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Review Article

Systematic Review: Early versus Delayed Surgical Fixation of Long Bone Fractures in Polytrauma Patients – Impact on Morbidity, Mortality, and Functional Outcomes

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Abstract

Background: *The question of optimal surgical timing for long bone fractures in polytrauma patients continues to generate considerable debate within the trauma surgery community. Three principal management strategies have emerged Early Total Care (ETC), advocating for immediate definitive surgical stabilization; Damage Control Orthopedics (DCO), which emphasizes initial temporary stabilization followed by staged definitive reconstruction; and Early Appropriate Care (EAC), a tailored approach that combines the benefits of both strategies based on physiological response to resuscitation. This systematic review synthesizes contemporary evidence comparing these approaches, with particular attention to their effects on patient morbidity, mortality, and functional recovery.*

Methods*: We performed an extensive literature search encompassing PubMed and Cochrane CENTRAL databases, identifying systematic reviews, meta-analyses, randomized controlled trials, and cohort studies published through October 2025. Our search targeted investigations comparing early surgical intervention (typically within 24-36 hours of injury) against delayed approaches (beyond 36 hours) for long bone fractures in adult polytrauma populations. We prioritized studies reporting mortality rates, major complications including Acute Respiratory Distress Syndrome (ARDS) and Multiple Organ Failure (MOF), and long-term functional outcomes.*

Results: *Our literature analysis identified substantial evidence from recent systematic reviews and meta-analyses. The evidence demonstrates that physiologically stable polytrauma patients benefit from early definitive fixation (ETC), particularly intramedullary stabilization of femoral fractures, which correlates with reduced intensive care unit stays and shorter mechanical ventilation periods. Unstable or physiologically compromised patients require DCO strategies to prevent the "second hit" phenomenon and minimize systemic inflammatory complications. The emerging EAC protocol offers a middle ground for borderline patients who demonstrate adequate response to resuscitation, allowing definitive fixation within 36 hours when specific physiological criteria are met (lactate <4.0 mmol/L, pH ≥7.25, base excess ≥-5.5 mmol/L). Notably, patients with concurrent severe traumatic brain injury do not demonstrate worsened outcomes with early fixation. Significant heterogeneity exists across studies regarding temporal definitions and patient stratification criteria.*

Conclusion: *Determining appropriate timing for long bone fracture fixation in polytrauma patients necessitates individualized physiological assessment rather than adherence to rigid temporal protocols. Stable patients derive clear benefits from ETC approaches, unstable patients require DCO management to prevent potentially catastrophic complications, and borderline patients who respond to resuscitation may benefit from the EAC protocol. This review documents the field's evolution from dichotomous ETC versus DCO protocols toward a three-tiered, physiology-driven decision-making model. Future investigations should focus on standardizing patient selection criteria and refining treatment algorithms through high-quality prospective research.*

Keywords: *Polytrauma, long bone fractures, early total care, damage control orthopedics, early appropriate care, mortality, morbidity, ARDS, functional outcomes, surgical timing.*

1. Introduction

Managing polytraumatized patients—individuals sustaining injuries across multiple anatomical regions or physiological systems—represents one of the most challenging scenarios in contemporary trauma care. Polytrauma typically involves injury severity scores exceeding 16 points, frequently encompassing life-threatening injuries requiring coordinated multidisciplinary intervention [34]. Long bone fractures constitute a common component of these complex injury patterns, and their management significantly influences overall patient outcomes [13]. The debate surrounding optimal surgical timing for these fractures has persisted for decades, generating three distinct management philosophies: Early Total Care (ETC), Damage Control Orthopedics (DCO), and the more recently developed Early Appropriate Care (EAC) [9, 10, 30].

The ETC concept emerged during the 1980s, proposing immediate definitive fracture stabilization within the initial 24 hours following injury [51]. Advocates of this strategy contend that early surgical fixation attenuates the systemic inflammatory cascade, diminishes pulmonary complications such as fat embolism syndrome, enables earlier patient mobilization, and reduces both hospital and intensive care unit (ICU) duration [9]. The theoretical underpinning of ETC posits that prompt skeletal stabilization eliminates the ongoing inflammatory stimulus from unstable fracture sites while facilitating improved pulmonary management through patient mobilization. Historical investigations from the late 1980s and early 1990s documented substantial reductions in pulmonary complications and mortality when femoral fractures received early stabilization compared with conservative or delayed management [50].

However, research conducted during the 1990s revealed that certain high-risk, physiologically compromised patients experienced detrimental outcomes when subjected to major primary surgical interventions. These procedures appeared to function as a harmful "second hit," amplifying the post-injury inflammatory response and precipitating increased rates of ARDS and MOF [16, 52]. This observation proved particularly striking among patients with severe thoracic trauma, where early intramedullary femoral nailing demonstrated higher ARDS incidence compared with delayed or staged approaches [16].

These findings catalyzed development of the DCO philosophy. DCO represents a staged management approach prioritizing physiological stabilization over immediate definitive orthopedic reconstruction. The strategy involves rapid temporary fracture stabilization through external fixation, splinting, or skeletal traction, followed by planned definitive surgical repair once adequate resuscitation achieves physiological stability, typically within a 5-10 day post-injury window [9, 22]. This approach aims to minimize initial surgical burden and mitigate "second hit" phenomenon risks [7]. The DCO strategy recognizes that the period spanning days 2-4 post-injury represents a critical phase of ongoing immunological changes and fluid redistribution, during which major surgery should be avoided in high-risk populations [9].

The recognition that many polytrauma patients fall into a "borderline" category—neither completely stable nor in extremis—led to the development of Early Appropriate Care (EAC), also known as Safe Definitive Surgery (SDS). This third management protocol, championed by Vallier and colleagues, represents a tailored approach that offers the benefits of ETC with the safety considerations of DCO [30, 31]. The EAC protocol is based on the observation that the majority of polytrauma patients demonstrate dramatic response to damage control resuscitation, creating an opportunity for early definitive surgical fixation (within 24-36 hours) in patients who meet specific physiological criteria indicating adequate resuscitation [30].

The EAC protocol recommends definitive fracture fixation within 36 hours of injury provided that patients achieve demonstrable response to resuscitative efforts, specifically: serum lactate <4.0 mmol/L, pH ≥7.25, or base excess ≥-5.5 mmol/L [30]. This approach recognizes that borderline patients who respond appropriately to resuscitation can safely undergo early definitive fixation, potentially avoiding the complications associated with prolonged temporary fixation while maintaining the safety principles of DCO. The decision remains case-specific, and intraoperative deterioration may necessitate abandoning definitive procedures in favor of safer temporizing options.

Recent advances in trauma resuscitation, critical care medicine, and understanding of post-injury inflammatory responses have fostered this more refined, three-tiered approach to polytrauma management [5, 8, 31]. Critical parameters including lactate concentrations, base deficit, coagulation status (incorporating rotational thromboelastometry or ROTEM values), vasopressor requirements, and presence of severe associated injuries (such as traumatic brain injury or significant chest trauma) now form integral components of risk stratification protocols [5, 13, 30].

Despite this conceptual evolution, substantial heterogeneity persists across clinical practice and literature regarding patient selection criteria, definitions of "early" versus "delayed" fixation, and outcome measurement. This systematic review provides a comprehensive synthesis of contemporary evidence comparing the three management strategies for long bone fractures in polytrauma patients. We analyze the impact of surgical timing on critical outcomes, including mortality, major morbidities such as ARDS and MOF, and long-term functional recovery and quality of life, providing an evidence-based summary to inform clinical decision-making for this complex patient population.

2. Methods

We conducted this systematic review through comprehensive literature searching to identify studies examining surgical timing for long bone fracture fixation in polytrauma patients. Our search strategy was designed to be inclusive and broad, capturing evidence ranging from high-level systematic reviews to influential cohort investigations.

2.1 Search Strategy

We performed multi-database searches, primarily targeting PubMed (MEDLINE) and Cochrane CENTRAL, for articles published through October 2025. Our search strategy employed combinations of keywords and Medical Subject Headings (MeSH) terms, including: "polytrauma," "multiple injuries," "multiply injured," "long bone fracture," "femoral fracture," "tibial fracture," "humeral fracture," "early fixation," "delayed fixation," "timing," "Early Total Care," "ETC," "Damage Control Orthopedics," "DCO," "Early Appropriate Care," "EAC," "Safe Definitive Surgery," "SDS," "mortality," "morbidity," "ARDS," "acute respiratory distress syndrome," "multiple organ failure," "MOF," "functional outcome," "quality of life," and "rehabilitation."

We did not impose publication date restrictions to capture seminal historical investigations, though we emphasized literature from the past decade to reflect current practice patterns. We manually screened reference lists of included articles to identify additional relevant studies not captured through electronic searching.

2.2 Study Selection

Our inclusion criteria encompassed:

1. **Population:** Investigations involving adult human subjects (age ≥16 years) with polytrauma and at least one major long bone fracture requiring surgical fixation.
2. **Intervention/Comparison:** Studies directly comparing outcomes between early (generally defined as <24-36 hours from injury or admission) and delayed (generally >36 hours) surgical fixation, or investigations comparing ETC versus DCO versus EAC strategies.
3. **Outcomes:** Studies reporting at least one of the following: mortality (early or overall), major complications (including ARDS, MOF, sepsis, pneumonia, deep vein thrombosis, pulmonary embolism), ICU length of stay, hospital length of stay, mechanical ventilation duration, and/or functional outcomes (including quality of life measures).
4. **Study Design:** Systematic reviews, meta-analyses, randomized controlled trials (RCTs), and prospective or retrospective cohort studies with adequate sample sizes and clear methodology.

We excluded case reports, studies examining isolated fractures without polytrauma, pediatric-only populations (though studies including both adults and children were considered), animal studies, and non-English language articles. We screened initial search results by title and abstract, followed by full-text review of potentially eligible articles to determine final inclusion.

2.3 Data Extraction and Synthesis

We extracted and synthesized data from included articles narratively. Key information collected included:

- Study citation and publication year
- Study design and evidence level
- Patient population characteristics (sample size, age, injury severity scores)
- Definitions of "early" and "delayed" fixation employed in each study
- Management protocol used (ETC, DCO, or EAC)

- Specific fracture types and fixation methods
- Reported outcomes (mortality, complications, length of stay, functional outcomes)
- Key findings and conclusions

Given substantial heterogeneity in study designs, patient populations, timing definitions, and outcome definitions across the literature, we determined that qualitative narrative synthesis was more appropriate than quantitative meta-analysis for this review's scope. We structured and presented findings thematically to provide coherent overview of the current evidence state, organized by key clinical questions and outcome domains.

3. Results

Our comprehensive literature search identified an extensive body of work spanning several decades, including numerous systematic reviews, meta-analyses, randomized controlled trials, and large cohort studies. We identified and included 64 key references in this review. We present synthesized findings below, organized by key thematic areas.

3.1 Evolution of Treatment Philosophies: From ETC and DCO to Early Appropriate Care

Management of polytrauma patients with long bone fractures has undergone substantial philosophical evolution over three decades. The initial ETC paradigm, championing definitive fixation within 24 hours, faced challenges during the 1990s when observations revealed increased complications in physiologically unstable patients [16]. This led to DCO development, a staged approach involving initial temporary stabilization followed by delayed definitive surgery [9, 20]. More recently, the EAC protocol has emerged as a third option, specifically designed for borderline patients who demonstrate adequate response to resuscitation [30, 31].

A seminal review by Nicola in 2013 detailed the transition from ETC to DCO, explaining the "second hit" model wherein major surgery in already inflamed patients can trigger catastrophic systemic inflammatory responses [9]. According to this model, initial trauma represents the "first hit," inducing Systemic Inflammatory Response Syndrome (SIRS) followed by compensatory anti-inflammatory response (CARS). In severely injured patients, this delicate equilibrium can be disrupted by major surgery's "second hit," leading to uncontrolled inflammation, ARDS, and MOF. The DCO approach was designed to mitigate this risk by limiting initial surgical insult to rapid, minimally invasive stabilization procedures.

A 2023 review by Gupta and Farooque comprehensively described the evolution to EAC, noting that this protocol represents a tailored approach offering the benefits of ETC and the safety of DCO [65]. The EAC concept is based on the observation that the response to damage control resuscitation is dramatic in the majority of patients, thus providing an opportunity for early (within 24-36 hours of admission) surgical fracture fixation in appropriately selected patients. The authors emphasized that EAC is best suited for borderline patients, with decisions being case-specific and requiring readiness to abandon definitive procedures if intraoperative deterioration occurs.

The "Safe Definitive Surgery" (SDS) concept, described by Pape and colleagues, emphasizes achieving specific physiological and laboratory endpoints before proceeding with definitive fixation, rather than adhering to strict timelines [5, 8]. A 2024 investigation by Kalbas et al. further elaborated the SDS concept, analyzing over 3,600 patients across three time periods and validating criteria for safely proceeding with early fixation [5]. These criteria include shock parameter normalization (vasopressor requirements <3 mL/h or absent within 4-6 hours), acid-base status normalization (base deficit 2-2.5 mmol/L within 12-24 hours), platelet count and coagulation normalization (>90,000 or rising within 8-12 hours), fluid balance equilibration (input/output ratio balanced without vasopressors within 24 hours), and absence or reduction of severe chest injury manifestations within 24 hours [5].

The Kalbas et al. investigation demonstrated significant decreases in early mortality, overall mortality, and complication rates when these SDS criteria were applied, compared with earlier eras when either rigid ETC or DCO protocols were followed [5]. This represents the field's maturation toward individualized, evidence-based decision-making.

3.2 The Three Management Protocols: ETC, DCO, and EAC

The current evidence supports a three-tiered approach to polytrauma management based on patient physiological status and response to resuscitation.

Early Total Care (ETC): This protocol is appropriate for physiologically stable patients who can tolerate immediate definitive surgical fixation. Stable patients are defined as those without significant acidosis, hypothermia, or coagulopathy, and who do not require ongoing massive transfusion or high-dose vasopressor support. For these patients, early definitive fixation (within 24 hours) offers advantages including reduced hospital stay, earlier mobilization, and potentially lower complication rates [1, 25, 50].

Damage Control Orthopedics (DCO): This protocol is indicated for unstable or "in extremis" patients who cannot tolerate major surgical procedures. The DCO approach consists of three stages: (1) life-saving procedures with temporizing fracture stabilization during the acute phase, (2) resuscitation and physiological optimization in the ICU, and (3) definitive fracture fixation once stability is achieved, typically 5-10 days post-injury [9, 22]. Borderline patient criteria include acidosis (pH <7.24, serum lactate >2.5 mmol/L), hypothermia (temperature <35°C), coagulopathy (platelets <90,000/ccm), expected surgical time >90 minutes, and transfusion requirements >10 units of packed red blood cells [65].

Early Appropriate Care (EAC): This protocol represents a middle ground, specifically designed for borderline patients who demonstrate adequate response to resuscitation. The EAC protocol, as described by Vallier and colleagues, recommends definitive fracture fixation within 36 hours of injury provided that patients achieve specific physiological criteria: serum lactate <4.0 mmol/L, pH ≥7.25, or base excess ≥-5.5 mmol/L [30]. This approach allows for the benefits of early definitive fixation while maintaining safety through objective physiological criteria. Studies have demonstrated that complications are reduced when fixation timing is standardized based on response to resuscitation rather than arbitrary time cutoffs [30].

3.3 Mortality Outcomes

Fixation timing effects on mortality have been a primary research focus, though results have been somewhat conflicting, likely reflecting differences in patient populations and selection criteria.

A 2025 systematic review and meta-analysis by Steinfeld et al., incorporating five randomized controlled trials with 335 total patients, found no statistically significant difference in overall mortality between early (<24 hours) and late fracture stabilization [1]. However, the authors acknowledged limitations from small patient numbers and included study heterogeneity. The lack of significant difference may reflect appropriate patient selection in included trials, where only stable patients were randomized to early fixation.

In contrast, several large cohort investigations suggest benefits for early fixation in specific patient populations. One study on femoral shaft fractures found delayed fixation associated with increased mortality, particularly in patients with higher Injury Severity Scores [24]. Cantu et al., analyzing large trauma database data, found that in-hospital mortality from femoral shaft fractures was significantly influenced by both fixation delay and ISS [14]. Specifically, they found definitive fixation within 12 hours in patients with isolated femur fractures led to low complication and mortality rates, while delays beyond 12 hours associated with increased mortality, particularly in patients with ISS >25 [14].

Interestingly, a study by Morshed et al. presented seemingly contradictory findings, suggesting that for patients with multisystem trauma, delayed internal fixation of femoral shaft fractures (performed between 2-5 days) might reduce mortality compared with very early fixation [24]. However, this study's findings likely reflect the importance of patient selection and avoiding "second hit" in unstable patients. The key insight is not that delayed fixation is universally superior, but rather that premature definitive surgery in physiologically unstable patients is harmful.

For patients with associated severe traumatic brain injury (TBI), a particularly challenging subgroup, a large 2024 cohort study by Zheng et al. from the CENTER-TBI database found no significant mortality difference between early (within 24 hours) and late fixation groups [11]. This study included 253 patients, with 74 undergoing early fixation and 179 undergoing late fixation. After propensity score matching, there was no statistically significant difference in unfavorable functional outcomes at 6 months (OR 1.12, 95% CI 0.51-1.99, P=0.77) [11]. This finding suggests early fixation is a safe option in TBI patients, provided appropriate intraoperative hemodynamic management is maintained.

3.4 Morbidity: Pulmonary Complications and Multiple Organ Failure

The risk of postoperative complications, particularly ARDS and MOF, constitutes a central argument for the DCO approach and the physiological criteria used in the EAC protocol. The "second hit" inflammatory response to major surgery is considered a primary driver of these complications.

An early, landmark investigation by Pape et al. in 1993 proved pivotal in identifying risks of early definitive surgery in certain patient populations [16]. This study found that primary intramedullary nailing of femur fractures in patients with associated lung contusion was a potential cause of post-traumatic ARDS. The investigation demonstrated that patients with chest trauma undergoing early femoral nailing had significantly higher ARDS rates compared with those receiving delayed or staged fixation [16]. This observation was instrumental in DCO philosophy development.

Subsequent research has refined this understanding. The DCO strategy, by delaying definitive surgical insult, aims to allow initial systemic inflammatory response subsidence. Studies have shown that performing definitive surgery during the peak inflammatory window (days 2-4 post-injury) associates with higher MOF incidence [22]. Pape's work on optimal timing for secondary surgery demonstrated that patients who later developed organ failure had their definitive osteosynthesis performed significantly more often between days 2 and 4, whereas patients without MOF were operated on between days 6 and 8 (P<0.0001) [22]. This

established the concept of a "window of opportunity" for safe definitive surgery, typically between days 5 and 10 post-injury.

The Steinfeld et al. meta-analysis from 2025 did not find significant differences in major complications between early and late fixation groups overall [1]. However, it noted that for femoral fractures specifically, intramedullary nailing was superior to external fixation in reducing ICU length of stay and mechanical ventilation duration [1]. This suggests that fixation *method*, in addition to timing, is a critical factor in determining outcomes. Intramedullary nailing, when performed in appropriately selected stable patients, appears to offer advantages over prolonged external fixation.

A 2023 study by von Lübken et al. comparing ETC and DCO for major fractures in severely injured patients found that pulmonary complication risk, hospital stay length, and ICU stay length tended to be lower in the ETC group, but only when patients were appropriately selected [7]. This underscores the importance of risk stratification and patient selection rather than blanket application of either strategy.

The EAC protocol addresses this issue by using objective physiological criteria to identify patients who have responded adequately to resuscitation and can safely undergo early definitive fixation. By ensuring that acidosis has been reversed (lactate <4.0 mmol/L, pH ≥7.25, base excess ≥-5.5 mmol/L) before proceeding with definitive surgery, the EAC protocol aims to minimize the risk of "second hit" complications while still allowing for the benefits of early fixation [30].

3.5 Functional Outcomes and Quality of Life

Beyond immediate survival and complications, long-term functional recovery and quality of life (QoL) of polytrauma patients are of paramount importance. Early fracture stabilization is believed to facilitate earlier mobilization, potentially leading to better functional outcomes and reducing complications of prolonged immobility, such as muscle atrophy, joint stiffness, and venous thromboembolism.

Studies specifically assessing functional outcomes have shown mixed results. The 2024 study by Zheng et al. on patients with TBI found no difference in unfavorable functional outcomes (measured by Glasgow Outcome Scale-Extended, GOSE) at 6 months between early and late fixation groups [11]. At 6 months, 34% of patients had unfavorable functional outcomes, but this rate was similar between timing groups. This suggests that for TBI patients, extremity fracture fixation timing does not significantly impact neurological recovery or overall functional status.

A study by Katsoulis and Giannoudis on pelvic fractures suggested that fixation timing does impact functional outcomes, with early fixation associated with better long-term function [28]. However, evidence for this relationship in long bone fractures is less clear.

The broader literature on long-term outcomes after polytrauma indicates that patients often experience significant and lasting QoL decreases. A 2019 study by Singaram et al. found substantial QoL decrease after long bone fractures according to the EQ-5D questionnaire, with results considered highly significant ($p<0.05$) [26]. Patients reported significant impairments in mobility, usual activities, and pain/discomfort domains. A 2021 study by Walter et al. found that even after a mean of 4.2 years following successful treatment of fracture-related infection (FRI), patients reported significantly reduced quality of life compared with non-FRI patients [27]. This highlights that complications, particularly infections, have profound and lasting impacts on patient outcomes.

Early mobilization, facilitated by stable fracture fixation, is theoretically beneficial for preventing these long-term complications. The EAC protocol, by allowing early definitive fixation in appropriately selected borderline patients, may offer advantages in terms of earlier mobilization compared with traditional DCO approaches that delay definitive fixation for 5-10 days. However, high-quality, long-term prospective studies directly comparing functional outcomes between ETC, DCO, and EAC strategies are still needed.

3.6 The "Borderline" Patient and Risk Stratification

The most significant challenge in clinical decision-making involves identifying the "borderline" patient—one who is not in extremis but may not be stable enough to tolerate major primary surgical procedures. Development of robust risk stratification tools is a key area of ongoing research, and the EAC protocol specifically addresses this patient population.

The Injury Severity Score (ISS) is a widely used anatomical scoring system assigning scores to injuries in six body regions, with the final score being the sum of squares of the three most severely injured regions [33]. While ISS correlates with mortality and is useful for epidemiological studies, its utility in predicting physiological response to surgery and guiding real-time clinical decision-making is limited [33, 35]. The ISS is an anatomical score and does not capture dynamic physiological status or resuscitation response.

More advanced scoring systems and physiological markers are being investigated. The "Safe Definitive Surgery" criteria proposed by Pape's group incorporate dynamic physiological parameters, such as initial

resuscitation response, lactate clearance, base deficit, temperature, and coagulation status (via ROTEM or thromboelastography) [5, 8]. These parameters are assessed serially over the first 24 hours to determine if the patient is improving with resuscitation (responsive borderline) or deteriorating (non-responsive borderline).

The EAC protocol provides specific, objective criteria for borderline patient management. As described by Gupta and Farooque, borderline patients are defined by acidosis (pH <7.24, serum lactate >2.5 mmol/L), hypothermia (temperature <35°C), coagulopathy (platelets <90,000/ccm), expected surgical time >90 minutes, and transfusion requirements >10 units of packed red blood cells [65]. For these patients, the EAC protocol recommends proceeding with definitive fixation within 36 hours if they achieve reversal of acidosis (serum lactate <4.0 mmol/L, pH ≥7.25, or base excess ≥-5.5 mmol/L) [30, 65].

A 2020 study by Halvachizadeh et al. validated and compared four different published scoring systems for identifying at-risk polytrauma patients: the Clinical Grading System (CGS), the modified Clinical Grading System (mCGS), the Early Appropriate Care (EAC) protocol, and the Polytrauma Grading Score (PTGS) [30]. This study, analyzing data from nearly 4,000 patients, highlighted the move toward more objective, data-driven decision-making. The study found that while all scoring systems had some predictive value, no single system was perfect, and clinical judgment informed by multiple parameters remains essential [30].

The consensus in the literature is that single time-point assessment is insufficient; serial reassessments are crucial to determine patient physiological trajectory and suitability for definitive surgery [7]. Markers such as lactate clearance, base deficit normalization, vasopressor support cessation, and coagulation parameter improvement all indicate successful resuscitation and readiness for definitive surgery.

3.7 Specific Fracture Considerations

While this review focuses broadly on long bone fractures, it is important to note that different fracture patterns may have different optimal management strategies within the ETC, DCO, and EAC framework.

Femoral Shaft Fractures: Femoral fractures have been most extensively studied. The consensus is that in stable patients, early intramedullary nailing (ETC approach) is beneficial, reducing pulmonary complications and mortality compared with conservative management or delayed fixation [23, 25, 50]. In unstable patients with severe chest trauma or borderline physiology, a DCO approach with initial external fixation or skeletal traction is safer [16]. For borderline patients who meet EAC criteria (lactate <4.0 mmol/L, pH ≥7.25, base excess ≥-5.5 mmol/L), early definitive intramedullary nailing within 36 hours may be appropriate [30].

Tibial Fractures: For closed tibial fractures, splinting is often an effective initial temporizing measure in unstable patients. For open tibial fractures, early debridement and stabilization are critical to prevent infection, but stabilization method (external fixation vs. intramedullary nailing) should be guided by patient stability and soft tissue injury extent. The EAC protocol can guide timing of conversion from external fixation to definitive intramedullary nailing in borderline patients.

Pelvic Fractures: Pelvic fractures in polytrauma patients associate with high mortality rates due to massive hemorrhage. A 2025 systematic review by Dormann et al. found limited evidence regarding optimal timing for definitive operative stabilization of pelvic fractures, but suggested early stabilization may reduce septic respiratory complications, ARDS, and MOF [2]. The EAC protocol may be applicable to pelvic fracture management in borderline patients who achieve adequate resuscitation.

Spinal Fractures: A 2025 systematic review by Ndlovu et al. on thoracolumbar spine fractures found that early surgical stabilization may be beneficial, but evidence remains limited [3]. The principles of ETC, DCO, and EAC can be applied to spinal fracture management based on patient physiological status.

3.8 International Perspectives and Practice Patterns

Practice patterns for polytrauma management vary internationally. A 2011 matched-pair comparison between US and European Level I trauma centers found differences in fracture fixation timing and method, with the European center more likely to employ DCO strategies in borderline patients [42]. A 2025 study from China by Ding et al. found that early fracture fixation significantly reduced pulmonary and other early complications, shortened hospital stays and costs, and enhanced quality of life outcomes, particularly in patients with femoral fractures [41]. This suggests that with appropriate patient selection and modern resuscitation techniques, early fixation (either ETC or EAC approaches) can be safely performed even in resource-variable settings.

4. Discussion

This systematic review synthesizes the extensive and evolving literature on long bone fracture fixation timing in polytrauma patients. The central finding is that the debate has matured from a dichotomous choice between Early Total Care (ETC) and Damage Control Orthopedics (DCO) to a more sophisticated, three-tiered, physiology-based approach that includes Early Appropriate Care (EAC) as a distinct third protocol. The

modern paradigm emphasizes individualized patient assessment over rigid, timeline-driven protocols [5, 8, 30, 65].

4.1 Key Findings and Clinical Implications

The evidence reviewed confirms there is no universal answer to the question of optimal timing for fracture fixation in polytrauma patients. Rather, the appropriate management strategy depends on patient physiological status and response to resuscitation, leading to three distinct approaches:

For Stable Patients (ETC): Physiologically stable polytrauma patients benefit from ETC principles. Early definitive stabilization, particularly of femoral fractures with intramedullary nailing, appears to offer significant advantages, including shorter ICU stays, reduced mechanical ventilation duration, and potentially lower rates of certain complications [1, 25, 50]. This approach facilitates earlier mobilization, which is crucial for preventing sequelae of prolonged recumbency, including pneumonia, pressure ulcers, muscle atrophy, and venous thromboembolism. Early mobilization also has psychological benefits, improving patient morale and rehabilitation engagement.

For Unstable Patients (DCO): For unstable or "in extremis" patients, the DCO philosophy is a critical life- and limb-saving strategy. The "second hit" concept is well-supported in the literature, where major surgical intervention in a patient with ongoing systemic inflammatory response can precipitate a cascade leading to ARDS and MOF [9, 16]. The three-stage DCO approach—initial life-saving procedures with temporizing fixation, ICU resuscitation and optimization, and delayed definitive fixation—remains the cornerstone of safe management for this patient population [9, 22, 65].

For Borderline Patients (EAC): The EAC protocol represents a significant advance in polytrauma management by specifically addressing the challenging borderline patient population. These patients are neither completely stable nor in extremis, and their management has historically been the most controversial. The EAC protocol provides objective physiological criteria (lactate <4.0 mmol/L, pH ≥7.25, base excess ≥-5.5 mmol/L) to identify borderline patients who have responded adequately to resuscitation and can safely undergo early definitive fixation within 36 hours [30, 65]. This approach offers the benefits of early fixation (earlier mobilization, reduced complications from prolonged temporary fixation) while maintaining safety through objective physiological endpoints.

Our review highlights that modern research focus has rightly shifted toward improving risk stratification processes. Simple anatomical scores like ISS, while useful for epidemiological purposes and initial triage, are insufficient alone for guiding surgical timing decisions [33, 35]. The most promising strategies involve dynamic assessment of patient physiological response to resuscitation, using markers such as lactate clearance, base deficit, temperature, vasopressor requirements, and coagulation status [5, 30]. Serial reassessments over the first 24-48 hours are critical to identify patients whose physiology is improving and who can safely undergo definitive surgery (either ETC or EAC approach), versus those who are deteriorating and require continued DCO management.

4.2 The Special Case of Traumatic Brain Injury

One of the most significant areas of controversy has been management of patients with concomitant severe traumatic brain injury (TBI). Historically, there was concern that early orthopedic surgery could exacerbate secondary brain injury through several mechanisms: intraoperative hypotension, hypoxia, increased intracranial pressure from positioning or anesthesia, or systemic inflammatory mediators crossing the blood-brain barrier. This led many centers to delay fracture fixation in TBI patients until neurological stability was achieved.

However, recent high-quality evidence, such as the 2024 cohort study by Zheng et al., provides reassurance that early fixation (within 24 hours) does not appear to worsen mortality or 6-month functional outcomes in this population [11]. This is a critical finding, as it allows benefits of early stabilization—including facilitation of nursing care, prevention of secondary complications, and earlier mobilization—to be extended to this complex patient group. The principles of the three-tiered approach (ETC, EAC, or DCO) can be applied to TBI patients based on their physiological status, with careful intraoperative management including maintenance of cerebral perfusion pressure, avoidance of hypoxia and hypercarbia, and judicious use of anesthetics remaining paramount. Close coordination between orthopedic surgeons, neurosurgeons, and anesthesiologists is essential.

4.3 The Role of Fixation Method

An important finding from this review is that fixation *method* is as important as fixation *timing*. The Steinfeld et al. meta-analysis found that intramedullary nailing of femoral fractures was superior to external fixation in reducing ICU length of stay and mechanical ventilation duration [1]. This has important implications for all three management protocols:

- **ETC patients:** Should receive definitive intramedullary nailing immediately
- **EAC patients:** Should receive definitive intramedullary nailing within 36 hours once physiological criteria are met
- **DCO patients:** Should receive temporary external fixation initially, with timely conversion to definitive intramedullary fixation once stability is achieved (typically 5-10 days)

Prolonged external fixation associates with risks of pin-site infections, loss of reduction, and delayed mobilization. Therefore, even when DCO approach is initially employed, timely conversion to definitive fixation is important to optimize outcomes.

Fixation method choice should also consider specific fracture pattern, soft tissue injury, and patient factors. For example, in patients with severe soft tissue injury or compartment syndrome, external fixation may be the safest initial option even in otherwise stable patients, with conversion to internal fixation once soft tissue conditions permit.

4.4 Advantages of the Three-Tiered Approach

The three-tiered approach (ETC, EAC, DCO) offers several advantages over the previous dichotomous ETC versus DCO paradigm:

1. **More Precise Patient Stratification:** Rather than forcing patients into either "stable" or "unstable" categories, the three-tiered approach recognizes the large population of borderline patients and provides specific guidance for their management.
2. **Objective Criteria:** The EAC protocol provides objective physiological criteria (lactate, pH, base excess) rather than relying solely on clinical judgment, reducing variability in decision-making.
3. **Flexibility:** The approach allows for dynamic reassessment, with patients potentially transitioning between protocols based on their response to resuscitation.
4. **Reduced Complications:** Studies have demonstrated that standardizing timing of fixation based on response to resuscitation (as in the EAC protocol) reduces complications compared with arbitrary time cutoffs [30].
5. **Optimized Resource Utilization:** By allowing early definitive fixation in appropriately selected borderline patients, the EAC approach may reduce ICU length of stay and overall hospital costs compared with traditional DCO approaches that routinely delay definitive fixation for 5-10 days.

4.5 Limitations of Current Evidence

Despite progress in this field, this review also identifies several limitations and areas of heterogeneity in current literature:

1. **Definition Variability:** The definition of "early" fixation varies across studies, with cutoffs ranging from 12 to 48 hours. The EAC protocol's 36-hour window represents a middle ground but is not universally adopted.
2. **Patient Selection Criteria:** While the EAC protocol provides specific criteria, not all studies use these criteria, making direct comparisons difficult. Different studies use different combinations of physiological parameters, injury severity scores, and clinical judgment.
3. **Outcome Measures:** While mortality and major complications are commonly reported, there is relative paucity of high-quality, long-term data on functional outcomes and health-related quality of life. Most studies focus on short-term outcomes (in-hospital or 30-day), with few studies reporting outcomes beyond 6-12 months.
4. **Randomized Controlled Trials:** There is a notable lack of large, multicenter RCTs comparing ETC versus EAC versus DCO strategies. The ethical and practical challenges of randomizing critically ill polytrauma patients are significant, but well-designed pragmatic trials could provide valuable evidence.
5. **EAC Protocol Adoption:** The EAC protocol is relatively recent, and many studies predate its widespread adoption. More research is needed to evaluate outcomes specifically with the EAC protocol compared with traditional ETC and DCO approaches.
6. **Heterogeneity of Polytrauma:** Polytrauma is not a homogeneous entity. Patients with similar ISS scores may have vastly different injury patterns, physiological responses, and outcomes. This heterogeneity makes it challenging to develop universal protocols.

4.6 Future Directions

Future research should focus on several key areas:

1. **Validation of EAC Protocol:** Large, multicenter prospective studies are needed to validate the EAC protocol and compare outcomes with traditional ETC and DCO approaches. These studies should include long-term functional outcomes and quality of life measures.

2. **Standardization of Criteria:** Efforts should be made to standardize the physiological criteria used to stratify patients into ETC, EAC, and DCO categories. This will facilitate comparison between studies and development of evidence-based guidelines.
3. **Long-Term Functional Outcomes:** Research should prioritize patient-centered outcomes, including long-term functional recovery, quality of life, return to work, and patient satisfaction. Studies should extend follow-up to at least 1-2 years post-injury to capture the full recovery trajectory.
4. **Optimal Timing for DCO Conversion:** For patients managed initially with DCO, the optimal timing for conversion to definitive fixation remains unclear. Research should explore whether earlier conversion (e.g., days 3-5) is safe and beneficial compared with the traditional window of days 5-10, particularly in the context of modern resuscitation and critical care techniques.
5. **Biomarkers and Precision Medicine:** Investigation of novel biomarkers of inflammation, coagulation, and organ function may allow more precise identification of patients at risk for complications. Precision medicine approaches that tailor treatment to individual patient biology hold promise for optimizing outcomes.
6. **Implementation Science:** Even with clear evidence, translating research findings into clinical practice is challenging. Implementation science research is needed to understand barriers to adoption of the three-tiered approach and to develop strategies for improving adherence to evidence-based protocols.
7. **Cost-Effectiveness Analysis:** With increasing focus on healthcare costs, economic analyses comparing ETC, EAC, and DCO approaches are needed. These analyses should consider not only immediate hospitalization costs but also long-term costs related to complications, rehabilitation, and lost productivity.
8. **Artificial Intelligence and Decision Support:** Development of AI-based decision support tools that integrate multiple physiological parameters, injury patterns, and patient factors may help clinicians make more accurate real-time decisions about surgical timing.

5. Conclusion

Management of long bone fractures in polytrauma patients has evolved from rigid protocol-based systems to sophisticated, physiology-driven decision-making processes. The choice between early and delayed surgical fixation is not a simple dichotomy but a complex decision that must be tailored to individual patient physiological status, injury pattern, and resuscitation response. The modern three-tiered approach—Early

Total Care (ETC), Early Appropriate Care (EAC), and Damage Control Orthopedics (DCO)—provides a comprehensive framework for managing the full spectrum of polytrauma patients.

For stable patients, early definitive fixation (ETC) offers clear advantages in reducing hospital stay, facilitating recovery, and improving outcomes. For unstable or "in extremis" patients, a DCO approach remains the cornerstone of safe and effective management, preventing the potentially lethal "second hit" of major, premature surgical intervention. The EAC protocol represents a significant advance by specifically addressing the challenging borderline patient population, providing objective physiological criteria to identify patients who have responded adequately to resuscitation and can safely undergo early definitive fixation within 36 hours.

Key Clinical Recommendations

Based on this review, we propose the following clinical recommendations:

1. **Three-Tiered Patient Stratification:** All polytrauma patients with long bone fractures should be stratified into stable, borderline, or unstable categories based on physiological parameters, not solely on anatomical injury scores.
2. **Stable Patients (ETC):** Stable patients should undergo early definitive fixation, preferably within 24 hours, to maximize benefits of early mobilization and minimize complications.
3. **Unstable Patients (DCO):** Unstable patients should receive rapid, minimally invasive temporary stabilization with planned conversion to definitive fixation once physiological stability is achieved, typically within 5-10 days.
4. **Borderline Patients (EAC):** Borderline patients should be managed according to the EAC protocol, with serial reassessment of physiological parameters over the first 24-36 hours. If patients achieve reversal of acidosis (lactate <4.0 mmol/L, pH ≥7.25, base excess ≥-5.5 mmol/L), proceed with definitive fixation within 36 hours. If patients fail to meet these criteria or deteriorate, manage with DCO approach.
5. **Serial Reassessment:** All patients, particularly borderline patients, require serial reassessment of physiological parameters to determine their trajectory and suitability for definitive surgery. Single time-point assessments are insufficient.

6. **TBI Patients:** Patients with traumatic brain injury can safely undergo early fracture fixation (ETC or EAC approach based on physiological status) provided that appropriate intraoperative hemodynamic and neurological management is maintained.
7. **Fixation Method Matters:** When definitive fixation is performed, intramedullary nailing is preferred over prolonged external fixation for femoral fractures to optimize outcomes.
8. **Multidisciplinary Approach:** Optimal management requires close coordination between orthopedic surgeons, trauma surgeons, intensivists, anesthesiologists, and other specialists.
9. **Individualized Decision-Making:** Surgical timing decisions should be individualized based on patient-specific factors rather than rigid adherence to temporal protocols. Clinical judgment remains essential, with readiness to modify the plan based on intraoperative findings**.**
10. **Documentation and Quality Improvement:** Institutions should track outcomes based on management protocol used (ETC, EAC, or DCO) to facilitate quality improvement and contribute to the evidence base.

The future of polytrauma care lies in continued refinement of dynamic risk stratification tools, focus on long-term, patient-centered functional outcomes, and application of precision medicine principles to individualize treatment. As our understanding of polytrauma pathophysiology and inflammatory response continues to evolve, so too will our ability to optimize fracture fixation timing and method to improve outcomes for these critically injured patients. The three-tiered approach represents the current state of the art, but ongoing research will undoubtedly lead to further refinements in the years to come.

Declaration of Originality: This systematic review represents an original synthesis and analysis of the published literature. All sources have been properly cited and referenced according to Vancouver style. The interpretations, conclusions, and recommendations presented are those of the author based on critical appraisal of the available evidence.

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