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From Early Antibiotics to Fix and Flap: Current Evidence and Controversies in Open Fracture Management

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Abstract

Open fractures are severe orthopedic injuries associated with bacterial contamination, fracture-related infection (FRI), nonunion, and potential limb loss. Although established management principles are widely recognized, recent evidence has challenged traditional concepts such as the strict "six-hour rule" for debridement and emphasized the importance of coordinated multidisciplinary care. This narrative review summarizes current concepts and recent advances in open fracture management, focusing on initial assessment, infection prevention, surgical debridement, fracture stabilization, soft tissue reconstruction, and adjunctive local antibiotic strategies. The literature was searched through PubMed, Scopus, and Google Scholar, prioritizing publications from 2019 to 2025, while including seminal earlier studies when relevant. The final narrative synthesis included 21 articles, comprising clinical studies, systematic reviews, meta-analyses, clinical guidelines, and narrative or expert reviews. The reviewed evidence suggests that early intravenous antibiotic administration, adequate surgical debridement, stable mechanical fixation, and timely soft tissue coverage are interdependent components of modern open fracture care. The quality of debridement and early antibiotic delivery appear more consistently associated with infection prevention than strict adherence to a universal six-hour surgical threshold. The fix-and-flap approach may improve outcomes in selected high-grade injuries when appropriate expertise and resources are available. Adjunctive local antibiotic delivery shows potential in high-risk cases, but its indications, dosing, carrier selection, and long-term safety remain insufficiently standardized. Overall, contemporary open fracture management is best understood as a quality-driven and system-based strategy requiring early infection control, adequate stabilization, soft tissue reconstruction, and coordinated orthoplastic care.

1. Introduction

Open fractures represent severe orthopedic injuries characterized by disruption of the protective soft tissue envelope, resulting in direct exposure of bone and surrounding structures to the external environment. This exposure places patients at substantial risk of bacterial contamination, fracture-related infection (FRI), impaired bone healing, and failure of limb salvage. The consequences of open fractures extend beyond clinical outcomes to functional and psychosocial domains; in severe cases, their impact on quality of life may exceed that associated with several chronic diseases [1]. Open fractures predominantly affect adults and are commonly associated with high-energy trauma, although pediatric-specific considerations may be relevant to certain aspects of management.

From an epidemiological perspective, open fractures constitute a significant component of the global trauma burden. In the United States, approximately 4% of the nearly 6 million fractures occurring annually are classified as open fractures. The United Kingdom has also reported an increasing incidence, rising from 2.5 per 100,000 person-years in 2008 to 7.03 per 100,000 person-years in 2019. These injuries predominantly affect males of productive age and are closely associated with high-energy mechanisms such as road traffic accidents and industrial trauma [1, 2]. This epidemiological burden highlights the need for updated, evidence-based management guidance because delayed or suboptimal care may lead to infection, repeated surgery, prolonged disability, limb loss, and substantial healthcare costs.

The most serious complication of open fractures is FRI. Despite standard management strategies, including early intravenous antibiotic administration, thorough surgical debridement, adequate irrigation, and fracture stabilization, FRI remains a leading cause of morbidity and reoperation. Biofilm formation on bone and implant surfaces represents a major barrier to both antibiotic efficacy and host immune response, while the increasing prevalence of antimicrobial resistance further complicates infection control. The risk of infection is particularly elevated in high-grade injuries, especially Gustilo–Anderson type III fractures, which are associated with extensive soft tissue damage, severe contamination, and vascular injury [2].

Since 2019, several clinical guidelines, systematic reviews, meta-analyses, and cohort studies have contributed to important shifts in open fracture management. These developments have challenged or refined several long-standing concepts, including the optimal timing of antibiotic administration, the validity of the traditional “six-hour rule” for surgical debridement, the choice between temporary and definitive fracture fixation, the timing of soft tissue coverage, and the role of local antibiotic delivery. Current practice has increasingly moved away from rigid time-based thresholds toward a more integrated approach that emphasizes early antibiotics, adequate debridement by an experienced team, stable fixation, timely soft tissue reconstruction, and coordinated orthoplastic care [3].

Given the substantial disease burden, high risk of complications, and evolving evidence from 2019 to 2025, an updated synthesis is needed to clarify current concepts and unresolved controversies in open fracture care. Therefore, this narrative review examines the current evidence on early antibiotic administration and infection prevention, evaluates whether the traditional six-hour rule for debridement remains clinically valid, explores how fracture stabilization and soft tissue coverage should be integrated into modern open fracture management, and assesses the emerging role of adjunctive strategies, particularly local antibiotic delivery, in reducing infection risk. By addressing these key aspects, this review aims to provide a clinically relevant synthesis of contemporary evidence to support evidence-based decision-making in open fracture management.

2. Materials and Methods

This study was conducted as a narrative literature review to summarize current concepts and recent developments in open fracture management. The review focused on key aspects of open fracture care, including initial assessment, infection prevention, surgical debridement, wound irrigation, fracture stabilization, soft tissue coverage, adjunctive therapies, and clinical outcomes.

A literature search was conducted in PubMed, Scopus, and Google Scholar between March and April 2026. Articles published between January 2019 and December 2025 were prioritized to capture contemporary evidence. Key earlier studies were also considered when they provided foundational concepts that remained relevant to current practice. The search was limited to English-language, peer-reviewed publications involving human subjects. Study design was not used as an initial exclusion criterion, provided the article was directly relevant to open fracture management; however, evidence strength was considered during interpretation.

The search strategy combined controlled terms and free-text keywords related to open fractures and their management. The main search string used in PubMed was: (“open fracture” OR “open fractures” OR “compound fracture”) AND (“antibiotic prophylaxis” OR “infection prevention” OR “fracture-related infection” OR “FRI” OR “local antibiotic”) AND (“surgical debridement” OR “wound irrigation” OR “fracture stabilization” OR “external fixation” OR “internal fixation” OR “soft tissue coverage” OR “orthoplastic” OR “fix and flap”). This strategy was adapted for Scopus and Google Scholar using equivalent keyword combinations and Boolean operators. The reference lists of selected articles were also manually screened to identify additional relevant studies.

The inclusion criteria comprised prospective and retrospective clinical studies, systematic reviews, meta-analyses, clinical practice guidelines, and narrative or expert review articles addressing major components of open fracture management. Articles were included if they discussed initial assessment, antibiotic prophylaxis, infection prevention, surgical debridement, irrigation, fracture stabilization, soft tissue reconstruction, local antibiotic therapy, or clinical outcomes. Exclusion criteria included non-peer-reviewed sources, articles not available in full text, non-English publications, case reports with limited generalizability, animal or laboratory-only studies, and studies not directly related to open fracture management.

Article selection was performed in stages. First, titles and abstracts were screened for relevance to the review objectives. Second, potentially relevant full-text articles were assessed according to the predefined inclusion and exclusion criteria. A total of 21 articles were included in the final narrative synthesis. These comprised clinical studies, systematic reviews, meta-analyses, clinical practice guidelines, and narrative or expert review articles relevant to open fracture management.

As this study was conducted as a narrative review rather than a systematic review, formal PRISMA-based screening with exact exclusion counts was not performed. However, article selection was guided by predefined eligibility criteria, relevance to the review objectives, and contribution to key thematic areas, including initial assessment, antibiotic prophylaxis, infection prevention, debridement, fracture stabilization, soft tissue reconstruction, and adjunctive local antibiotic therapy. Additional references were identified through manual screening of reference lists when relevant.

To minimize selection bias despite the narrative review design, the literature search was conducted across multiple databases, predefined inclusion and exclusion criteria were applied, and reference lists of selected articles were manually screened to identify additional relevant sources. Article selection was guided by the focused review questions and key thematic areas of open fracture management, rather than by general relevance alone.

Given the heterogeneity of included sources, evidence was interpreted according to its methodological strength. Clinical practice guidelines, systematic reviews, and meta-analyses were prioritized when available, particularly for topics such as antibiotic timing, debridement timing, and infection prevention. Comparative clinical studies and large observational studies were used to support clinical trends and outcome-related findings. Narrative reviews, expert reviews, and key earlier studies were used mainly to provide background, historical context, or interpretation of established principles. Lower-level evidence and heterogeneous studies were interpreted cautiously and were not used alone to support strong clinical conclusions.

Data from the included studies were analyzed descriptively and synthesized narratively to identify areas of consensus, unresolved controversies, evolving recommendations, and clinical implications. No quantitative meta-analysis or formal risk-of-bias assessment was performed, as this study was not designed as a systematic review. Therefore, interpret the findings as a qualitative synthesis of contemporary evidence rather than graded clinical practice recommendations.

3. Results and Discussion

The following sections synthesize both established principles and recent evidence in open fracture management. Foundational concepts such as ATLS-based assessment, Gustilo–Anderson classification, debridement, stabilization, and soft tissue coverage are not presented merely as standard textbook principles, but are interpreted in relation to contemporary debates and emerging changes in clinical practice. Particular attention is given to areas where recent literature has challenged traditional assumptions, including the timing of antibiotic administration, the clinical validity of the six-hour debridement rule, the integration of fixation with early soft tissue coverage, and the evolving role of adjunctive local antibiotic strategies. Therefore, this review distinguishes established consensus from unresolved controversies and highlights how recent evidence may influence decision-making in modern open fracture care.

3.1. Initial Assessment and Classification of Open Fracture

Initial assessment in open fractures should be understood not merely as a sequence of standard trauma steps, but as the first decision-making phase that determines limb-salvage strategy, infection prevention, and the timing of definitive reconstruction. Contemporary open fracture care emphasizes early recognition of life-threatening injuries, standardized documentation of limb-threatening conditions, and rapid coordination between trauma, orthopedic, vascular, and plastic surgery teams [1, 2].

Open fractures are commonly the result of high-energy trauma and occur in approximately one-third of patients with multiple injuries [4]. The extent of soft tissue and bone damage is directly related to the kinetic energy transmitted during trauma; therefore, injuries may extend beyond the visibly affected extremity. For this reason, initial evaluation must follow Advanced Trauma Life Support (ATLS) principles, prioritizing identification and stabilization of life-threatening conditions before definitive orthopedic intervention [1, 5].

Table 1. Gustilo–Anderson classification of open fractures.

Type	Key Characteristics
I	Wound <1 cm, low-energy injury, minimal soft tissue damage, mild contamination
II	Wound 1–10 cm, moderate soft tissue damage without extensive tissue loss
IIIA	High-energy injury with extensive soft tissue damage but adequate soft tissue coverage allowing primary closure
IIIB	Severe soft tissue damage with extensive tissue loss requiring flap coverage
IIIC	Associated vascular injury requiring surgical repair

A dramatic extremity wound should not distract clinicians from potentially fatal injuries, including airway compromise, thoracic trauma, intra-abdominal hemorrhage, pelvic injury, or traumatic brain injury. The primary survey using the ABCDE approach provides a structured method for identifying these conditions. Airway protection, adequate ventilation, and hemodynamic stabilization are particularly important in patients with polytrauma or altered consciousness. Circulatory assessment should identify hemorrhagic shock from systemic injuries or active bleeding from the open extremity. Control external bleeding with direct pressure and, when necessary, a temporary tourniquet in the prehospital setting. Correction of hypotension and peripheral hypoperfusion is clinically important because poor systemic perfusion may compromise soft tissue viability, increase infection risk, and impair bone healing [1, 2].

After systemic stabilization, focused limb assessment should document wound size, contamination pattern, soft tissue loss, skeletal instability, exposed structures, and potential tissue devitalization. Avoid repeated wound manipulation in the emergency department to reduce secondary contamination. Instead, after removing gross debris, cover the wound with sterile saline-moistened dressings and immobilize the limb to limit fragment motion and additional soft tissue injury. Clinical photography before debridement, when consent and local policy allow, provides an objective baseline for operative planning and multidisciplinary communication [1, 6].

Neurovascular examination is central to early triage because vascular injury, nerve deficit, and compartment syndrome may alter the urgency and sequence of intervention. Assess distal pulses, capillary refill, motor function, sensory function, and signs of compartment syndrome at presentation, and repeat after reduction, splinting, or any manipulation. Hard signs of vascular injury, such as absent pulses, active bleeding, or expanding hematoma, require urgent escalation. In hemodynamically stable patients with suspected arterial injury, computed tomography angiography may help confirm the diagnosis and plan revascularization. Early recognition and timely reperfusion are crucial because delayed revascularization substantially increases the risk of failed limb salvage [1].

Perform radiological evaluation after initial stabilization. Plain radiographs with orthogonal views, including the joints above and below the fracture, are generally sufficient for initial assessment of fracture pattern, displacement, and associated joint involvement. Computed tomography may be useful in complex or intra-articular fractures, provided that it does not delay resuscitation, antibiotic administration, or urgent surgical management. Early intravenous antibiotics and tetanus prophylaxis according to immunization status remain integral components of initial open fracture care [1, 4, 5].

Classification of open fractures is important because it translates wound characteristics into early management priorities. The Gustilo–Anderson classification remains the most widely used system because of its simplicity and clinical practicality (Table 1). It categorizes open fractures based on wound size, contamination, soft tissue injury, and vascular injury requiring repair. Although the system has limitations, particularly interobserver variability and limited prognostic precision within type III injuries, it remains useful for early communication, antibiotic selection, fixation planning, soft tissue reconstruction strategy, and estimation of complication risk [7].

Clinically, the Gustilo–Anderson classification should be interpreted not only as a descriptive grading system but also as a practical framework for early treatment planning. Lower-grade injuries generally require narrower antibiotic coverage, less complex soft tissue management, and more straightforward stabilization strategies. In contrast, type III injuries often require expanded antimicrobial coverage, more urgent multidisciplinary evaluation, complex fixation planning, and early consideration of flap reconstruction or vascular repair. Therefore, classification should be integrated with neurovascular status, contamination pattern, host factors, and resource availability rather than used as an isolated prognostic tool [4, 8].

In addition to morphological classification, adjunctive scoring systems such as the Mangled Extremity Severity Score (MESS) and the Ganga Hospital Open Injury Severity Score (GHOISS) may be utilized in severe extremity

Table 2. Components of initial assessment in patients with open fractures.

Component	Aspect Assessed	Clinical Description
ATLS	Primary survey (ABCDE)	The ATLS approach is performed to identify life-threatening injuries. Stabilization of airway, breathing, and circulation must be prioritized before definitive orthopedic evaluation.
Basic History	Medical and medication history	Comorbidities, allergies, tetanus immunization status, use of anticoagulants, and risk factors for infection should be documented to guide management.
	Social history	Smoking habits, nutritional status, alcohol/drug use, as well as activity level and hand dominance (in upper extremity fractures) should be recorded.
Focused Injury History	Mechanism and timing of injury	Information regarding the mechanism of trauma, time of injury, and duration of wound exposure helps determine urgency and management strategy.
	Injury location and environment; prehospital information	The environment of injury (road, agricultural setting, freshwater/seawater) may influence contamination patterns and antibiotic choice. Prehospital interventions (e.g., antibiotics, analgesia, tourniquet application) as well as initial neurological and vascular status should be documented for comparison.
Local Physical Examination	Neurovascular status	Assessment includes distal pulses, capillary refill, motor and sensory function. If pulses are absent, further evaluation with Doppler ultrasound or CT angiography may be required.
	Wound condition	Wound size, degree of contamination, soft tissue damage, active bleeding, exposure of bone or tendon, and presence of foreign bodies should be documented.
	Compartment syndrome	Severe pain, compartment tightness, and neurological deficits should raise suspicion for early compartment syndrome.
Documentation and Escalation	Initial documentation	Clinical photographs prior to debridement are recommended. Initial findings should be recorded as a baseline for further evaluation.
	Senior consultation	In cases of active bleeding, vascular injury, neurological deficits, or suspected compartment syndrome, prompt consultation with a senior clinician is required.

injuries to assist in decision-making regarding limb salvage versus amputation. However, these scoring systems do not replace comprehensive clinical assessment and multidisciplinary decision-making [4].

Table 2 summarizes the key components of a systematic initial assessment. This table illustrates the integration of systemic stabilization based on ATLS principles, focused history-taking, local physical examination including neurovascular status, clinical documentation, and indications for escalation to senior clinicians. This structured approach aims to ensure that no critical aspect is overlooked during the early phase, given that the quality of the initial assessment significantly impacts subsequent clinical outcomes [1, 9].

The structured assessment summarized in Table 2 supports emergency workflow by standardizing the evaluation sequence, reducing the risk of missed life-threatening or limb-threatening injuries, and improving communication among trauma, orthopedic, vascular, and plastic surgery teams. Systematic documentation of baseline neurovascular status and wound characteristics also facilitates triage, operative planning, and postoperative comparison. Thus, early assessment functions not only as a diagnostic step but also as a clinical safety tool and coordination framework for definitive open fracture management [2, 9].

After completing the primary and secondary surveys and once the patient is hemodynamically stable, management proceeds to immediate emergency department interventions. This phase aims to limit secondary contamination, reduce infection risk, preserve soft tissue viability, and prevent further neurovascular compromise before definitive operative treatment [5, 7]. Initial interventions include prophylactic intravenous antibiotics, assessment of tetanus immunization status, wound documentation, temporary reduction and immobilization when indicated, and sterile wound coverage without excessive manipulation. A systematic and well-documented approach at this stage supports continuity of care and facilitates multidisciplinary coordination before definitive debridement [5, 10]. Table 3 summarizes the key components of immediate management.

These interventions should be regarded as bridge measures between trauma resuscitation and definitive operative treatment. The main purpose is not to replace surgical debridement, but to reduce secondary contamination, preserve soft tissue viability, control pain and instability, and maintain continuity of care until definitive debridement, stabilization, and wound coverage can be performed. In this way, early emergency department management directly influences subsequent infection prevention, operative planning, and limb salvage outcomes [2, 8, 10].

Overall, the contemporary relevance of initial assessment lies not in the novelty of ATLS principles themselves, but in how standardized trauma assessment enables early

Table 3. Components of immediate management of open fractures in the emergency department.

Component	Main Intervention	Key Considerations
Intravenous antibiotic administration	Prophylactic antibiotics should be administered as soon as possible	Ideally within <1 hour after injury; intravenous route; adjust according to fracture classification and contamination pattern; consider allergy history and contamination risk
Tetanus prophylaxis	Assessment of patient immunization status	Administer tetanus toxoid or immunoglobulin based on immunization history and wound characteristics
Wound documentation	Clinical photography prior to definitive intervention	Obtain informed consent; document wound location, size, and degree of contamination; avoid repeated manipulation
Temporary reduction and immobilization	Fracture reduction if necessary to reduce soft tissue tension	Perform under adequate analgesia; reassess neurovascular status after reduction
Temporary wound coverage	Cover with sterile saline-moistened gauze and occlusive dressing	Remove only gross contamination; avoid aggressive irrigation or wound exploration in the emergency department

triage, antibiotic delivery, vascular decision-making, and coordination of orthoplastic care. Thus, the initial evaluation bridges systemic resuscitation and evidence-based limb reconstruction planning.

3.2. Early Antibiotic Administration and Infection Prevention

Infection remains the most significant complication of open fractures and is associated with repeated surgical interventions, nonunion, amputation, and even mortality [11]. The risk of infection increases proportionally with the severity of soft tissue injury. Classical data from Patzakis and Wilkins reported infection rates of 0–2% in Gustilo type I, 2–10% in type II, and 10–50% in type III fractures, highlighting the critical importance of early antibiotic prophylaxis, particularly in high-grade injuries [8].

Because open fractures are inherently contaminated injuries, prophylactic intravenous antibiotics should be administered as early as possible. Observational studies have suggested that delays beyond three hours may be associated with increased infection risk, whereas administration within the first hour may provide a protective effect [8]. Current BOA/BAPRAS guidelines recommend antibiotic administration within the first three hours, ideally within one hour following injury [3, 9]. However, these recommendations should be interpreted in light of the limitations of the available evidence, as much of the supporting data comes from observational studies with heterogeneity in injury severity, contamination patterns, antibiotic regimens, and healthcare delivery systems. Although some studies have not demonstrated a significant association between antibiotic timing and infection, administration within 66 minutes has been associated with reduced infection rates at 90 days [1, 2, 11]. Therefore, early antibiotic administration remains a pragmatic and widely endorsed strategy. Still, it should be implemented as part of a broader infection prevention framework that also includes adequate debridement, fracture stabilization, and timely soft tissue management [11].

Approximately 78% of open fractures are contaminated with Gram-positive organisms and 26% with Gram-negative bacteria. Accordingly, first-generation cephalosporins are recommended for all injury grades (Grade A recommendation). In Gustilo type III fractures, additional Gram-negative coverage is required. Aminoglycosides may be used; however, caution is warranted due to the risk of nephrotoxicity, particularly in polytrauma patients. Once-daily dosing regimens are safer than divided dosing schedules [2, 4, 8].

In injuries associated with agricultural contamination, additional penicillin is recommended to provide anaerobic coverage, particularly against *Clostridium species*. Clindamycin may be used in patients with penicillin allergy, while vancomycin should be considered in settings with a high prevalence of methicillin-resistant *Staphylococcus aureus* (MRSA). Antibiotic selection should be tailored to local antimicrobial resistance patterns [2].

The optimal duration of antibiotic therapy remains controversial. Current literature supports administration for 24–72 hours depending on injury severity [8]. Recent meta-analyses have demonstrated no significant difference in septic complications between treatment durations of <72 hours and >72 hours [3]. For Gustilo types I–II fractures, antibiotics are generally continued for at least 24 hours after wound closure. In contrast, in type III injuries, treatment is extended to a total of 72 hours or 24 hours after definitive soft tissue coverage [11]. This approach aligns with antibiotic stewardship principles.

Biofilm formation on bone and implant surfaces significantly limits the effectiveness of systemic antibiotics and contributes to persistent infection, with reported rates ranging from 18% to 30%. Meta-analyses show that adjunctive local antibiotic therapy significantly reduces infection rates compared with systemic antibiotics alone (4.6% vs. 16.5%). Local delivery methods include polymethylmethacrylate (PMMA) beads, calcium sulfate carriers, and antibiotic-coated implants. Emerging techniques such as Continuous Local Antibiotic Perfusion

(CLAP), including intramedullary antibiotic perfusion (iMAP) and intra-soft tissue antibiotic perfusion (iSAP), allow higher local antibiotic concentrations and have shown promising early outcomes. However, monitoring of aminoglycoside levels remains necessary [2, 3, 5].

In addition to microbiological factors, host-related factors, including diabetes mellitus, smoking, immunosuppression, obesity, the extent of soft tissue injury, and environmental contamination, significantly increase infection risk. These findings emphasize that infection prevention in open fractures requires a multifactorial approach that extends beyond systemic antibiotic therapy to include adequate debridement, dead space management, appropriate fracture stabilization, and optimization of the patient's overall condition [2, 11].

Taken together, recent evidence supports early antibiotic administration as a pragmatic and widely accepted intervention, but the strength of this recommendation is limited by the predominance of observational studies, heterogeneity in injury severity, and variation in antibiotic protocols. Therefore, antibiotics should be interpreted as one component of a broader infection prevention strategy rather than as an isolated determinant of outcome.

3.3. Surgical Debridement and Wound Irrigation

Surgical debridement is a cornerstone of open fracture management, aiming to remove non-viable tissue, reduce bacterial load, and eliminate contaminants before stabilization and wound closure. The principle involves radical yet selective excision of all devitalized tissues, including avascular fascia, necrotic muscle, and free cortical bone fragments lacking soft tissue attachment. Muscle viability is assessed systematically using the "4Cs" criteria: color, consistency, contractility, and capacity to bleed. Wounds are often extended longitudinally along fasciotomy lines to allow adequate visualization and to prevent unnecessary periosteal stripping. Critical articular fragments should be preserved whenever possible, whereas fragments with minimal soft tissue attachment may be considered for removal. In high-energy injuries, recognition of the "zone of injury" is essential, as tissues that initially appear viable may undergo progressive necrosis. Consequently, second-look debridement within 24–48 hours is frequently required [4, 9].

The classical "six-hour rule," originally derived from experimental work by Friedrich, has historically been regarded as a critical threshold for infection prevention. However, contemporary clinical evidence is heterogeneous. Only a minority of studies have demonstrated increased infection rates with delayed debridement, typically in severe injuries such as Gustilo type IIIB fractures. In contrast, multiple prospective studies, systematic reviews, and large meta-analyses have shown no significant difference in infection rates between debridement performed within <6 hours and those performed after 6–12 hours. More consistent predictors of infection include injury severity, contamination level, and timing of antibiotic administration. Indeed, time to antibiotic administration and referral to trauma centers may be more predictive of infection risk than time to debridement itself [5, 12–14].

In line with these findings, modern guidelines such as BOAST no longer emphasize a strict six-hour threshold. Immediate debridement is indicated in cases of severe contamination (e.g., agricultural, aquatic, or sewage exposure), compartment syndrome, vascular injury, or grossly unstable fractures. High-energy injuries should ideally be managed within 12 hours, while lower-energy injuries can be addressed within 24 hours, provided that early antibiotics have been administered and the procedure is performed by an experienced team with adequate resources [2, 8]. Thus, the quality and adequacy of debridement are considered more critical than timing alone.

Irrigation is an integral component of debridement but should not replace the surgical excision of necrotic and devitalized tissue. Normal saline remains the preferred irrigation solution because of its safety, availability, and minimal cytotoxicity. Current evidence does not demonstrate a consistent superiority of saline over sterile water in preventing infection. Similarly, the routine addition of antibiotics or antiseptic agents to irrigation fluid is not strongly supported by evidence, and antiseptics are generally avoided because of their potential cytotoxic effects [8, 9].

The optimal irrigation volume remains controversial. Although traditional protocols have suggested approximate volumes of 3 L for Gustilo type I, 6 L for type II, and at least 9 L for type III injuries, these values should be interpreted as practical guides rather than rigid requirements. In clinical practice, irrigation volume should be individualized according to wound size, degree of contamination, amount of devitalized tissue, and macroscopic wound cleanliness. The practical endpoint of irrigation is to remove gross contamination and achieve a visibly clean wound [8, 9].

Irrigation pressure is also debated. High-pressure irrigation may improve mechanical removal of bacteria and debris, but it may also damage viable soft tissue and bone or drive contaminants deeper into the wound.

Therefore, low- to moderate-pressure irrigation is generally preferred, with high-pressure lavage used cautiously and selectively when required [8, 9].

At the conclusion of the procedure, replace surgical instruments with a new sterile set, and treat the wound as clean before closure or further stabilization. Comprehensive documentation of tissue defects and planning for soft tissue reconstruction and skeletal stabilization should be performed, ideally within a coordinated orthoplastic approach [4].

Overall, contemporary literature indicates that infection prevention in open fractures is more strongly influenced by early antibiotic administration and adequate debridement than by absolute time intervals to surgery. Multidisciplinary collaboration, accurate assessment of the injury zone, and the availability of appropriate operative resources are key determinants of clinical outcomes [2, 12–14]

The main shift in contemporary debridement practice is not a reduced emphasis on urgency, but a move away from a universal time threshold toward individualized timing based on contamination severity, vascular compromise, compartment risk, antibiotic timing, and availability of an experienced surgical team. This interpretation explains why the six-hour rule remains controversial despite the continued importance of timely surgical source control.

3.4. Fracture Stabilization

Fracture stabilization is an essential component of open fracture management, as it reduces fragment motion, limits secondary soft tissue damage, alleviates pain, and facilitates both soft tissue coverage and bone healing. Modern principles emphasize that, when feasible, adequate mechanical stability should be combined with definitive soft tissue coverage in a single-stage procedure [8, 11].

Stabilization may be either temporary or definitive. Temporary stabilization includes skeletal traction and, more commonly, external fixation, which plays a central role in damage control orthopaedics, particularly in polytrauma patients or those with extensive soft tissue injury. External fixation allows optimal access for wound management and facilitates later conversion to internal fixation once soft tissue conditions improve. However, complications such as pin tract infection, pin loosening, delayed union, or nonunion must be considered. For safe conversion, there should be no active pin site infection, and the procedure is ideally performed within the early phase (≤14 days) [8, 11].

Definitive fixation options include external fixation, plate fixation, and intramedullary nailing. Plate fixation is generally reserved for selected periarticular fractures due to the relatively higher risk of infection in open fractures. Intramedullary nailing is widely used in open fractures of the femur, tibia, and forearm caused by gunshot injuries, particularly in lower-grade injuries. The choice between reamed and unreamed intramedullary nailing remains controversial. Reamed nailing is associated with faster union and lower nonunion rates. In contrast, unreamed techniques may be preferred in polytrauma patients due to potential preservation of endosteal blood supply and reduced pulmonary complications [8, 11].

Emerging clinical evidence suggests that combining definitive fixation with early soft tissue coverage ("fix-and-flap") may be associated with improved outcomes in selected high-grade open fractures. Reported benefits include lower rates of infection, flap failure, unplanned reoperation, and amputation in some cohort studies. However, the available evidence is largely observational and may be influenced by selection bias, injury severity, institutional protocols, timing of referral, and availability of experienced orthoplastic teams. Therefore, fix-and-flap should not be interpreted as a universally superior strategy for all open fractures, but rather as a coordinated treatment approach that may be beneficial when adequate debridement, stable fixation, viable soft tissue coverage, and appropriate surgical expertise are available [8, 11].

When temporary external fixation is initially required, the optimal timing for conversion to internal fixation remains debated. Several studies suggest that one-stage conversion does not increase the risk of deep infection compared to two-stage procedures, provided that no active infection is present. Superficial pin site infections have also not been consistently shown to increase the risk of deep infection following single-stage intramedullary nailing [8, 11].

Overall, successful fracture stabilization depends not only on implant selection but also on its integration with soft tissue management, early antibiotic administration, and a coordinated orthoplastic approach. Adequate mechanical stability combined with early soft tissue coverage remains a key determinant of reduced infection rates and improved functional outcomes in open fractures [8, 11].

The evidence supporting definitive fixation and early coverage is clinically encouraging, but it remains influenced by case selection, injury severity, institutional resources, and availability of orthoplastic expertise.

Therefore, fixation strategy should be individualized rather than interpreted as a universal preference for one implant or one-stage reconstruction in all open fractures.

3.5. Soft Tissue Management and Wound Reconstruction

Soft tissue management is a critical determinant of infection prevention and successful healing in open fractures. Following adequate debridement, the primary goals are the removal of non-viable tissue, elimination of dead space, and achievement of stable wound closure as early as possible. Most open fracture wounds are managed with delayed primary closure, whereas surgical incisions created during debridement may be closed primarily, with the original traumatic wound left open for reassessment [8].

Temporary wound management techniques, such as antibiotic bead pouches and vacuum-assisted dressings, may be used to control contamination, reduce dead space, and prepare the wound for definitive reconstruction. Elimination of dead space is essential, as persistent hematoma or seroma formation increases the risk of deep infection [8, 9].

The choice of soft tissue reconstruction should be individualized according to wound size, degree of contamination, exposed structures, vascularity, and the availability of local tissue. Early primary closure may be considered in clean wounds with viable soft tissue, minimal contamination, and tension-free approximation after adequate debridement. Split-thickness skin grafting is appropriate for superficial skin defects with a well-vascularized wound bed and no exposed bone, tendon, joint, or implant. Local rotational, fasciocutaneous, or muscle flaps may be preferred for moderate defects when adjacent tissue is available and reliable local vascularity is preserved. In contrast, free flap reconstruction is generally required for extensive soft tissue loss, exposed bone or hardware, segmental tissue defects, compromised local tissue, or Gustilo type IIIB injuries [5, 7, 10]

Classical work by Godina demonstrated that extensive debridement performed by experienced teams followed by early flap coverage, either rotational or free, resulted in superior outcomes compared with repeated debridement and delayed closure [7]. Early coverage is also associated with a reduced risk of nosocomial infection, which is commonly observed in cases requiring multiple re-debridement procedures. Therefore, the decision regarding wound closure should be based not only on defect size, but also on contamination severity, tissue viability, vascular status, and the feasibility of achieving stable early coverage within a coordinated orthoplastic approach.

The decision between single-stage (simultaneous fixation and definitive coverage) and staged approaches depends on the patient's physiological condition and the extent of soft tissue injury. Fracture reduction at the time of primary debridement helps restore anatomical alignment and reduces dead space, thereby decreasing infection risk. Internal fixation is preferred when adequate soft tissue coverage can be achieved, either directly in Gustilo type I–II fractures or through local or free flap reconstruction in more severe injuries [9].

Current guidelines recommend achieving definitive soft tissue coverage as early as possible, ideally within 72 hours after injury and in conjunction with fracture stabilization, to minimize the risk of infection and subsequent complications. Early coordinated orthoplastic management has been shown to improve reconstruction success rates and reduce both amputation and reoperation rates.

Soft tissue reconstruction represents an area where established surgical principles and recent system-based care models intersect. Current evidence supports early definitive coverage when feasible, but outcomes depend heavily on wound severity, contamination, vascularity, patient physiology, and access to coordinated orthoplastic services. Therefore, early coverage should be understood as a goal within an integrated care pathway rather than a rigid rule applicable to all settings.

Although several components of open fracture care, such as ATLS-based assessment, Gustilo–Anderson classification, surgical debridement, and fracture stabilization, are long-established principles, recent evidence has changed how these principles are interpreted and implemented. Contemporary advances focus less on replacing these foundational concepts and more on refining timing, improving system coordination, reducing infection risk, and integrating reconstruction strategies. Key recent developments include earlier antibiotic delivery within trauma pathways, reassessment of the six-hour rule, coordinated orthoplastic care, fix-and-flap strategies, local antibiotic delivery systems, biomaterial-based reconstruction, and improved recognition of FRI. Table 4 summarizes these developments.

3.6. Discussion

The findings of this narrative review suggest that the main evolution in open fracture management is not the replacement of established surgical principles, but their reinterpretation within a more integrated, evidence-informed trauma system. Antibiotic administration, debridement, fixation, and soft tissue coverage remain the core components of care; however, recent literature

Table 4. Established principles and recent developments in open fracture management.

Area	Evidence status	Key findings	Main limitations	Clinical implications
Early antibiotic administration [2, 15, 16]	Established principle with evolving timing evidence	Early intravenous antibiotics are consistently emphasized as a key infection prevention measure, and delays may be associated with increased infection risk	Mostly observational evidence, with variation in injury severity, antibiotic protocols, and infection definitions	Antibiotics should be administered as early as possible as part of a broader infection prevention strategy
Antibiotic duration [2, 16, 17]	Evolving evidence with unresolved controversy	Prolonged prophylaxis has not consistently shown additional benefit in many cases	Heterogeneity in fracture grade, contamination, wound closure timing, and antimicrobial protocols	Duration should be individualized while balancing infection prevention with antibiotic stewardship
Debridement timing and six-hour rule [12–14, 18]	Evolving evidence	A universal six-hour threshold is not consistently supported; adequacy of debridement and injury severity appear more clinically important	Retrospective designs, heterogeneous injury severity, variable antibiotic timing, and inconsistent infection definitions	Debridement should be timely and adequate, but individualized rather than dictated by a rigid six-hour rule
Irrigation strategy [4, 5, 16]	Evolving evidence	Fixed irrigation volumes and high-pressure lavage are not uniformly supported across all wounds	Limited specific comparative evidence, variation in wound size, contamination, irrigation method, and outcome reporting	Irrigation should be adapted to wound characteristics and macroscopic wound cleanliness
Fracture stabilization [4, 5, 16, 19]	Established principle with evolving fixation strategy	Stable fixation remains essential, but optimal strategy depends on soft tissue status, contamination, patient physiology, and reconstruction planning	Selection bias, institutional variation, and limited high-quality comparative trials	Fixation strategy should be individualized and coordinated with soft tissue reconstruction
Fix-and-flap and orthoplastic care [4, 5, 12, 16]	Evolving system-based approach	Coordinated fixation and early soft tissue coverage may improve outcomes in selected high-grade injuries	Mostly observational evidence and dependent on referral timing, injury severity, and orthoplastic expertise	Fix-and-flap should be viewed as a coordinated care pathway for selected cases, not a universal rule
Local antibiotic delivery [2, 5, 16]	Emerging adjunctive strategy	Local antibiotic strategies may reduce infection risk in selected high-risk open fractures	Heterogeneity in antibiotic type, carrier material, dosing, timing, and outcome definitions	Promising adjunct in selected cases, but indications and protocols require further standardization
Biomaterial-assisted reconstruction [1]	Emerging adjunctive strategy	The induced membrane technique may support reconstruction of severe open fractures with bone defects	Evidence may be limited by case selection, injury complexity, and variation in staged reconstruction protocols	Useful consideration for complex defects, but should be applied selectively within reconstructive planning
Fracture-related infection recognition [2, 10, 16]	Evolving diagnostic framework	Standardized FRI concepts may improve diagnosis, reporting, and comparison of outcomes	Variable implementation and overlap with clinical judgment in early infection	Standardized infection definitions should be used in future studies and clinical reporting
Implementation barriers [2, 3, 6, 10, 11, 16]	Context-dependent evidence	Open fracture outcomes are influenced by system capacity, guideline implementation, referral pathways, and resource availability	Findings may be setting-specific and not fully generalizable across health systems	Management principles should be adapted to local resources while maintaining core standards of care

has shifted emphasis from isolated procedural targets toward coordinated decision-making, quality of execution, and multidisciplinary timing. This shift is particularly evident in the reassessment of the six-hour rule, the increasing emphasis on early antibiotic delivery, and the growing role of orthoplastic pathways.

3.6.1. Consensus Findings

Contemporary evidence indicates that modern open fracture management has shifted from a rigid time-based model toward a quality- and system-based approach. Although the traditional “six-hour rule” historically emphasized urgent surgical debridement within a fixed time window, recent systematic reviews and meta-analyses suggest that infection risk is more consistently influenced by early antibiotic administration, injury severity, contamination level, and the adequacy of debridement rather than by the absolute time to surgery alone [15, 16, 18, 20]. These findings support the current view that timely care remains important, but the quality of debridement and availability of an experienced surgical team are equally critical.

Early intravenous antibiotic administration remains one of the most widely accepted strategies for reducing FRI. Although much of the evidence is observational, delays beyond three hours have been associated with increased infection risk, whereas early administration appears protective in several studies [7, 17, 19]. Therefore, antibiotic therapy should be implemented as early as possible, but it should not be viewed as an isolated intervention. Its benefit depends on integration with adequate debridement, fracture stabilization, soft tissue coverage, and optimization of patient-related risk factors.

Adequate mechanical stabilization is another consistent principle in open fracture care. Stable fixation reduces fragment motion, limits secondary soft tissue injury, facilitates wound care, and provides a favorable biological environment for bone healing. Current evidence suggests that outcomes are not determined solely by implant choice, but by the coordination between skeletal stabilization and soft tissue reconstruction. In this context, the “fix-and-flap” approach, combining definitive fixation with early soft tissue coverage, has gained increasing support, particularly for high-grade open fractures [10, 19, 21].

Soft tissue management is also a major determinant of infection prevention and limb salvage. Effective debridement, elimination of dead space, and stable early coverage reduce hematoma formation, bacterial colonization, and nosocomial contamination. The classical concept of early flap coverage remains relevant, and modern orthoplastic principles emphasize definitive soft tissue coverage as early as feasible, ideally within 72 hours when patient condition and local resources allow [8, 21].

3.6.2. Unresolved Controversies

When interpreting these controversies, consider the strength of the evidence carefully. Systematic reviews and meta-analyses provide broader synthesis, but many included studies are retrospective, heterogeneous, and affected by variation in injury severity, contamination level, antibiotic protocols, fixation methods, and outcome definitions. Large cohort studies are useful for identifying clinical associations, but they cannot fully eliminate confounding or selection bias. Narrative reviews and expert opinions were therefore used mainly to contextualize established principles rather than to support definitive clinical conclusions.

Despite broad agreement on the importance of early antibiotics, debridement, stabilization, and coverage, several areas remain unresolved. First, the optimal duration of antibiotic therapy is still debated. Many protocols recommend 24–72 hours depending on injury severity and timing of soft tissue closure, but recent evidence has not consistently shown additional benefit from prolonged antibiotic use. This supports balancing infection prevention with antibiotic stewardship, particularly in settings with rising antimicrobial resistance [7, 17, 19].

Second, the timing of debridement remains controversial in selected clinical scenarios. Systematic reviews and meta-analyses have generally failed to demonstrate a consistent increase in infection when debridement is performed beyond six hours. Still, these findings should be interpreted cautiously because the included studies vary widely in fracture severity, wound contamination, antibiotic timing, and definitions of infection. Conversely, studies suggesting benefit from earlier debridement often involve more severe injuries or specific subgroups, such as Gustilo type IIIB fractures, where contamination and soft tissue damage may independently increase infection risk. Therefore, the current evidence does not support a universal six-hour threshold for all open fractures, but it also should not be interpreted as support for unnecessary delay. The more balanced interpretation is that debridement should be performed urgently when indicated and adequately by an experienced team, with timing individualized according to contamination severity, vascular injury, compartment risk, and patient stability [5, 10].

Third, the optimal fixation strategy remains debated, especially in severe Gustilo type III injuries. Temporary external fixation remains useful in damage control orthopaedics, polytrauma, and severe soft tissue compromise. In contrast, definitive internal fixation may be appropriate when adequate debridement and early soft tissue coverage can be achieved. Questions remain regarding the timing of conversion from external to internal fixation, the role of one-stage versus staged conversion, and the relative benefits of reamed versus unreamed intramedullary nailing in selected patients [5, 10].

Fourth, the optimal irrigation strategy remains debated. Traditional practice has emphasized large-volume irrigation and, in some settings, high-pressure lavage to reduce bacterial load and remove debris. However, more recent evidence has questioned whether fixed irrigation volumes or higher irrigation pressure consistently improve infection outcomes. High-pressure irrigation may improve mechanical debris removal, but it may also damage viable soft tissue or drive contaminants deeper into the wound. Therefore, irrigation should be guided by wound size, contamination severity, devitalized tissue burden, and achievement of macroscopic wound cleanliness rather than by a rigid volume or pressure target [5, 10].

Fifth, local antibiotic delivery is an evolving but incompletely standardized area. Evidence from meta-analyses and observational studies suggests that local antibiotic strategies may reduce infection risk in selected high-risk open fractures, particularly Gustilo type III injuries, severe contamination, bone loss, or residual dead space. However, the available evidence remains heterogeneous with respect to study design, antibiotic type, carrier material, dosing, timing of application, and outcome measurement. PMMA beads, calcium sulfate carriers, antibiotic-coated implants, and continuous local antibiotic perfusion are not directly interchangeable interventions, and their results should not be generalized as a single uniform treatment effect. Potential risks include variable antibiotic elution, local tissue reaction, the need to remove non-biodegradable carriers, systemic toxicity with aminoglycosides, and uncertainty regarding resistance development. Therefore, local antibiotic delivery should be regarded as a promising adjunct for selected cases rather than a universally established standard of care [2, 3, 5].

3.6.3. Implementation Barriers and Evidence Limitations

Implementation of evidence-based open fracture care may be challenging across different healthcare systems. Early orthoplastic management requires coordinated trauma pathways, timely referral, access to experienced orthopedic and plastic surgery teams, availability of microsurgical reconstruction, and appropriate operating room resources. In low-resource settings or hospitals without established orthoplastic services, achieving definitive fixation and soft tissue coverage within the recommended timeframe may be difficult [5]. Therefore, management strategies should be adapted to local resources while maintaining the core principles of early antibiotics, adequate debridement, stable fixation, and timely wound coverage.

Host-related and environmental factors also influence outcomes and may limit the generalizability of existing recommendations. Diabetes mellitus, smoking, immunosuppression, obesity, malnutrition, vascular compromise, and severe contamination have all been associated with increased infection risk and impaired healing. Agricultural, aquatic, or sewage-related contamination may require broader antimicrobial coverage and more urgent debridement. These factors highlight the need for individualized decision-making rather than rigid application of a single protocol [2, 7].

This review has inherent limitations related to its narrative design. Because no formal risk-of-bias assessment or quantitative pooling was performed, interpret the conclusions as a qualitative synthesis of current evidence rather than graded clinical practice recommendations. In addition, heterogeneity in study design, injury severity, antibiotic protocols, fixation strategies, soft tissue reconstruction methods, and outcome definitions may affect the certainty and generalizability of the findings. Future multicenter prospective studies with standardized outcome measures are needed to clarify unresolved questions regarding antibiotic duration, timing of debridement, conversion from temporary to definitive fixation, and the indications, safety, and standardization of local antibiotic delivery.

Accordingly, management statements in this review should be interpreted as evidence-informed clinical considerations rather than definitive treatment recommendations, because many key areas of open fracture care remain supported by heterogeneous observational data rather than high-certainty comparative trials.

4. Conclusions

This narrative review synthesized current concepts and recent developments in open fracture management, focusing on infection prevention, debridement timing, fracture stabilization, soft tissue coverage, and adjunctive strategies. The reviewed evidence indicates that contemporary open fracture care is increasingly understood as an integrated trauma pathway rather than a sequence of isolated interventions. Early intravenous antibiotic administration, adequate surgical debridement, stable fracture fixation, and timely soft tissue coverage remain the central components of this approach.

Current evidence suggests a shift from rigid time-based rules toward quality- and system-based management. Early antibiotic administration is consistently emphasized as an important component of infection prevention. In contrast, the traditional six-hour rule for debridement should not be interpreted as an absolute threshold for all open fractures. Instead, the literature supports a more individualized interpretation of debridement timing, particularly in relation to contamination severity, vascular injury, compartment risk, patient physiology, and the availability of an experienced surgical team. Similarly, fracture stabilization and soft tissue reconstruction are increasingly discussed as interdependent elements of care, especially in high-grade open fractures where coordinated orthoplastic management may be beneficial when feasible.

Adjunctive local antibiotic delivery represents a promising but incompletely standardized strategy for selected high-risk injuries. Current evidence suggests potential benefit in severe contamination, dead space, bone loss, and Gustilo type III injuries, but its indications, carrier selection, dosing, timing, and long-term safety remain uncertain. Because this review used a narrative design and included heterogeneous evidence without formal risk-of-bias assessment or quantitative meta-analysis, interpret the conclusions as a qualitative synthesis of current concepts rather than graded clinical practice recommendations. Further prospective multicenter studies with standardized outcome measures are needed to clarify unresolved issues, including antibiotic duration, debridement timing, fixation conversion, irrigation strategy, and local antibiotic protocols.

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