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MINIMALLY INVASIVE AND MICROSURGICAL SURGERY IN OSTEOMYELITIS: ADVANCES, CLINICAL RESULTS, AND FUTURE PERSPECTIVES

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Abstract: Introduction: Osteomyelitis is one of the most complex musculoskeletal infections, whose surgical management has evolved towards minimally invasive and microsurgical techniques that seek to improve infection control and functional recovery.

Objective: To analyze the advances, clinical results, and future prospects of minimally invasive surgery and microsurgery in the treatment of osteomyelitis, based on the most recent scientific evidence.

Methodology: A narrative review was conducted in the PubMed, Scopus, Web of Science, and Cochrane Library databases, including articles published between 2020 and 2025. Original studies, systematic reviews, meta-analyses, and clinical series evaluating minimally invasive techniques (arthroscopy, endoscopy, percutaneous debridement) and microsurgical techniques (vascularized free flaps, tissue reconstructions) in osteomyelitis were selected. Results: Minimally invasive surgery proved effective in localized cases, with lower morbidity rates, reduced hospital stays, and better functional preservation. Microsurgery achieved success rates of 85–95% in the reconstruction of bone and soft tissue defects, with low recurrence of infection. Both techniques showed significant benefits over traditional open surgery, although they have limitations related to technological availability, the learning curve, and costs. Conclusions: Minimally invasive and microsurgical techniques represent a paradigm shift in the treatment of osteomyelitis, with encouraging clinical results. The future integration of computer navigation, 3D printing, robot-assisted surgery, and regenerative therapies will consolidate a hybrid model of surgical management, focused on precision, personalization, and improving patients' quality of life.

Keywords: Osteomyelitis; Minimally invasive surgery; Microsurgery; Bone debridement; Bone reconstruction.

INTRODUCTION

Osteomyelitis is one of the most challenging musculoskeletal infections in traumatology and orthopedic practice. Its incidence varies between 1 and 2 cases per 10,000 inhabitants in developed countries, and is even higher in regions with limited access to healthcare and in populations with comorbidities such as diabetes mellitus, chronic renal failure, and immunosuppression[1] .

It is a complex pathology characterized by inflammation and infection of bone tissue, which can progress to necrosis, bone sequestration, and permanent dysfunction if not diagnosed and treated promptly[2] .

Traditionally, surgical treatment of osteomyelitis has been based on extensive resections and debridements, accompanied by prolonged antibiotic therapy. However, this approach has significant limitations: high associated morbidity, prolonged recovery times, and risk of infectious recurrence, which in some cases exceeds 20–30%.[3] .

Given this scenario, technological and surgical advances over the last decade have led to the incorporation of less invasive techniques, with the aim of optimizing clinical and functional outcomes.

Minimally invasive surgery has gained prominence in this field through the use of image-guided endoscopic, arthroscopic, and percutaneous procedures, which allow access to the site of infection with less tissue

damage, reduced bleeding, and accelerated postoperative recovery[4] .

Complementarily, reconstructive microsurgery has positioned itself as an alternative for covering bone and soft tissue defects through the transfer of free flaps and microvascular anastomosis techniques that improve tissue viability and reduce the risk of reinfection[4] .

Preliminary results from recent studies show that these innovative surgical modalities not only achieve lower recurrence rates, but also promote faster functional reintegration, reduce hospital stays, and improve patients' quality of life. In addition, the incorporation of emerging technologies such as computer navigation, 3D printing of surgical guides, and robot-assisted surgery opens up promising horizons for precision debridement and customized reconstruction [5] .

In this context, it is pertinent to review the available evidence on the role of minimally invasive surgery and microsurgical techniques in the treatment of osteomyelitis, analyzing recent advances, reported clinical results, and future prospects in traumatology and orthopedic practice. This approach not only contributes to academic knowledge but also guides clinical decision-making based on the best available evidence.

METHODOLOGY

A narrative review of the literature was conducted in the PubMed, Scopus, Web of Science, and Cochrane Library databases, covering the period from January 2020 to September 2025. MeSH and DeCS terms were used in combination with free keywords related to osteomyelitis, minimally invasive surgery, microsurgery, bone debridement, and reconstruction.

Original articles, systematic reviews, meta-analyses, and clinical series in English and Spanish that evaluated minimally invasive techniques (arthroscopy, endoscopy, percutaneous debridement) or microsurgical techniques (vascularized free flaps, tissue reconstructions) applied to osteomyelitis were included. Pediatric and veterinary studies and those without full-text access were excluded.

The selected studies were critically analyzed in terms of design, population, and clinical outcomes, and the evidence was organized into three thematic areas: (1) minimally invasive techniques, (2) microsurgical techniques, and (3) clinical outcomes and technological perspectives.

DEVELOPMENT

MINIMALLY INVASIVE TECHNIQUES IN OSTEOMYELITIS

Chronic osteomyelitis represents a persistent challenge in orthopedic practice due to its recurrent nature and the structural damage it causes to the affected bone[6].

The need for effective surgical control with the least possible impact on the patient's function and anatomy has driven the development of minimally invasive techniques that seek to improve functional prognosis without compromising infection control. These modalities are emerging as intermediate alternatives between conventional open debridement and complex reconstructive surgery[7] .

Arthroscopy in articular osteomyelitis

Arthroscopy allows direct exploration of the joint space and access to hard-to-reach areas with minimal tissue damage. In subacute or chronic osteomyelitis of the knee, ankle, and shoulder, arthroscopy has been shown to facilitate the removal of necrotic debris, thorough lavage, and targeted biopsies[6].

Recent studies report infection resolution rates of over 85%, with better functional preservation and less joint stiffness compared to open approaches. In addition, the use of arthroscopy in combination with local antibiotics (cement beads or hydrogels) has been shown to improve bacterial eradication in scenarios of persistent infection[8].

An additional aspect to highlight is the possibility of performing concomitant joint repair procedures, such as selective synovectomies or partial cartilage reconstructions. This is of great value in young patients, in whom joint preservation is a priority. Furthermore, arthroscopy has been shown to facilitate a faster return to functional mobility, reducing the risk of post-surgical joint stiffness, a common complication in open techniques[9]removal of infected tissue inside the medullary cavity requires extensive osteotomy to create a bone window of adequate size. Bone endoscopy (medulloscopy .

Endoscopy in vertebral osteomyelitis

In vertebral osteomyelitis, conventional approaches often involve extensive surgery with risks of instability and neurological complications. Transforaminal and interlaminar endoscopy has shown encouraging results, allowing targeted debridement under endoscopic vision, reducing perioperative complications, and preserving spinal stability[10].

A systematic review with meta-analysis showed that spinal endoscopy achieves infection resolution rates of 80–90%, with a reduction in hospital stay of up to 40% and better pain control. These findings are particularly relevant in patients with severe comorbidities that contraindicate major surgery[11] .

Another benefit described is the possibility of obtaining accurate microbiological samples during the procedure, which increases the pathogen isolation rate compared to percutaneous biopsies. This optimizes targeted antibiotic selection, a crucial aspect in the era of antimicrobial resistance. In addition, less manipulation of nerve structures reduces the incidence of postoperative neurological deficits, improving the safety of the procedure[12]particularly the radius and ulna, poses significant challenges. These defects, resulting from trauma, tumors, infections, or congenital anomalies, require precise surgical intervention for functional restoration. Traditional non-vascularized autogenous bone grafts have limitations, such as resorption and limited biological activity. To address these challenges, free vascularized fibular grafts (FVFGs .

Image-guided percutaneous debridement

Percutaneous debridement, assisted by fluoroscopy or computed tomography, allows purulent collections to be evacuated and residual bone cavities to be cleaned with minimal invasion. Its use is especially valuable in osteomyelitis of long bones and the

pelvis, where open surgery is often highly complex[8] .

Cohort studies show that the combination of percutaneous drainage with local antibiotic instillation achieves cure rates of 70–85% in selected patients. Likewise, computer navigation and preoperative planning with 3D printing improve the accuracy of the approach and reduce recurrence[13] .

Additionally, this technique has been used in high-risk surgical patients, such as those with advanced cardiovascular disease or severe immunosuppression, in whom open surgery carries a high morbidity and mortality rate[10].

The possibility of repeating the procedure in case of persistent necrotic material, with low cumulative risk, makes it a flexible and adaptable strategy. Similarly, the integration of hybrid techniques, combining initial percutaneous drainage followed by reconstructive microsurgery, opens up new perspectives in the management of complex cases[14] .

Combination with local antibiotic therapy

A key aspect of minimally invasive techniques is their potential to be combined with local antimicrobial delivery. The use of polymethyl methacrylate (PMMA) beads impregnated with antibiotics or biodegradable controlled-release systems allows local concentrations to be achieved that are much higher than those obtained systemically, reducing the risk of toxicity and increasing bactericidal efficacy. This synergistic approach reinforces the role of less invasive procedures as part of the comprehensive management of osteomyelitis[15].

In recent years, biodegradable matrices with controlled release of vancomycin, gentamicin, and daptomycin have been developed, which avoid the need for a second surgery to remove the material, as is the case with PMMA. The combination of minimally invasive surgery with these systems has been shown to reduce the recurrence of infection in recent multicenter studies, as well as promoting bone regeneration thanks to their integration with osteoconductive biomaterials[16].

Documented clinical benefits

The main benefits described for these techniques include:

- Lower surgical morbidity: by preserving healthy structures and avoiding extensive resections.
- Reduction in postoperative pain and intraoperative bleeding.
- Shorter hospital stays and lower associated costs.
- Better functional recovery in the short and medium term.
- Comparable or superior results in infection control, especially when combined with local antibiotic therapy.

In comparative analyses with conventional surgery, the most recent multicenter studies highlight that minimally invasive techniques show particularly significant benefits in young patients and those with localized infections. However, there are still limitations in cases of diffuse osteomyelitis, where open procedures remain necessary. Randomized clinical trials are needed to

standardize indications, surgical protocols, and follow-up regimens in order to consolidate these techniques within international management guidelines[17]operation time, and intraoperative blood loss were statistically compared between two groups. Specifically, the clinical efficacies of two methods were statistically evaluated according to the external fixation time/index, recurrence rate of deep infection, incidence of complications, the times of reoperation, and final functional score of the affected extremities. Results: Gender, age, cause of injury, Gustilo grade of initial injury, proportion of complicated injuries in other parts of the affected extremities, and numbers of femoral/tibial defect cases did not differ significantly between treatment groups, while infection site distribution after debridement (shaft/metaphysis.

MICROSURGICAL TECHNIQUES AND RECONSTRUCTION IN OSTEOMYELITIS

The surgical management of osteomyelitis is not limited to controlling the infection. Once debridement has been performed, bone and soft tissue defects often appear, requiring complex reconstructive strategies[13] .

In this scenario, microsurgery has become an essential tool, offering vascularized coverage and tissue transfer options that restore function and prevent recurrence[18] .

Microvascular flaps in bone and soft tissue reconstruction

Free microvascular flaps are currently the standard for reconstructing post-infectious bone and tissue defects. The vascularized fibula flap is one of the most widely used, as it provides strong cortical bone and can incorporate skin or muscle depending on the reconstructive needs[14] .

Recent multicenter studies have shown consolidation rates of over 90% in defects larger than 6 cm, with good graft integration and low rates of infectious recurrence[19] .

In addition to the fibula, other flaps such as the vascularized iliac, scapular, and radial flaps have shown promising results in complex segmental defects. Continuous vascular supply promotes not only bone integration but also local delivery of systemic antibiotics, which increases resistance to reinfection[20] .

Muscle and fasciocutaneous flaps

In cases with extensive soft tissue involvement, muscle flaps (gracilis, rectus abdominis, latissimus dorsi) and fasciocutaneous flaps (anterolateral thigh) are effective alternatives. Their ability to provide well-vascularized tissue helps to eradicate residual infectious foci and cover post-debridement cavities, reducing the risk of recurrence[21].

Advances in microsurgery have made it possible to refine vascular anastomosis techniques and reduce rates of partial or total flap necrosis. Likewise, the development of supermicrosurgery techniques, with

anastomosis of vessels smaller than 0.8 mm, opens up new possibilities in small-volume defects, particularly in distal extremities[21].

Combined tissue transfer (bone and soft tissue)

The combination of bone and soft tissue flaps in a single surgical procedure has proven to be an efficient strategy for the comprehensive management of complex defects. Examples such as the osteocutaneous fibula flap allow for the simultaneous reconstruction of bone and skin coverage, shortening surgical and hospital times[22] .

These techniques have proven particularly useful in post-traumatic osteomyelitis and in cases of infected pseudoarthrosis, where simultaneous reconstruction of bone and skin coverage is essential to achieve consolidation[22] .

Clinical results and limitations

Recent literature shows that microsurgical techniques achieve success rates of around 85–95% in infection control and functional reconstruction.

In addition, they allow for faster recovery of mobility and early reintegration into daily activities. However, they are not without limitations: they require highly specialized equipment, adequate infrastructure, and a long learning curve[4] .

Another relevant aspect is cost, as microsurgical procedures involve greater use of hospital resources. However, several cost-benefit analysis studies suggest that, in the long term, these approaches may be more cost-effective by reducing infectious recurrence, rehospitalizations, and major amputations[15]filling the bone's dead space and covering the defect may be necessary. This study describes the successful treatment of chronic calcaneal OM using a de-epithelialized perforator flap to reconstruct soft-tissue and bone defects simultaneously. The study retrospectively reviewed the medical records of 10 patients diagnosed with Cierny–Mader type III–IV calcaneus OM treated with de-epithelialized free perforator flaps between 2015 and 2023. The data included patient demographics (age, sex, and comorbidities .

Future prospects

Future prospects in the field of microsurgery applied to osteomyelitis include the use of hybrid biomaterials that integrate vascular grafts with osteoconductive matrices, as well as the incorporation of 3D printing to customize the shape and size of bone flaps. In addition, protocols are being developed that combine microsurgery with regenerative therapies based on mesenchymal stem cells and growth factors, with the aim of enhancing osseointegration and tissue regeneration[7].

These innovations suggest that microsurgery is not only a reconstructive tool, but also a bridge to personalized regenerative medicine in the treatment of osteomyelitis[23] .

LIMITATIONS AND FUTURE PERSPECTIVES

Despite documented advances in the use of minimally invasive and microsurgical techniques for the treatment of osteomyelitis, the available evidence has significant limitations.

First, most current studies are retrospective case series or cohorts with a small number of patients, which limits the ability to draw solid and generalizable conclusions[2].

Furthermore, there is heterogeneity in diagnostic criteria, osteomyelitis classification, and follow-up protocols, which makes it difficult to compare different studies.

Another relevant limitation is the limited availability of randomized, multicenter clinical trials that directly evaluate the efficacy of these techniques compared to conventional surgery. This results in a lack of standardized clinical guidelines that define precise indications, therapeutic algorithms, and patient selection criteria. Similarly, cost-effectiveness studies are still limited, which is crucial for validating the applicability of these techniques in resource-constrained settings[10].

In terms of future prospects, the field is moving toward the integration of new technologies that enhance both surgical precision and functional outcomes. The use of computer navigation and robot-assisted surgery is projected to be a valuable tool for optimizing the resection of infected tissue with minimal aggression. 3D printing and virtual planning will allow for the customization of bone flaps and cutting guides, improving anatomical adaptation and subsequent functionality[11] .

On the other hand, the combination of microsurgery with regenerative therapies based on mesenchymal stem cells, growth factors, and bioactive grafts opens the door to a new paradigm in the management of osteomyelitis. These strategies not only seek to cover post-infectious defects, but also to promote tissue regeneration and reduce the long-term recurrence rate[14] .

Finally, the implementation of high-quality multicenter studies, together with the evaluation of economic impact and quality of life, will be essential to consolidate these techniques as an integral part of therapeutic algorithms in osteomyelitis.

DISCUSSION

The surgical approach to osteomyelitis has evolved significantly over the last decade, moving from extensive open procedures to less invasive and advanced microsurgical techniques. This transition responds to the need to reduce surgical morbidity, improve functional outcomes, and optimize hospital resources[3] .

Recent literature shows that both minimally invasive surgery and microsurgery have promising results, although each has specific indications, benefits, and limitations[6] .

Minimally invasive techniques, including arthroscopy, endoscopy, and image-guided percutaneous debridement, have proven particularly useful in subacute and chronic localized phases of osteomyelitis. Comparative studies show that these approaches achieve infection eradication rates similar to those of open surgery, with additional advantages such as less postoperative pain, shorter hospital stays, and better functional preservation[24].

However, they have limitations in cases of diffuse osteomyelitis or extensive bone destruction, where limited access could compromise the effectiveness of debridement.

On the other hand, microsurgical techniques have established themselves as the reconstructive option of choice for bone and soft tissue defects following debride-

ment. The use of free vascularized flaps has shown success rates of over 90%, with adequate integration and low recurrence[25].

These techniques provide well-vascularized tissue, which not only promotes osseointegration but also contributes to the eradication of residual bacteria through improved delivery of systemic antibiotics. However, microsurgery requires advanced infrastructure, trained multidisciplinary teams, and higher costs, which may limit its availability in health systems with limited resources[15].

It is important to note that these two modalities should not be considered mutually exclusive, but rather complementary. The combination of minimally invasive procedures for initial infection control with microsurgical techniques for the reconstruction of complex defects is an increasingly recommended comprehensive approach in clinical practice. In addition, technological innovations such as computer navigation, 3D printing, and local antibiotic delivery can enhance the effectiveness of both approaches, promoting more precise and personalized surgery[26] .

Despite these advances, knowledge gaps remain. Most of the available studies are retrospective case series or cohorts, with heterogeneity in inclusion criteria and follow-up protocols. Controlled, multicenter clinical trials are needed to directly compare the different approaches, as well as cost-effectiveness studies that will allow solid recommendations to be established for clinical practice and the development of international guidelines[27] .

In summary, current evidence supports minimally invasive techniques as an effective tool in the management of localized osteomyelitis, while microsurgery is the best option in scenarios involving complex post-infectious defects. The future of osteomyelitis surgery will likely move toward a hybrid model, in which the integration of less invasive procedures, microsurgical reconstruction, and regenerative therapies will improve clinical outcomes and reduce recurrence rates.

CONCLUSIONS

Minimally invasive surgery and microsurgical techniques have transformed the contemporary approach to osteomyelitis, offering safer and more functional alternatives compared to traditional open surgery.

Recent evidence supports that arthroscopic, endoscopic, and percutaneous procedures allow adequate control of infection in localized cases, reducing surgical morbidity, hospital stay, and functional recovery times. At the same time, reconstructive microsurgery, using free vascularized flaps and tissue transfers, is the strategy of choice for complex defects, providing well-vascularized tissue that promotes osseointegration and reduces infectious recurrence.

However, the widespread implementation of these techniques faces limitations associated with the heterogeneity of the available evidence, the need for highly specialized equipment, and high costs in certain healthcare contexts. These factors underscore the importance of developing multicenter studies and randomized clinical trials to standardize indications, define surgical protocols, and establish their cost-effectiveness in different healthcare systems.

Looking ahead, the integration of innovations such as computer navigation,

3D printing, robot-assisted surgery, and regenerative therapies based on stem cells and bioactive biomaterials will consolidate a hybrid model of surgical management of osteomyelitis. This model, focused on precision and personalized medicine, has the potential to significantly improve clinical outcomes, reduce rates of recurrence , and optimize patients' quality of life.

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