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Hallmarks of amputation surgery

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Abstract

Purpose To highlight the most important innovations and milestones in the historical evolution of amputation and disarticulation surgery through the ages, from the early antiquity until the modern era.

Method A thorough search of the literature was undertaken in PubMed and Google Scholar as well as in physical books in libraries to summarize current and classic literature on the hallmarks of the history of amputation surgery in the course of medical history.

Results Amputation of a limb is one of the oldest surgical procedures. Initially, it was fraught with complications and dismal outcome of the patients because of hemorrhage and infection. Due to lack of analgesics and narcotics the operation had to take only a few minutes. Obtaining experience, the surgeons evolved the operative technique and refined the procedure, anesthesia and perioperative analgesia was introduced, instruments were developed, and rehabilitation has enabled functional and social reintegration of amputees.

Conclusion From the Hippocratic era until currently, the surgical approach to amputation has changed little. However, the indications for amputations have changed a lot and had been refined, especially in diabetic patients and in those with severe chronic peripheral vascular disease. An exponential decrease in mortality for an operation once fraught with complications was due to the development of the tourniquet, proper vessel ligation and repair, antisepsis, and anesthesia.

Keywords Amputation · History

Introduction

Amputation of an irreparably damaged limb from trauma or gangrene is one of the oldest surgical procedures. Amputation is dismembering of a limb cutting through bone. Similarly, disarticulation is an amputation through a joint without cutting through bone tissue. Initially, it was fraught with complications and dismal outcome of the patients from haemorrhage and infection. Due to lack of analgesics and narcotics, the operation had to take only a few minutes. Within the ages, the surgeons improved the operative technique with evolution of the instrumentation, analgesics, antisepsis, and wound coverage. Obtaining experience, the procedure was refined and morbidity reduced significantly [1–6]. The purpose of this historic review is to highlight the most important innovations and milestones in the historical evolution of amputation and disarticulation surgery through the ages, from the early antiquity until the modern era.

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Prehistoric era–antiquity

Amputations of limbs have been performed since the down of mankind in antiquity. They were initially performed with the rationale to save lives by sacrificing a limb. Nevertheless, they rarely resulted in the desired outcome due to massive haemorrhage and septic shock. Early surgeons could only rely on their speed and surgical technique to improve outcomes and minimize pain; because of lack of anaesthesia, the procedure had to last only a couple of minutes [7, 8].

Prehistoric era: France (4900 BC)

The earliest human remains with evidence of an amputation, dated approximately in 4900 BC, were found in Buthiers-

Boulancourt near Paris [9–11]. The remains were a skeleton of a male who was lacking bones in the left forearm, wrist, and hand. Analysis of the possible site of amputation indicated a clear oblique section through the medial and lateral epicondyle consistent with the flint tools available at the time. The amputation was successful and he not only survived the amputation but lived for months or years afterward. The Rig-Veda, an ancient Indian poem composed between 3500 and 1800 BC, is the oldest written account of an amputation performed on Queen Vishpla after a battle wound; she had her leg amputated, fitted with a prosthesis, and courageously returned to battle shortly after [7, 8].

Antiquity: Egypt, Arabic countries, and India (1st millennium BC)

In antiquity, amputations were generally performed for therapeutic reasons after major war trauma in the arms and legs to save the life of a patient by stopping massive haemorrhage. Amputations were also imposed by cultural views, traditional beliefs, taboos, and religious convictions, such as in cases of self-mutilation to appraise the gods during religious ceremonies [12]. Moreover, amputations were performed as a retribution for a judicial punishment; there are crimes and law offenses punished with amputation as early as the Babylonian era in the law code of Hammurabi (1810–1750 BC), which was one of the first law codes to place greater emphasis on the physical punishment of the offender. In the Arabic culture, a foot was removed for laziness, both arms for rebellion, and a hand for theft. However, the main medical indications for an amputation were the hindering of mobility and impairment to work, as well as the growth of tumours [13].

In ancient Egypt, according to archeologic sources, ancient Egyptian papyri, medical texts, and iconography of the fifteenth century BC, Egyptians used surgical techniques, such as trephination and amputation, as a means of therapeutic medical treatment. Amputations were performed by expert surgeons; however, they were feared more than death and thought to affect the amputee in the afterlife (Fig. 1) [14]. For the purpose of afterlife, several types of prostheses were manufactured from leather and wood to replace an amputated limb [7, 15]. In India, in the ancient vedic text of Sushruta Samhita (1st millennium BC), an amputation was proposed for the treatment of infected thorns and poisonous inoculations embedded in the hands and feet of his patients. In extreme trauma situations, such as crushed or mangled limbs, amputation was suggested as well [8, 15].

Greek and Roman era (fifth to fourth century BC)

In the fifth to fourth century BC in Greece, physicians were remarkably conservative towards amputations. They were avoiding and delaying an amputation with the hope that gangrenous or necrotic tissue would drop off at the demarcation line with living tissues. After occasional amputations, ointments, dressings, and bandages were used to counter suppuration and odor. Hippocrates recommended amputation to stop gangrene only as a last resort; he described amputation to be performed distal to the necrotic demarcation at the time, where it was fairly dead and had completely lost sensation [16, 17]. According to the Hippocratic corpus of medicine, when the necrotic part of the limb comes away, the patients recover from the disease (gangrene). Hippocrates also preferred a disarticulation compared to an amputation. To control haemorrhage, he proposed the use of cautery and vascular ligatures. Nevertheless, he described the complications of an amputation as devastating in most cases [8, 18].

In the first century AD, Aulus Cornelius Celsus (25 BC–50 AD) in his work De medica proposed an amputation for a gangrenous limb; he advised cutting between the living and diseased part, but not through a joint [19, 20]. He also proposed the ligation of vessels to control blood loss, the proximal division of bone in order to allow a "flap" of skin to cover the stump, and the packing of the wound with lint soaked in vinegar to prevent further infections [7, 8]. In the first and second century AD, Archigenes proposed amputation of a limb for sepsis and trauma and elective amputations for ulcers, tumours, and deformities. He used cold water to control haemorrhage and a cataplasm made of leek, bread, and salt for wound coverage [7, 15]. At the same time period, the first rehabilitation aids used as orthoses were designed in Greece and Rome. Initial prostheses for combating and hiding deformity were heavy, crude devices made of the available materials of the era (wood, metal and leather). According to historic sources, the Roman general Marcus Sergius wore an iron replacement hand during the Second Punic War [7, 21]. Similar ancient orthoses can be found all over the world.

From the Middle Ages to the Renaissance

During the Middle Ages in the Western world (eleventh to twelfth century AD), the domination of the church over medicine and education prohibited any haemorrhage ("*Ecclesia abhorret a sanguine*"), leading to a discredit on surgery and surgeons (the dark ages). Surgery was placed in the hands of empirics and barber surgeons who formed their medieval guilds with masters and apprentices. In the twelfth century, the most important contributions concerned the advent and use of pain-relieving plant remedies used as early anaesthetic drugs in order to relieve pain during an amputation. Those remedies were usually based on opium, mandragora, and henbane [8, 22].

In the East, surgery continued to flourish. In Egypt, the work of Paul of Aegina (625–690 AD), a surgeon of Greek origin and education, summarized the existing knowledge of surgery in the work "*Epitome of Medicine*" where he described the traditional

Fig. 1 Depictions of amputations in ancient Egypt (Edwin Smith Papyrus, New York Academy of Medicine)

surgical technique for amputations and wound dressing with various cataplasms [23]. In the Arabic world, Albucasis (936–1013 AD) is considered the greatest medieval surgeon of the Islamic World and the Middle Ages and the father of surgery. His most important work, "*On Surgery and Instruments*," is the first illustrated surgical guide ever written (Fig. 2) [19]. According to Albucasis, an amputation could be used to treat congenital malformations (such as polydactyly) and gangrene secondary to poisonous reptile and spider bites. He used tourniquets proximal and distal to the site of incision to tense the soft tissue, which was then protected by linen dressings to avoid saw injury. He also pioneered the double suture, which is still used today for high tension closures [8, 13, 15].

At the Renaissance, innovations occurred in instrumentation and techniques. Haemostasis was achieved with haemostyptic substances, such as hot oil and vitriol, or cautery, and cleansing was made with water, wine, balsams, and other herbal solutions. In 1517, Gersdorff described elective amputation above the level of injury for war trauma with the use of constricting bands as tourniquets above and below the amputation site. He relied on styptics to stop haemorrhage; he used a haemostatic containing egg, and if it did not work he employed cautery or warm oil [24, 25]. Last, he proposed coverage of the wound with a cow or pig bladder [7, 8]. In 1556, Franco in his "*Little Treatise*" proposed the ingestion by the patient of a mixture of syrups and herbs for several days both before and after surgery and the use of ligatures to control haemorrhage; Franco and Croce suggested a heated sickle-shaped knife instead of a razor in order to cauterize haemorrhage during the incision [7, 8].

Surgical instruments, ligatures, and prosthetics: Ambroise Paré (1510–1590 AD)

The greatest innovation in the era is attributed to Ambroise Paré (1510–1590 AD), who is considered the father of surgery and modern forensic pathology (Fig. 3) [1]. Paré was a keen observer and anatomist and invented several surgical instruments. He was a barber surgeon of the Parisian Barber Surgeon guild and contributed both to the practice of surgical amputation and to the design of limb prostheses. He used tourniquets and vessel ligatures (forceps and sutures) for haemostasis, emphasized on patients' ability to function post-amputation, and designed functional prosthetics for both upper and lower limbs. When he designed legs, he gave them a mechanical knee that could be locked when standing and bent at will. He drew sketches of an arm that could be bent with a pulley that mimicked arm muscles. He used the progress in technology that occurred in his era to create prostheses that worked with the mechanical devices invented for robotic toys or clocks. "Le Petit Lorrain" was a mechanical hand operated by catches and springs that was worn into battle by a French army captain; it had a fixed thumb, but spring loaded fingers that could move with the press of a button, allowing the French army captain who wore it to move easily and effectively (Fig. 4). Paré was an important innovator of his era, and his surgical technique for amputations is similar to those used today. However, his technique required an assistant and because too many ligatures were applied, it did not become popular until the eighteenth century with the advent of the first working tourniquet by Jean Louis Petit [8, 21, 26, 27].

Fig. 2 Surgical instruments form Treatise on Surgery by Albucasis (Collectie Universitaire Bibliotheken Leiden)

Additionally, Paré introduced cauterization and rediscovered the use of ligatures made by thread-like or wire material to constrict blood vessels. This surgical application greatly reduced bleeding and risk for collapse or death from haemorrhagic shock [26, 27]. Probably, the most important innovation of Paré was his technique and contribution to the treatment of gunshot wounds. Up to this point in the history of medicine, such wounds were treated with cauterization by applying burning iron or scalding oil. The aim was to destroy the so-called poison and to forestall putrefaction [1, 26, 27].

Paré described an incident when he was a novice surgeon in Italy in 1537 on a military campaign of the French Army. When he ran out of oil he had to improvise in order to treat the wounded soldiers. He made a healing salve consisting of egg-white, rose-oil, and turpentine. The following night he could not sleep feeling guilty for the patients whose wounds he had not cauterized because of lack of oil, so he got up early to pay them a visit in distress. He was surprised to see that those treated with the salve suffered little pain, had no inflammation or swelling, and they had a quiet, relatively painless night. In contrast, those treated with burning oil suffered from high fever with aches and inflammation around the wound. Therefore, he concluded never again to burn

Fig. 3 Ambroise Paré performing a leg amputation of a wounded soldier in the field of battle (illustration for "La Ciencia Y Sus Hombres" by Luis Figuier; D Jaime Seix, 1876)

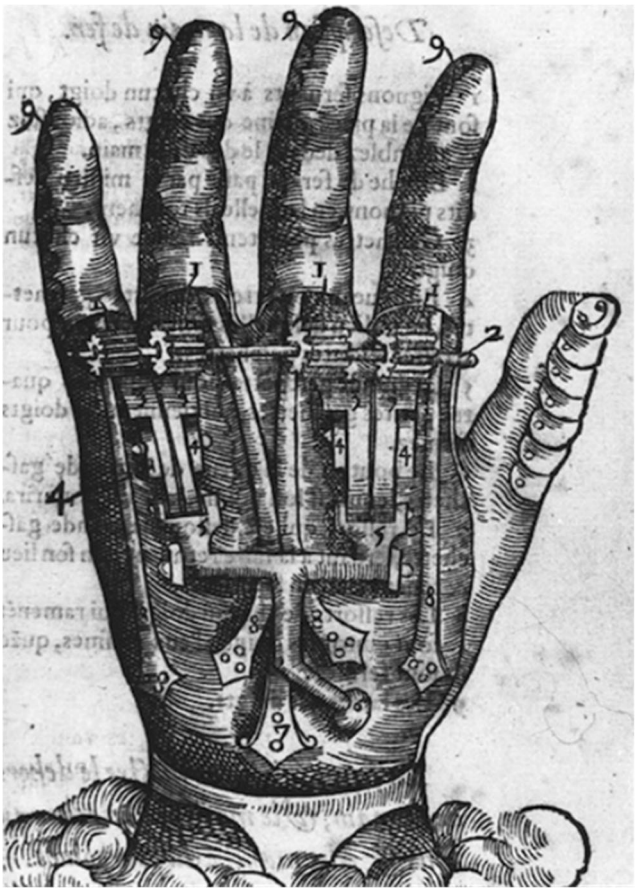

Fig. 4 Le Petit Lorrain prosthetic hand by Ambroise Paré (the Dix livres de la chirurgie, 1564)

patients suffering from shot wounds and discarded the myth that gunpowder and gunshots were poisonous. He thereafter started treating gunshot wounds through the application of the cataplasm he had invented, and he used the same cataplasm to treat soft tissue and surgical traumas after amputation in order to avoid swelling, blistering, and distraction of the skin [1, 13, 26, 27].

During the sixteenth century, barber surgeons mainly in France and Germany practiced amputations with innovative instrumentation and tools with a reduced operating time of three to four minutes at the thigh. However, analgesic drugs were not yet commonly used, and the mortality rate was nearly 60% for most cases; the main causes of death were infection or haemorrhagic shock [13, 15].

From the seventeenth to the twentieth century

The most important innovation of the seventeenth century was the theory of blood circulation by William Harvey (1578–1657 AD) and the central role of the heart in it (1616 AD). The second important innovation was the advent of the "classic circular cut" amputations with one cut, without removing the scalpel. This was made possible through innovations in instrumentation. In 1679 AD, the first "flap amputation" was reported by Lowdham of Exeter; he used a single flap and wound coverage with animal bladders. In the same year, James Yonge described the "flap" approach to amputation. Instead of performing a circular cut, Yonge constructed a long flap of skin and fascia to cover bone ends, divided the musculature in a circular fashion, which accommodated a drain, and allowed closure with four or five sutures without tension. By using turpentine as a wound dressing, his method was claimed to heal stumps within 3 weeks. According to Yonge, his method came from Lowdham of Exeter, who left no personal record of his own operation [7, 8, 22]. In 1696 AD, Verduin described the posterior flap for amputation wound coverage [8].

In the eighteenth century, the most memorable innovation in amputation surgery was the "Guillotine" amputations as described by Guillot (1791 AD). These amputations were performed without closure of the skin in an urgent setting after devastating trauma or extensive gangrene and were completed later in a second operation for the coverage of bone. Guillotine amputations became popular at the level of the ankle and below the knee. In the same era, the "classic (one stage) circular cut" amputations became popular, however, with the disadvantage of the application of tension in the soft tissue after wound coverage [8, 22].

In that period, Jean-Louis Petit (1674–1760 AD) introduced the "two-stage circular cut" amputation that reduced the tension on the soft tissue envelope around the limb. However, his most important contribution was the invention and application of the screw tourniquet to control hemorrhage during an amputation. The operational tourniquet of Jean-Louis Petit helped reduce blood loss and risk of hypovolaemic shock and death during amputation surgery and gave a new paradigm in amputation surgery compared to complex surgery with extensive ligatures as described by Ambroise Paré and his successors; it was easy to be applied in emergency hostile environments like battlefields [2, 27].

In the same era, William Bromfield (1712–1792 AD) described the "three-stage circular cut" amputation with the advantage of better coverage and closure. The evolution of instrumentation for amputations greatly facilitated the work of surgeons of the era. The invention of the nerve compressor by Moore in 1784 and the "three-stage circular cut" amputation with the use of a soft tissue retractor by Benjamin Bell in 1787 were some of the most significant innovations of the era in terms of surgical instrumentation [18, 22]. In 1810 AD, Langenbeck introduced the "double flap amputation" for wound coverage. In 1832 AD, Alfred Velpeau summarized the indications for limb amputation as partially divided limbs or fingers, classified gangrene including traumatic and hospital gangrene, frostbite and severe burns, open fractures, especially due to gunshot, severe bone infection, carious joints, cancer and sarcoma, severe leg ulceration, supernumerary fingers and toes, and rarely exostoses, severe joint contractures, tetanus, and hydrophobia. In 1845 AD, Cox applied an improved vascular compressor for the control of haemorrhage. Nevertheless, the problems of pain through the operation and sepsis remained unsolved leading to an increased mortality rate for the amputees [8, 18, 22].

Antisepsis: Joseph Lister (1827–1912 AD) and Louis Pasteur (1822–1895 AD)

The problem of infection was started to solve with the work of Joseph Lister (1827–1912 AD) and the introduction of antisepsis in 1867 (Fig. 5). Based on the contemporary work of Louis Pasteur (1822–1895 AD) on the microbial theory of infection and the success of Ignaz Semmelweis (1818–1865 AD) on the treatment of gynecological infections, he introduced for elective surgery the soaking of the patient's skin, his hands, instruments and dressings, and spraying the air around wounds with phenol. This practice was proved successful for the prevention of post-operative infections; the mortality rate of the amputees dropped from 45 to 15% and the amputation wounds healed successfully through that practice. Pasteur himself in 1874 described the process of antisepsis through careful hand-washing and flaming of surgical tools, the use of dressings subjected to heat at 130–150 °C, and water at 110–120 °C [3, 13, 15].

Fig. 5 Portrait of Joseph Lister, the pioneer of antisepsis in surgery (the Royal Society of Chemistry, 1855)

Sterilization: Gustav Adolf Neuber (1850–1932 AD)

The era of antisepsis soon gave its position to the era of sterilization in the operating theater with Gustav Adolf Neuber of Kiel being the first to set standards for aseptic practice. He opened his own private hospital on Königsweg in Kiel, where he implemented modern principles of asepsis. He used autoclave operating gowns in 1883 and advocated sterile caps and rubber shoes in 1886. Surgeons were required to wash their hands, faces, and arms before entering the operating rooms. The rooms were also isolated from other parts of the building so that no materials could enter or exit the operating rooms. The air was sterilized by running through vents that passed the building's heating system, heating the air, and kill bacteria. He used dry, peat aprons when operating on patients that would dry very quickly and would stay sterilized longer than aprons and articles of clothing soaked in antiseptic fluids. In 1881, Charles Chamberland invented the steam sterilizer, known as the autoclave. The autoclave was used to clean surgical tools and kill bacteria by heating water, held within the autoclave, to 140 °C for approximately 20 minutes. By 1890, with the establishment of thermal sterilization techniques, all-metal knives became obligatory and, about the same time, knives longer than 11 in. disappeared from instrument catalogs as it was difficult to be sterilized [13, 15].

Anaesthesia (mid-nineteenth century)

The problem of pain during an amputation was solved with the introduction of anaesthesia in the mid-nineteenth century. In 1842, the American physician Crawford Long removed two tumours from a patient with the use of diethyl ether for a painless operation; he reported his practice in 1849. Morton and Warren in 1846 used ether through inhalation to induce peri-operative anesthesia in the Massachusetts General Hospital. Later came the use of other anaesthetic drugs like chloroform, nitrous oxide, and others and the administration through inhalation machines for a safer outcome and to avoid complications [13, 15].

Replantation and rehabilitation (twentieth century)

A significant development of the twentieth century was the advent of limb replantation surgery after an amputation, as reported by Malt and McKhann in the Massachusetts General Hospital in 1962. Additional significant refinements in the post-operative stage of an amputation were soft tissue management and prevention of complications, engineering of custom-made prostheses in the industrial level, and rehabilitation of the amputees. Rehabilitation is essentially a twentieth century concept, spurred on by World War I with a vast number of disabled amputees who wished to resume employment despite residual physical defects. Since then, a significant number of modalities have been developed by expert physicians wishing to assist amputees to return to everyday habits and employment [8, 18, 22].

Since 1920, the use of disposable scalpels became a common practice. Sterilization evolved with improvements in bacteriological knowledge, chemotherapy, antibiotics, and ventilated clean-air operating theaters making amputations almost completely free from infection events. Additionally, important knowledge was obtained on hypovolaemic shock due to haemorrhage, safe blood transfusions for major surgery according to blood groups, and enhanced anaesthetic and sterilization techniques. All that made amputation surgery safe and commonly practiced in World War II and henceforth [8, 18, 22]. With these innovations, the indications for amputation surgery were widened comprising congenital abnormalities, crushing injuries and compound fractures, gunshot wounds, vascular failures, joint injuries and diseases, severe chronic leg ulceration, tumors, severe pain, neurological deficits, limb entrapment, and more. Amputation was done as urgent cases to prevent shock or, as elective cases as in most civil amputations as soon as a careful assessment has taken place [18, 22].

Twenty-first century

At the end of the twentieth century, more than half of limb amputations are attributable to diabetes and related

complications; the majority of limb amputations are performed on the lower extremities. Diabetic neuropathy, peripheral vascular and arterial disease, ulcers and osteomyelitis, uncontrolled diabetes, and Charcot foot contribute to amputation for diabetics. Currently, with comprehensive foot exam and better understanding of the pathophysiology of the disease, amputations for diabetic foot problems have decreased; however, they remain a big problem for diabetics.

Conclusion

From the Hippocratic era until currently, the surgical approach to amputation has changed little. However, the indications for amputations have changed a lot and had been refined, especially in diabetic patients and in those with severe chronic peripheral vascular disease. An exponential decrease in mortality for an operation once fraught with complications was due to the development of the tourniquet, proper vessel ligation and repair, antisepsis, and anesthesia. Rehabilitation has improved enabling functional and social reintegration of amputees.

Compliance with ethical standards

Conflicts of interest The authors declare that they have conflicts of interest.

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