlusions\textsuperscript{91}. However, many surgeons found a high incidence of rethrombosis after thromboendarterectomy and turned to bypass grafting in search of improved results\textsuperscript{92}.

The choice of materials available for bypass grafting lay between arterial homografts, autogenous vein or synthetic material. Following Carrell’s early work on the storage of homografts (1910)\textsuperscript{44}, it was found that they were a good conduit for blood. In a Hunterian Oration, Eastcott (1953) described methods of harvesting and storage of arterial homografts, along with early results of the insertion into patients\textsuperscript{93}. In the USA, DeBakey (1957) reported restoration of pulsatile flow in 90\% of 155 patients receiving homografts\textsuperscript{92}. However, the early promise of arterial homografts was not maintained. The grafts were not incorporated as living tissue as had been hoped, and as the years passed many became aneurysmal causing thrombosis, embolism and even rupture\textsuperscript{94,95}. Thus there was a search for synthetic grafts which could be non-thrombogenic and technically easy to insert. Many cloth fibres were tested including Nylon, Ivalon, Teflon and Dacron. The latter has become the material of choice for bypass of large diameter vessels and has been used successfully in many thousands of patients worldwide. For small calibre arteries, autogenous vein remains superior to synthetic grafts.

Carell (1902) used vein grafts in his experiments on animals to bypass arterial obstructions. Vein grafts were also used occasionally for arterial repair in the First World War (Makins, 1919)\textsuperscript{82}. Lexner from Jena (1907) is credited as one of the first to use of a vein graft successfully in an elective operation to bypass a popliteal aneurysm\textsuperscript{86}. There are few other reports of successful cases, though Goyanes (1906)\textsuperscript{97} and Hogarth Pringle from Glasgow (1913) reported vein bypass for popliteal aneurysm with beneficial results\textsuperscript{98}. However, other surgeons who used autogenous vein grafts for arterial replacement with end to end anastomosis did not duplicate these results, and for many years the technique was not widely adopted\textsuperscript{84}. It was not until Kunlin (1951) suggested the end to side anastomotic technique that results improved\textsuperscript{89}. This method remains the standard approach for femoropopliteal grafting. Linton and Darling (1962) reported the first series with long-term follow-up using the technique on 62 patients, 91\% of whose grafts were functioning at hospital discharge\textsuperscript{100}. Four (6\%) further grafts thrombosed within 18 months of operation, but none thereafter during an average four-year follow-up. Only two legs in the series were amputated and one patient died. After these results, autogenous vein became the material of choice for femoropopliteal grafting.

Early concepts in specialist management of acute leg ischaemia

It was not easy to determine the true early incidence of acute peripheral arterial ischaemia due to the varied presentations and the diversity of the clinical specialties involved. An early study was performed in Stockholm in 1980\textsuperscript{101}. In an area with a population of 1.5 million, 138 patients developed acute arterial ischaemia (nine per hundred thousand per year). Most of
these cases occurred in the seventh decade when the incidence was 48 per hundred thousand per year. Some 81% of the arterial occlusions were classified as emboli and 19% as thromboses\textsuperscript{101}. Others confirmed the relative incidence of embolism to thrombosis of about 4 to 1\textsuperscript{102}. The relative incidence of thrombosis to embolism depended on the pattern of referral. Specialist vascular units reported a higher relative incidence of thromboses, while emboli were managed by general surgeons\textsuperscript{103,104}. It was suggested the incidence of acute leg ischaemia was increasing in parallel with the epidemic of ischaemic heart disease for the same reasons, namely increasing elderly population with smoking and dietary habits and a sedentary lifestyle.

One important question is whether the distinction between thrombosis and embolism matters? Sewell (1985) stated that ‘\textit{clinically it may be difficult to distinguish between the two, nor does it matter since the endpoint may be the same and the management similar}’\textsuperscript{105}. Blaisdell (1978) reviewed the results of treatment in 3330 published cases of acute leg ischaemia from the literature between 1964 and 1977 and found that the mortality rate from treatment was approximately 25%\textsuperscript{106}. In an attempt to reduce the mortality, a selective policy of management was described, based not on the distinction between thrombosis and embolism, but on the severity of ischaemia at presentation. In a series of 54 patients with ischaemia for less than one week, those with loss of sensation or limb paralysis had urgent thromboembolectomy or a primary amputation. The remainder, whose limbs were not immediately threatened, received high-dose heparin therapy and were then reassessed after several days when appropriate management was undertaken. The result of this technique was a limb salvage rate of two thirds and 7.5% mortality. Blaisdell concluded that ‘\textit{limbs were traded for lives}’ and that the underlying cause of the occlusion was less important than the severity of the ischaemia\textsuperscript{106}. Persson (1977) agreed with this statement and stressed the importance of collaterals in maintaining limb viability\textsuperscript{107}.

Several authors have compared retrospectively the results of surgical treatment in patients with thromboses and emboli. The conclusion of all the authors was the same: that the outcome was different for each. The overall amputation rate after thrombosis was 28%, compared with 13% after embolism. Conversely the mortality rate was higher after emboli (17 percent) then after arterial thrombosis (9%), though others have reported higher rates than these\textsuperscript{108}. The higher mortality rate after emboli is a result of the associated cardiac disease, most deaths not being associated with the peripheral arterial ischaemia. In particular, the group of patients with the highest mortality rate were those with emboli after myocardial infarction\textsuperscript{109}. Patients with acute thromboses have a higher amputation rate due to underlying atherosclerosis. Thromboembolectomy in these patients only restores backbleeding in 45%\textsuperscript{110}, and is often not sufficient alone to obtain limb salvage\textsuperscript{104}. The difference in outcome between thromboses and emboli is not accounted for by differences in the sites of the occlusion, as these are similar\textsuperscript{110,111}. Several authors state that the most important predictor of outcome is the severity of the ischaemia at presentation\textsuperscript{103,104}, and it has been shown that emboli are more likely to produce severe ischaemia than thromboses\textsuperscript{112}. These differences mean that it is not acceptable to ignore the distinction between thrombosis and embolism\textsuperscript{104}. It is important to identify those patients with thromboses as the results of treatment by thromboembolectomy alone maybe very poor. The concept of differential management is by no means new\textsuperscript{113}, however, the distinction between thrombosis and embolism can be tricky.

Management of arterial emboli after the introduction of the Fogarty catheter
Since the introduction of the Fogarty embolectomy catheter in 1963, the treatment of arterial emboli became accepted as surgery. Balloon catheter embolectomy can be performed under local anaesthetic in frail, elderly patients and in those in poor medical condition. Age itself is not a bar to successful outcome\textsuperscript{14}. The ease of surgery has meant that the old guidelines on the acceptable duration of ischaemia and site of occlusion can be ignored. Recently the general medical condition of the patients has been stated to be the most important predictor both of survival and limb salvage\textsuperscript{115}. Hight (1976) compared the outcome for his patients before and after the introduction of the embolectomy catheter\textsuperscript{16}. The mortality rate and the amputation rates were both greatly reduced, though mainly in patients with ischaemic, rather than rheumatic heart disease. This improvement was mirrored in other studies\textsuperscript{117,118}. The reason for the improvement has been stated to be the balloon catheter itself and the fact that all procedures can be performed under local anaesthetic. The technique of embolectomy has been well described\textsuperscript{86,119,120}. The most impressive results come from Fogarty’s own clinic in California (Tawes, 1985) where 739 patients have been treated in 20 years\textsuperscript{121}. Limb salvage was achieved in 95% of the patients, though 15% subsequently died. These results were obtained by the following approach:

(a) early diagnosis due to wide awareness of the condition;

(b) the use of heparin pre-and postoperatively. Although this increased the rate of wound haematoma and infection, there was a worthwhile trade-off in prevention of propagated thrombus, rethrombosis after embolectomy and recurrent embolism;

(c) patients with loss of limb sensation or paralysis had very urgent surgery. Renal function was maintained by intravenous infusion. During operation the venous return of the limb was isolated and after resumption of arterial flow, the first 300 to 500ml of venous effluent was drained to prevent hyperkalaemic acidosis.

(d) there was no reluctance to perform secondary procedures e.g. angioplasty, sympathectomy, popliteal exploration or repeat embolectomy as these did not increase morbidity or mortality. These were necessary in 135 of 739 patients (18%)\textsuperscript{121}.

Another adjunct to embolectomy was the performance of completion on table angiography to ensure that all embolus has been removed and that there was good distal flow\textsuperscript{122}.

It is reported that the outcome is different for emboli at different sites. Galbraith (1985) reviewed the Oxford experience of emboli over a five-year interval\textsuperscript{123}. It was found that lower limb emboli could be divided into two types: type one (n= 93) where large emboli occluded major arteries, and type II (n=24) where emboli occluded small peripheral arteries. Type one emboli presented earlier due to more severe symptoms and were usually treated by prompt embolectomy. Death followed in 26% of the patients and 57% had limb salvage although one third of them still suffered claudication. Type two emboli were often managed without embolectomy as the ischaemia was not so severe. Although there were no deaths in this group, one third required amputation. It was concluded that distal emboli were more likely to result in amputation and that all symptomatic emboli should be removed, where possible\textsuperscript{123}.

The special problems of popliteal and tibial emboli were highlighted by Abbott (1984)\textsuperscript{124}. Distal emboli are often incompletely removed if the femoral route is used for exploration. The anatomical explanation for this is that the balloon catheter preferentially passes down only one tibial vessel, usually the peroneal artery. Therefore, it was recommended that popliteal and tibial emboli should be removed surgically via a direct popliteal approach below the knee, so that each tibial artery can be catheterised individually. Completion arteriography is also important after popliteal exploration. This method produced successful embolectomy in 14 of 17 cases, but did require general anaesthesia with all its attendant risks\textsuperscript{124}.

Late presentation of emboli is another problem, being defined usually as more than 48 hours after onset of ischaemia. It was shown in the earliest series, that late emboli have a poor prognosis\textsuperscript{125}. Since 1953, when it was demonstrated that late emboli could be removed successfully\textsuperscript{126}, an active surgical approach has been advocated by several authors. The mortality rate of 9% was lower than that reported earlier for acute emboli, and the limb salvage data support a surgical approach to the problem. Operative arteriography was again stated to be valuable\textsuperscript{127}. The main problem with late revascularisation is that if the circulation is restored to dead muscle, renal failure may follow, due to myoglobinuria\textsuperscript{128}. This may only occur in severe ischaemia with loss of sensation and paralysis, and signs of irreversible ischaemia including calf muscle tenderness and turgor. An implication from this study was that myoglobinuria was associated with a muscle compartment syndrome. Whether fasciotomy could prevent myoglobinuric renal failure was not known. However, fasciotomy was recommended as important
after revascularisation of severe acute leg ischaemia and should be done promptly if there is any doubt.\textsuperscript{20}

The benefit from anticoagulants before and embolectomy was reviewed retrospectively in 65 patients by Jivegard (1986)\textsuperscript{129}. Adequate perioperative anticoagulation with heparin was found to improve the clinical outcome, although hospital mortality was unaffected. Haematoma formed in 23\% of heparin-treated patients. Patients given long-term warfarin had lower (though not statistically significantly) five-year survival. A total of 10\% of the deaths in warfarin treated patients were associated with bleeding. Despite warfarin, the cumulative rate of recurrent embolism was 30\% after three years, and the authors concluded that the potential benefits of anticoagulants needed further study in a prospective randomised trial.

Conclusion

The primacy of surgery as treatment for acute leg ischaemia lasted only 50 years, from the first successful embolectomy in 1910 to the 1960s when the use of thrombolytic drugs was first reported, to the mid 1980s, when endovascular techniques were first described. Arguably, the first non-surgical method of removing emboli was reported by Stark (1985), who described how clot dislodged during angioplasty could be aspirated through the catheter. In a series of 45 patients who had a percutaneous aspiration thromboembolectomy, the cause was a thrombus dislodged during angioplasty in half, but nine patients had primary emboli originating from the heart. The embolus was aspirated successfully in 42 of the 45 patients and it was reported the technique is certainly worthy of further study\textsuperscript{130}.

The history of surgical management of acute leg ischaemia has a fascination for vascular surgeons because it parallels the rise of arterial surgery, and the ability to treat patients with vascular diseases. Much has changed, and there are now many more options for vascular patients, and those with acute leg ischaemia. The latter remains a threat to both limb and life. The recently published guidelines on the management of acute limb ischaemia (2019), contains all the evidence from studies of different treatments distilled into a best practice document\textsuperscript{131}. There remains much to learn, and of course, the aetiology of acute leg ischaemia continues to evolve. The importance of the history of the surgical management of acute leg ischaemia is that it encompasses an understanding of the physiology of the circulation, the mechanisms of thrombosis and haemostasis, and the birth of the specialty of vascular surgery, all in less than a century\textsuperscript{132}.

References

5. Pfolspeundt H. Buch der Bundth-Ertznei. 1868.


