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Peculiarities and Analysis of Minimally Invasive Elastic Titanium Nail Osteosynthesis for Forearm Bone Fractures in Children

Abstract: This article presents an analysis of the treatment of 365 children with diaphyseal fractures of the forearm bones. The features of treatment, long-term outcomes, and clinical-radiological justification are based on the study of medical histories of children who were treated from 2022 to 2024 in the paediatric trauma department of the Emergency Hospital in Chernivtsi**.** The aim of the study was to evaluate the outcomes and provide clinical and radiological justification for the treatment of complex forearm bone fractures in children through osteosynthesis of fragments using Titanium Elastic Nails (TEN), ensuring reliable fixation, rapid restoration of limb function, and minimisation of complication risks. Three clinical groups were identified. The first clinical group included 185 children treated with conservative methods. The second group comprised 102 children who underwent osteosynthesis with Titanium Elastic Nails. The third group consisted of 78 children who received other types of osteosynthesis (plating, repositioning, external fixation). The main indication for this functionally stable osteosynthesis was intraoperative fracture instability after primary repositioning, i.e., the inability to achieve a stable and satisfactory alignment of fragments solely with external immobilisation. The minimally invasive nature of the method, combined with functionally stable osteosynthesis, made it applicable for unstable forearm fractures in children at risk of impaired bone healing (older age, diaphyseal location, and associated risk factors). The method of treating forearm fractures in children using TEN is considered one of the most effective and safe approaches in modern paediatric orthopaedics. It provides stable fracture fixation, rapid healing, and a swift return to normal life. Due to its minimally invasive nature, this method significantly improves patients' quality of life and shortens treatment duration.

Keywords: fracture, forearm, diaphysis, functionally stable osteosynthesis, titanium elastic nails.

Introduction

Fractures of the forearm bones are among the most common injuries in paediatric traumatology and occupy one of the leading positions in the general structure of musculoskeletal trauma in children (*Ivanova, 2018*; *Levytskyi & Oliinyk, 2013*; *Tarniță et al., 2010*). The most widely used method for treating stable and slightly displaced fractures of the forearm bones in children remains conservative management, which usually includes closed reduction, external immobilisation, and further radiological follow-up (*Levytskyi et al., 2012*; *Myers et al., 2004*). In stable fractures, residual permissible displacement of bone fragments may be corrected during growth due to the remodelling potential of the child's skeleton.

However, diaphyseal fractures of both forearm bones with complete displacement of fragments are unstable by nature and are associated with a higher probability of secondary displacement during conservative treatment. These fractures are clinically significant because the radius and ulna form a complex functional unit responsible not only for flexion and extension in adjacent joints, but also for pronation and supination of the forearm. Therefore, malalignment, residual rotational deformity, angular displacement, shortening, or delayed consolidation may result in functional impairment, reduced range of motion, prolonged immobilisation, joint contractures, and deterioration in the child's quality of life.

The relevance of this study is determined by the need to optimise the treatment of unstable diaphyseal forearm fractures in children, especially in older age groups, where the remodelling potential of bone decreases and the risk of unsatisfactory outcomes after conservative treatment increases. Although conservative treatment remains effective for many stable fractures, unstable diaphyseal injuries often require surgical stabilisation. The main surgical options include plate osteosynthesis, Kirschner wire fixation, external fixation in open fractures, and intramedullary osteosynthesis using Titanium Elastic Nails (TEN) (*Fernandez et al., 2010*; *Flynn et al., 2010*; *Lascombes, 2010*; *Patel et al., 2021*; *Xu et al., 2018*).

Despite the widespread use of these methods, the choice of the optimal surgical stabilisation technique for paediatric forearm fractures remains a matter of discussion in the specialised literature. Plate osteosynthesis provides rigid fixation, but it is more invasive, requires wider surgical access, may be associated with additional soft tissue trauma, and usually requires subsequent implant removal. Kirschner wire fixation is technically simple, but may not provide sufficient stability in some diaphyseal fractures and often requires prolonged external immobilisation. External fixation is usually reserved for open, infected, or combined injuries. In contrast, elastic stable intramedullary osteosynthesis with titanium nails combines relative stability, minimal invasiveness, preservation of growth zones, and the possibility of early functional recovery (*Fernandez et al., 2010*; *Lascombes, 2010*; *Patel et al., 2021*).

The technique of osteosynthesis with elastic titanium nails, developed and popularised by Jean Prévot and Jean-Paul Métaizeau, has been widely used since the beginning of the twenty-first century and has gradually established its indications in paediatric orthopaedic trauma practice (*Lascombes, 2010*). Earlier and more recent publications by Ukrainian and international authors confirm the increasing use of intramedullary metal osteosynthesis with TEN for the treatment of children with unstable fracture patterns (*Ivanova, 2018*; *Levytskyi et al., 2012*; *Levytskyi & Oliinyk, 2013*; *Patel et al., 2021*; *Xu et al., 2018*). At the same time, several clinical questions remain insufficiently clarified, including indications for surgery after failed closed reduction, the need and duration of postoperative immobilisation, complication risks, implant removal timing, and long-term functional outcomes.

The research problem of the present article lies in the need to determine the clinical and radiological justification for the use of TEN osteosynthesis in children with unstable diaphyseal forearm fractures. In particular, it is necessary to evaluate whether minimally invasive elastic intramedullary fixation provides reliable fragment stability, allows early mobilisation, reduces the duration of external immobilisation, minimises the risk of complications, and ensures full functional recovery of the injured limb. This issue is especially important for children with complete displacement of fragments, secondary displacement after conservative treatment, recurrent fractures, diaphyseal localisation, and older age, all of which may increase the risk of impaired consolidation under conservative management.

The scientific novelty of this study consists in the clinical and radiological analysis of a large single-centre cohort of paediatric patients with diaphyseal forearm fractures treated during 2022–2024, with particular attention to the comparative clinical characteristics of conservative treatment, TEN osteosynthesis, and other types of surgical fixation. The article systematises indications for functionally stable intramedullary osteosynthesis using titanium elastic nails, evaluates early and long-term outcomes, identifies the main types of complications, and substantiates the role of TEN in restoring anatomical integrity and functional activity of the forearm in children.

The object of the study is the treatment process of children with diaphyseal fractures of the forearm bones.

The subject of the study is the clinical and radiological effectiveness of minimally invasive osteosynthesis with Titanium Elastic Nails in children with unstable diaphyseal forearm fractures.

The aim of the study is to evaluate treatment outcomes and provide clinical and radiological justification for the use of Titanium Elastic Nail osteosynthesis in children with complex diaphyseal forearm fractures, with an emphasis on reliable fragment fixation, rapid restoration of limb function, and minimisation of complication risks.

To achieve this aim, the study addresses the following objectives:

- to analyse the structure of paediatric forearm fractures treated in the paediatric trauma department during 2022–2024;
- to identify the clinical groups of patients treated conservatively, with TEN osteosynthesis, and with other types of osteosynthesis;
- to determine the main indications for minimally invasive elastic titanium nail osteosynthesis in children with unstable diaphyseal forearm fractures;
- to evaluate the clinical and radiological outcomes of TEN osteosynthesis, including fracture consolidation, position of fragments, and restoration of limb function;
- to analyse the frequency and nature of postoperative complications associated with TEN osteosynthesis;
- to determine the role of postoperative immobilisation, rehabilitation, and implant removal timing in the treatment process;
- to assess the advantages and limitations of TEN osteosynthesis in comparison with conservative treatment and other surgical techniques;
- to substantiate practical recommendations for the use of elastic titanium nails in paediatric orthopaedic and traumatological practice.

The theoretical significance of the study lies in deepening the understanding of functionally stable osteosynthesis in paediatric diaphyseal forearm fractures. The research contributes to the development of clinical reasoning regarding the limits of conservative treatment, the indications for surgical fixation, and the biomechanical advantages of elastic intramedullary stabilisation in the growing skeleton. It also clarifies the relationship between fracture localisation, age-related remodelling potential, fixation stability, and functional recovery.

The practical significance of the study lies in the possibility of using its results in the daily practice of paediatric orthopaedic and traumatological departments. The findings may help clinicians determine indications for TEN osteosynthesis, select appropriate nail diameter according to the medullary canal, reduce the risk of secondary displacement, minimise the duration of immobilisation, optimise rehabilitation, and improve functional outcomes. The use of minimally invasive elastic titanium nail osteosynthesis may shorten the period of treatment, reduce the need for prolonged plaster immobilisation, improve cosmetic results, and facilitate a faster return of children to normal daily activity.

Materials and Methods

Study Design and Clinical Setting

This study was designed as a retrospective clinical and radiological analysis of paediatric patients with diaphyseal fractures of the forearm bones. The research was conducted on the basis of medical records of children treated between 2022 and 2024 in the Paediatric Trauma Department of the Emergency Hospital in Chernivtsi. The retrospective design made it possible to evaluate the real clinical practice of treating forearm fractures in children, including conservative management, minimally invasive osteosynthesis with Titanium Elastic Nails, and other surgical fixation techniques.

The study focused on the assessment of treatment outcomes, indications for surgical stabilisation, fracture consolidation, restoration of limb function, postoperative complications, and the clinical-radiological justification for using Titanium Elastic Nails in unstable diaphyseal forearm fractures in children.

Study Population and Eligibility Criteria

The total study population included 365 children with diaphyseal fractures of the forearm bones. All patients were hospitalised and treated in accordance with the accepted clinical principles of paediatric orthopaedic and traumatological care.

The inclusion criteria were as follows:

- paediatric age;
- diaphyseal fracture of one or both forearm bones;
- presence of radiologically confirmed fracture of the radius and/or ulna;
- treatment in the Paediatric Trauma Department of the Emergency Hospital in Chernivtsi during 2022–2024;
- availability of complete medical records and radiological documentation sufficient for retrospective analysis.

The exclusion criteria were distal and proximal meta-epiphyseal fractures, stable greenstick fractures, subperiosteal fractures, incomplete documentation, and cases in which the clinical or radiological data were insufficient for evaluating treatment outcomes.

According to these criteria, 365 medical histories were selected and analysed. Among them, 102 patients underwent minimally invasive osteosynthesis using Titanium Elastic Nails. In this subgroup, the mean age was 11.0 ± 2.2 years. The largest proportion of surgically treated patients belonged to the age group of 11–13 years, which accounted for 57% of all cases treated with TEN osteosynthesis. This age group was of particular clinical interest because the remodelling potential of the forearm decreases with age, while the risk of secondary displacement and unsatisfactory outcomes after conservative treatment increases.

Clinical Groups

For comparative clinical analysis, all patients were divided into three groups according to the treatment method used.

The first clinical group included 185 children treated with conservative methods. Conservative treatment consisted of closed reduction where necessary, plaster immobilisation, radiological follow-up, and rehabilitation after removal of the cast.

The second clinical group included 102 children who underwent osteosynthesis with Titanium Elastic Nails. This group represented the main focus of the study because TEN osteosynthesis was analysed as a minimally invasive and functionally stable method for treating unstable diaphyseal forearm fractures in children.

The third clinical group included 78 children who underwent other types of osteosynthesis, including plate fixation, repositioning fixation, Kirschner wire fixation, or external fixation depending on the fracture type, soft tissue condition, and clinical indications (*Figure 1*).

Indications for TEN Osteosynthesis

The main indication for Titanium Elastic Nail osteosynthesis was instability of the fracture after primary repositioning, that is, the inability to achieve or maintain stable and satisfactory alignment of bone fragments by closed reduction and external immobilisation alone. The method was used in children with unstable diaphyseal fractures characterised by complete displacement of fragments by length and width, pronounced angular displacement, complete rupture of the periosteum, residual unacceptable displacement after closed manual reduction, or secondary displacement during conservative treatment.

Additional indications included recurrent fractures, insufficient stability after plaster immobilisation, and fracture patterns in which prolonged external immobilisation could increase the risk of joint contractures or delayed functional recovery. Surgical stabilisation was also considered in older children with diaphyseal localisation of the fracture, since this group has a reduced potential for spontaneous remodelling and a higher risk of impaired consolidation under conservative treatment.

The choice of TEN osteosynthesis was based on its minimally invasive nature, preservation of growth zones, relative elastic stability, and potential for early functional rehabilitation. These advantages correspond to the general principles of paediatric elastic stable intramedullary nailing described in the specialised literature (*Fernandez et al., 2010*; *Lascombes, 2010*; *Patel et al., 2021*; *Xu et al., 2018*).

Surgical Technique

All children in the TEN group underwent osteosynthesis with Titanium Elastic Nails. The diameter of the nail was selected according to the width of the medullary canal. The preferred diameter of the metal fixator corresponded to approximately 60–70% of the diameter of the medullary canal at its narrowest point. Nails with a diameter of 2.0 to 4.0 mm were used, depending on the child’s age, bone size, and anatomical characteristics.

The key biomechanical feature of this technique was relative elastic stability achieved through three-point intramedullary fixation. Before insertion, the nail was pre-bent into an arc so that its apex corresponded to the fracture zone after placement in the medullary canal. The physiological curvature of both the radius and ulna was taken into account during the formation and insertion of the implant. This allowed restoration of the anatomical axis of the forearm bones and provided sufficient stability during fracture consolidation.

In fractures of both forearm bones, elastic nails were inserted into both the radius and ulna. In cases of isolated radial fracture, one nail was inserted into the radius. In cases of ulnar fracture associated with radial head dislocation, corresponding to Monteggia injury, fixation was performed by inserting one nail into the ulna.

Standard surgical access was used according to the anatomical characteristics of the injured bone. Particular attention was paid to minimising soft tissue trauma and avoiding damage to the sensory branch of the radial nerve and the tendon of the extensor pollicis longus during insertion of the nail into the radius. Careful exposure of the bone and atraumatic manipulation were used to prevent these complications.

If closed reduction was unsuccessful, a Kirschner wire with a diameter of 1.5–1.8 mm was introduced percutaneously near the fracture site and used as a “joystick” to reposition the bone fragments. This technique made it possible in most cases to avoid conversion to open osteosynthesis. In cases where closed reduction was impossible because of significant soft tissue interposition, the intramedullary nail was advanced to the fracture area, the interposed tissues were released through a small incision of approximately 3–4 cm, and the fracture was then stabilised by advancing the nail into the proximal bone fragment.

All stages of the surgical procedure were performed under radiological control using an image intensifier, or C-arm. Intraoperative fluoroscopy was used to confirm the quality of reduction, correct positioning of bone fragments, appropriate location of the nails, and sufficient stability of fixation.

Postoperative Management and Rehabilitation

Postoperative management included pain control, monitoring of the surgical wound, assessment of peripheral circulation and sensitivity, and early functional rehabilitation. Plaster immobilisation of the injured limb was performed for 10–14 days until pain subsided. In most cases, immobilisation was performed without including the elbow joint, which allowed earlier restoration of movement and reduced the risk of elbow stiffness.

Although correct nail sizing may theoretically allow treatment without plaster immobilisation, a plaster splint was used in selected cases because TEN provides relative elastic stability rather than absolute rigid fixation. Since micro-mobility of fragments remains and consolidation occurs through callus formation, short-term plaster immobilisation was considered useful for reducing excessive fragment mobility, decreasing pain in the early postoperative period, and preventing the formation of excessive paraosteal callus.

Stable osteosynthesis with elastic titanium nails allowed the duration of plaster immobilisation to be reduced to 2–4 weeks in most patients. This enabled earlier initiation of rehabilitative treatment and restoration of active movements in the elbow and wrist joints. Early mobilisation was considered one of the principal advantages of TEN osteosynthesis in comparison with prolonged conservative immobilisation.

Clinical Outcome Assessment

Clinical assessment was performed during the treatment period and at follow-up visits. The main clinical criteria included patient complaints, pain intensity, external appearance of the operated limb, presence or absence of swelling or deformity, condition of postoperative wounds, peripheral circulation, skin sensitivity, and signs of muscle hypotrophy.

Functional assessment included evaluation of active range of motion in the elbow and wrist joints, as well as pronation and supination of the forearm. Particular attention was paid to restoration of symmetrical function in comparison with the contralateral upper limb. The presence or absence of complications was also assessed, including inflammatory complications, irritation caused by nail protrusion, superficial infection at the nail insertion site, migration of the nail, nerve injury, tendon injury, delayed consolidation, contracture, angular deformity, rotational deformity, synostosis, limb shortening, or growth disturbance.

Radiological Assessment

Radiological assessment was performed using standard radiographs of the forearm in appropriate projections. Radiographs were analysed to evaluate fracture type, initial displacement, quality of reduction, position of fragments after fixation, location and stability of the nails, restoration of the anatomical axis, and stages of radiopaque callus formation.

Particular attention was paid to the restoration of the physiological curvature of the radius and ulna, since this parameter is important for preserving pronation and supination of the forearm. Radiological evidence of fracture consolidation was used to determine the timing of implant removal. Complete union and satisfactory bone remodelling were considered necessary conditions for safe removal of the metal fixators.

Follow-Up and Implant Removal

Patients who underwent TEN osteosynthesis were followed dynamically after surgery. Follow-up included clinical examination, functional testing, radiological assessment, and evaluation of the quality of recovery. Observations were performed at different postoperative intervals, including 1, 3, and 6 months, and in selected cases later follow-up was conducted at 12 and 18 months after surgery.

The removal of elastic titanium nails was performed after radiological confirmation of fracture union. In most cases, implants were removed between 6 and 14 months after surgery under general anaesthesia in hospital conditions. The timing of removal was determined individually, taking into account fracture consolidation, age of the child, stability of bone remodelling, absence of pain, and restoration of limb function.

Data Processing and Statistical Analysis

The obtained clinical and radiological data were processed using descriptive statistical methods. Quantitative variables were presented as mean values with standard deviation where applicable. Categorical variables were presented as absolute numbers and percentages. The analysis included the distribution of patients by treatment group, age, fracture type, type of fixation, duration of immobilisation, timing of functional recovery, timing of implant removal, and frequency and type of complications.

The study did not involve randomisation or prospective allocation of patients to treatment groups, since the treatment method was determined by clinical indications, fracture stability, fracture localisation, patient age, and the decision of the treating orthopaedic-traumatological team.

Therefore, the results were interpreted as retrospective clinical evidence reflecting real practice in paediatric traumatology.

Ethical Considerations

The study was retrospective in nature and was based on the analysis of medical histories and radiological documentation. Personal identifying data were not used in the analysis or presentation of results. The research was conducted in accordance with the principles of confidentiality and ethical handling of medical information.

Literature Review

Forearm bone fractures in children remain one of the most frequently discussed problems in paediatric traumatology and orthopaedics because of their high prevalence, functional significance, and variability of treatment approaches. The radius and ulna form a single biomechanical unit responsible not only for support and flexion-extension movements of the upper limb, but also for pronation and supination of the forearm. Therefore, even a relatively small residual deformity after fracture healing may affect rotational function, especially in diaphyseal fractures where the remodelling capacity is lower than in metaphyseal injuries. Ukrainian and international studies emphasise that the choice of treatment method should take into account the child's age, fracture localisation, degree of displacement, rotational deformity, stability after reduction, and potential for further skeletal growth (*Ivanova, 2018*; *Levytskyi & Oliinyk, 2013*; *Levytskyi et al., 2012*).

Conservative treatment remains the traditional and most widely used approach for stable or slightly displaced paediatric forearm fractures. Its main advantage is the absence of surgical trauma and anaesthetic risks. Closed reduction followed by plaster immobilisation may be sufficient in younger children and in cases where the displacement is within acceptable limits. Myers et al. (*2004*) noted that satisfactory results may be achieved in selected diaphyseal fractures when reduction is stable and further displacement does not occur. At the same time, the effectiveness of conservative treatment depends on accurate reduction, proper cast application, adequate follow-up, and the biological capacity of the growing skeleton to remodel residual angulation.

However, the literature also shows that conservative treatment has important limitations in unstable diaphyseal fractures of both forearm bones. Complete displacement, pronounced angular deformity, rotational malalignment, rupture of the periosteum, and fracture localisation in the diaphysis increase the probability of secondary displacement. This problem becomes more clinically significant in children older than 10 years, since the remodelling potential decreases with age and the risk of persistent functional limitation increases. Levytskyi et al. (*2012*) emphasised that surgical treatment should be considered when closed reduction is ineffective, when fragment stability cannot be maintained, or when the fracture pattern itself indicates a high risk of unsatisfactory consolidation. Thus, the current literature supports a differentiated approach rather than an unconditional preference for either conservative or surgical treatment.

Surgical stabilisation of paediatric forearm fractures includes several methods: plate osteosynthesis, Kirschner wire fixation, external fixation, and elastic stable intramedullary nailing with titanium elastic nails. Each technique has its own indications, advantages, and limitations. Plate osteosynthesis provides rigid anatomical fixation and is effective in complex fractures, but it requires wider surgical access, greater soft tissue dissection, and subsequent implant removal. In paediatric practice, these features are important disadvantages because they increase surgical trauma, cosmetic defects, and potential risks to the periosteal blood supply. Kirschner wire fixation is less invasive but may provide insufficient stability in some diaphyseal fractures and often requires prolonged immobilisation. External fixation is usually reserved for open fractures, infected injuries, polytrauma, or severe soft tissue damage (*Fernandez et al., 2010*; *Flynn et al., 2010*; *Xu et al., 2018*).

Elastic stable intramedullary nailing has become increasingly important in paediatric orthopaedics since the development of the method by Prévot and Métaizeau and its subsequent systematisation in the Nancy school. Lascombes (*2010*) described flexible intramedullary nailing as a biologically favourable technique that provides relative stability while preserving the fracture haematoma, periosteal blood supply, and growth zones. The principle of three-point fixation allows elastic nails to stabilise bone fragments without rigid compression, creating conditions for callus formation and functional recovery. This method is particularly relevant in children because it corresponds to the biological characteristics of the growing skeleton and minimises iatrogenic damage.

The main advantages of TEN osteosynthesis reported in the literature include minimal invasiveness, small incisions, reduced soft tissue trauma, preservation of the periosteum, stable fragment alignment, shorter immobilisation period, earlier rehabilitation, satisfactory cosmetic results, and easier implant removal. Fernandez et al. (*2010*) analysed failures and complications associated with intramedullary nailing of children's forearm fractures and showed that most complications are preventable when the correct indications, implant diameter, entry point, and surgical technique are respected. Patel et al. (*2021*) also reported favourable outcomes in paediatric forearm fractures treated with titanium elastic nails, emphasising the method's ability to provide stable fixation and satisfactory functional recovery.

Comparative studies further support the clinical value of elastic intramedullary fixation. Xu et al. (2018) compared elastic stable intramedullary nailing and plating in paediatric forearm fractures and demonstrated that both methods may provide good union rates, but intramedullary nailing is associated with lower invasiveness and a more favourable soft tissue profile. Flynn et al. (2010), in their long-term operative experience with paediatric forearm fractures, also supported the use of surgical stabilisation in unstable fractures when conservative treatment fails or when there is a high risk of secondary displacement. These findings are consistent with Ukrainian clinical observations that TEN osteosynthesis may be preferable in unstable diaphyseal fractures, especially in older children and adolescents (*Ivanova, 2018*; *Levytskyi & Oliinyk, 2013*).

A separate issue in the literature concerns single-bone versus both-bone fixation in fractures of the radius and ulna. Myers et al. (*2004*) studied Nancy nailing of diaphyseal forearm fractures and discussed the possibility of single-bone fixation in selected cases. This approach may reduce surgical trauma, but it requires careful assessment of fracture stability and restoration of the anatomical relationship between both bones. In fractures of both forearm bones, fixation of both the radius and ulna may provide more reliable restoration of the forearm axis and reduce the risk of rotational limitation. Therefore, the decision should be individualised according to fracture morphology, intraoperative stability, and the surgeon's assessment.

Biomechanical studies provide additional justification for the need to restore the anatomical axis and curvature of the forearm bones. Anderson et al. (*2005*) developed a three-dimensional finite element model of the radiocarpal joint, demonstrating the importance of load distribution in the forearm-wrist complex. Edwards and Troy (*2012*) and Troy and Grabiner (*2007*) showed that bone strength and fracture behaviour depend on loading direction and structural properties. Shefelbine et al. (*2005*) used micro-CT and finite element analysis to predict mechanical properties of fracture callus, highlighting the relationship between fracture healing and mechanical stability. These studies support the clinical principle that adequate fixation should provide sufficient stability while preserving biological conditions for callus formation.

The design and material properties of implants are also significant in paediatric fracture treatment. Titanium elastic nails are valued because of their elasticity, biocompatibility, and ability to provide stable intramedullary support without excessive rigidity. Studies of fixation plates and alternative materials, including carbon fibre composites, Nitinol-based plates, and modular orthopaedic plates, show the continuing search for fixation systems that combine mechanical reliability with biological compatibility (*Frydrýšek et al., 2014*; *Saidpour, 2006*; *Tarniţă et al., 2010*). However, in paediatric diaphyseal forearm fractures, TEN remains attractive because it combines sufficient mechanical stability with minimal surgical invasiveness.

The literature also emphasises the importance of complication analysis. Possible complications of TEN osteosynthesis include irritation of soft tissues at the nail entry site, superficial infection, migration or protrusion of the nail, delayed union, refracture after early implant removal, injury to the superficial radial nerve, tendon irritation, and, rarely, synostosis or rotational limitation. Fernandez et al. (2010) stressed that technical errors, incorrect nail diameter, insufficient pre-bending, inadequate fixation, or premature removal may increase the risk of complications. Therefore, successful TEN osteosynthesis requires strict adherence to surgical technique, correct implant sizing, careful protection of neurovascular and tendon structures, and appropriate follow-up.

Timing of implant removal remains a subject of clinical discussion. Lascombes (*2010*) recommended that removal should be performed only after complete consolidation and adequate remodelling. Premature removal may increase the risk of refracture, whereas excessive delay may cause irritation, discomfort, or technical difficulties during extraction. Clinical practice therefore usually requires radiological confirmation of union before removal. This issue is especially important in children because implant removal should be planned in relation to bone healing, growth, psychological comfort, and the need to minimise repeated surgical trauma.

Another important aspect is early mobilisation and functional recovery. Prolonged plaster immobilisation may lead to stiffness of adjacent joints, muscle hypotrophy, delayed return to activity, and the need for rehabilitation. In this respect, TEN osteosynthesis has a significant functional advantage because it allows a reduction in immobilisation time and supports earlier restoration of movement. The literature suggests that early mobilisation is particularly important for maintaining pronation and supination, which are sensitive to residual angular and rotational deformities of the radius and ulna (*Fernandez et al., 2010*; *Lascombes, 2010*; *Patel et al., 2021*).

Despite the growing body of research, several issues remain insufficiently resolved. First, there is still no universal consensus regarding the exact indications for TEN osteosynthesis in paediatric forearm fractures, especially in borderline cases after closed reduction. Secondly, the optimal duration of postoperative immobilisation remains debated because TEN provides relative elastic stability rather than absolute rigid fixation. Thirdly, the timing of implant removal varies across clinical practices. Fourthly, the relationship between patient age, diaphyseal localisation, fracture morphology, and long-term rotational function requires further clinical analysis. Finally, there is a need for more single-centre and multicentre studies based on real clinical practice and long-term follow-up.

Thus, the reviewed literature confirms that minimally invasive elastic titanium nail osteosynthesis is a clinically justified and widely accepted method for the treatment of unstable diaphyseal forearm fractures in children. It provides reliable fixation, preserves biological healing mechanisms, reduces surgical trauma, allows early rehabilitation, and improves functional outcomes. At the same time, the effectiveness of the method depends on correct patient selection, precise surgical technique, adequate postoperative management, and timely implant removal. These considerations define the relevance of the present study, which analyses clinical and radiological outcomes of TEN osteosynthesis in children with diaphyseal forearm fractures treated in a specialised paediatric trauma department.

Results

Certain difficulties in treating forearm fractures in children arise when they are localized in the diaphyseal region. In such fractures, bone fragments are usually displaced laterally (by width) and angularly, which significantly complicates the process of reduction and fixation given the small diameter of the bones. There is no single consensus regarding treatment tactics for patients of different age groups or the choice of treatment strategies, as it is necessary to consider the anatomical features and the potential for growth and development of the forearm in children of various ages. Currently, the conservative method of treating diaphyseal forearm fractures in children remains the primary approach. The prognosis of treatment results is determined by the patient's age, the nature of the fracture, the quality of the reduction and cast application, the duration of fixation, and adequate rehabilitation. It is worth noting that in paediatric traumatology, the concept of permissible displacement is widely used, with the exception of rotational displacement. During a child's growth, spontaneous remodelling occurs at the level of the callus at a rate of approximately 10 degrees per year.

However, this property of the growing organism has its limits, determined by the magnitude of the displacement and the patient's age; therefore, these indicators have limitations for conservative treatment, and the frequency of unfavourable outcomes and complications with the conservative method increases significantly in children over 10 years old. The advantages of this method suggest the absence of surgical risk. However, the conservative method has its drawbacks: high probability of secondary displacement of bone fragments, limitations for use in open fractures, immobilization of adjacent joints leading to the development of joint contractures, inconvenience and potential destruction of the plaster cast itself, the necessity for rehabilitation after its removal. Surgical methods for treating diaphyseal fractures in children were not historically primary and, as a rule, became relevant in cases of ineffective closed manual reduction, the occurrence of secondary displacements, malunited fractures, and refractures. There is an opinion supporting primary indications for surgical treatment in cases of open injuries, unstable fractures, polytrauma, and in children older than 10 years. In our opinion, a certain group of patients faces a risk of impaired fracture consolidation during conservative treatment related to the patient's age (older age group) and fracture localization (diaphyseal).

All this leads to the need for prolonged immobilization, the risk of developing contractures in adjacent joints, or the development of severe complications such as non-union. Due to the abovementioned factors, the article justifies the use functionally stable osteosynthesis in such patients, which ensures early mobilization of the injured segment and avoids the formation of contractures. The use of TEN osteosynthesis allows for the avoidance of long-term external immobilization while simultaneously ensuring segment stability throughout the entire consolidation period, regardless of its duration. This type of osteosynthesis was used in patients with diaphyseal forearm fractures with complete displacement of fragments by length and width, pronounced angular displacement, complete rupture of the periosteum, residual unacceptable displacements after closed manual reduction, and secondary displacement of fragments. The minimally invasive TEN technique was used in 82 cases of fractures of both forearm bones; nails were inserted into both the ulna and the radius. In 14 children, one nail was inserted for an isolated radial fracture; in 6 cases of ulnar fractures with associated radial head dislocation (Monteggia injury), one nail was inserted into the ulna. Naturally, there is a risk of damaging the sensory branch of the radial nerve and the tendon of the extensor pollicis longus when passing the nail into the radius. However, careful exposure of the bone without gross tissue damage allows for the avoidance of this complication. Plaster immobilization of the injured limb was performed for 10–14 days until the pain subsided; notably, immobilization was carried out without including the elbow joint. We observed no purulent-inflammatory complications, sensory radial nerve palsies, or injuries to the tendon-ligamentous apparatus. In 14 patients, phenomena of delayed consolidation were noted at 3–5 months post-surgery; however, simply extending the time before removal to 12 months allowed for complete organotypic remodelling.

This group of patients required no special treatment. The size (diameter) of the metal fixator was determined according to the width of the medullary canal, aiming for 60–70% of the diameter of the canal at its narrowest point. Nails from 2.0 to 4 mm were used. A key feature of this osteosynthesis was its relative elastic stability, achieved through three-point intramedullary fixation. For greater stability in the fracture zone, the nail was pre-bent into an arc so that when positioned in the medullary canal, its apex was located at the fracture zone, taking into account the physiological curvature of both the radius and ulna. Satisfactory positioning of the fragments and sufficient stability were confirmed using an Image Intensifier (C-arm). While proper nail sizing could allow for the omission of plaster immobilization, we still utilised a plaster splint (long-leg or short-arm equivalent) for the following reasons. TEN is a method of relative stability (elastic fixation), meaning micro-mobility of fragments remains. Consolidation occurs through callus formation. A plaster splint reduces the micromobility of fragments and prevents the formation of excessive paraosteal callus. Additionally, in the early postoperative period, the plaster splint reduces pain syndrome and decreases the use of non-narcotic analgesics.

Furthermore, stable osteosynthesis of both forearm bones with elastic titanium nails allowed for a reduction in the duration of plaster immobilisation to between 2 and 4 weeks in our patients; this enabled an earlier start to rehabilitative treatment. If closed reduction was unsuccessful, a Kirschner wire (K-wire) with a diameter of 1.5–1.8 mm was inserted percutaneously near the fracture site to reposition the bone fragments using the so-called “joystick” technique, which in most cases allowed us to avoid converting to open osteosynthesis. In instances where closed reduction was impossible due to significant soft tissue interposition, the intramedullary nail was advanced to the fracture area, after which the interposition was cleared through a 3–4 cm incision; the fracture was then synthesized by driving the nail into the proximal bone fragment. All stages of the surgery were strictly monitored using an Image Intensifier (C-arm). During the treatment analysis, we focused on the following clinical criteria: patient's complaints, external appearance of the operated limb (with the assessment of peripheral circulation and sensitivity), presence or absence of muscle hypotrophy, range of active motion in the wrist and elbow joints, pronation and supination of the forearm, presence of complications. Radiologically, we analyzed the stages of radiopaque callus formation and the positioning of bone fragments and nails. The primary advantages of TEN osteosynthesis, compared to other methods, were earlier mobilization of the forearm and lower invasiveness compared to plate osteosynthesis. The elastically stable intramedullary nail has proven to be a modern tool for treating children with forearm fractures when surgical stabilization is indicated.

On average, sufficient bone callus formation was observed as early as 4 weeks post-intervention, confirmed both clinically and radiologically. In its characteristics, this consolidation was not inferior to the healing processes observed with conservative treatment and, in some cases, surpassed them in terms of timing and stability. The number of postoperative complications was negligible. Out of the total 102 operated patients, 12 (7.8%) experienced temporary complications that did not require significant medical intervention. Six children developed skin irritation in the ulnar region due to nail protrusion, and another six developed a superficial skin infection at the radial nail insertion site. One case required the premature removal of the ulnar nail due to migration. No serious complications leading to functional impairment (such as angular or rotational deformity, growth arrest, synostosis formation, significant restriction of elbow joint mobility, or limb shortening) were detected. All identified complications were reversible, did not affect the duration or outcome of treatment, and did not require repeat surgical interventions.

The best results were observed in children aged 6–13 years, where the ratio between the diameter of the medullary canal, the anatomical features of the growth zones, and the nature of the injury proved to be most favorable for the application of this method.

Most patients began performing active movements in the joints as early as 10–14 days post-surgery, without complaints of pain or restriction. In 90% of cases, full functional recovery was achieved within 4 to 6 weeks. A significant contribution to such results was the possibility of early limb loading and the reduction—or even total absence—of postoperative immobilization. In no case were significant deformations found that would affect the function of the forearm. All patients, including those who experienced minor complications, were discharged with full restoration of movement and symmetrical functionality of both upper limbs. Angular or rotational deformities, synostosis, significant limb length discrepancy, or axial malalignment were not detected. Furthermore, it was noted that the method was well-tolerated by patients and was not accompanied by the psychological discomfort typically associated with, for example, wearing external fixation devices. Parents highly praised the short postoperative period, the absence of noticeable scarring, and the child's rapid return to their usual lifestyle.

Discussion

The study included 365 children with diaphyseal and metadiaphyseal fractures of the forearm bones who were hospitalized over the last three years in the paediatric orthopaedic-traumatology department of the Emergency Hospital; 102 of these children underwent TEN osteosynthesis. The age of the patients ranged from 6 to 16 years, with an average age of 11,0±2,2 years old. In terms of gender distribution: 67 (65.7%) were boys and 35 (34.3%) were girls. From the moment of admission, all patients received full orthopaedic and traumatological care in accordance with the current protocols of the Ministry of Health of Ukraine. All fractures were classified as unstable with fragment displacement. In all cases, the indications for osteosynthesis were: ineffectiveness of closed reduction, secondary displacement following plaster immobilization, recurrent fractures (refractures), combined trauma (2 cases). All patients underwent osteosynthesis with Titanium Elastic Nails (TEN). The choice of this method was justified by its ability to provide stable fixation with minimal soft tissue trauma, preservation of the growth zones (physes), and the possibility of early mobilization. Closed osteosynthesis of both forearm bones was performed in 69 patients (67.65%). In 16 cases (15.69%), only the radius was synthesized, and in 2 cases (1.96%), only the ulna. A combined technique (open-closed) was used in 9 patients, 3 of whom required additional revision due to soft tissue interposition.

In most cases, nails with diameters ranging from 2.0 to 4.0 mm were used, depending on the child's age and the width of the medullary canal. Surgical access followed the standard technique: through the proximal metaphysis of the radius and the distal metaphysis of the ulna. The average duration of surgery was 45±12 minutes. In 56 cases, stable fixation was achieved without the need for additional plaster immobilization. The postoperative period proceeded without complications in the majority of cases. From the first postoperative days, all patients underwent comprehensive rehabilitation, including early mobilization, therapeutic exercise, pain management, and monitoring of the surgical wound. The early restoration of functional activity was made possible by the stability of the fixation and the minimally invasive nature of the intervention.

According to dynamic follow-up at 1-, 3-, and 6-months post-surgery, complete functional recovery of the forearm was recorded in the majority of children. This assessment accounted for the range of rotational and flexion-extension movements in the elbow and wrist joints, as well as the presence of any deformities or complaints. The overall complication rate was 13.2% (14 cases). All of these were of a mild degree and did not require repeat surgical intervention (with the exception of one case). Serious complications, such as angular or rotational deformities, limb shortening, growth impairment, contractures, or ankylosis, were not registered. This indicates the safety and reliability of the technique when the surgical protocol and postoperative care are strictly followed.

Compared to other surgical methods for treating forearm bone fractures in children (plate osteosynthesis, Kirschner wires, external fixation), elastic titanium nails demonstrated a series of indisputable advantages: minimal soft tissue trauma; preservation of growth zones; no requirement for wide surgical access; stable fixation without the need for plaster immobilization; rapid restoration of activity; satisfactory cosmetic results; technical simplicity given a sufficient level of surgical training. Plate osteosynthesis, while providing reliable fixation, is more invasive and requires subsequent hardware removal, which is a significant drawback in paediatric practice. K-wire fixation is accompanied by the need for external immobilization and a higher risk of instability, especially in diaphyseal fractures. External fixation devices are justified only in cases of open, infected, or combined injuries. The results of this study support the assertion that the minimally invasive elastic titanium nail osteosynthesis technique is a modern and effective approach to treating forearm fractures in children.

Stable results, a low complication rate, rapid functional recovery, and minimal invasiveness attest to the feasibility of broader implementation of this method into the daily practice of paediatric orthopaedic-traumatology departments. The use of this method is particularly justified for children aged 6 to 14 years with diaphyseal and metadiaphyseal fractures of both forearm bones. Thus, the obtained clinical data confirm that intramedullary elastic stabilization of fractures allows not only for the restoration of anatomical integrity but also ensures a high quality of life for patients in both the immediate and long-term postoperative periods. The analysis of long-term treatment results for patients who underwent forearm bone osteosynthesis using elastic titanium nails is crucial for assessing the long-term effectiveness of the method. In children, given the growth and development of the musculoskeletal system, it is especially important not only to achieve union of bone fragments but also to ensure the anatomical and functional integrity of the limb in the long term. Observation of the 102 patients who underwent minimally invasive intramedullary osteosynthesis with elastic titanium nails was carried out at intervals of 3, 6, 12, and 18 months following the surgical intervention. Monitoring included clinical assessment, analysis of radiographic data, functional testing, psychological questioning of patients, and parent surveys regarding the children's quality of life.

Functional assessment was performed by measuring the range of motion in the elbow and radiocarpal (wrist) joints, as well as the rotational movements of the forearm. In 97% of patients, full or nearly full recovery of limb mobility (within a 5–10° deviation) was achieved as early as 6 months after treatment. After 12 months, full recovery was recorded in 100% of the children. Some temporary reduction in the range of motion during the early postoperative period was observed in patients with concomitant muscle contractures or minor residual deformities; however, function was subsequently fully restored. Radiological assessment demonstrated satisfactory results in most cases. A complete bone callus formed on average 3–4 weeks after surgery. All fixators were removed between 8 and 14 months without complications. No signs of pathological remodelling or growth asymmetry were detected. In several children, forearm growth was monitored 18–24 months after the intervention, and no abnormalities were registered. The removal of the metal fixators was primarily performed between 6 and 14 months in a hospital setting under general anaesthesia. The average timeframe for removal is 7.9 months (*Table 1*).

In all operated patients, the alignment of fragments post-surgery and the subsequent union of fractures was observed with a deformity of less than 10%.

Overall, 98% of all patients demonstrated full restoration of the range of flexion and extension in the elbow and wrist joints of the operated limb by the 8-week mark post-surgery. This occurred regardless of the fracture type or the nature of fragment displacement. At the same time, pronation and supination were restricted by more than 25% of the normal range of motion in 52% of patients, which corresponded to a "satisfactory" result. This deficit in movement was fully restored by the time of hardware removal, allowing these patients to transition into the group with "excellent" treatment results. Full restoration of the range of motion in adjacent joints is possible when the anatomical curvature of the ulna and radius is restored following osteosynthesis with elastic titanium nails—a result observed radiographically in all operated patients. The complications identified in our patients were not irreversible and occurred in a small number of cases (8.8%). The removal of elastic titanium fixators is the final stage of minimally invasive osteosynthesis in children. The procedure requires a balanced approach to the choice of timing, methodology, and type of anesthesia, taking into account both the anatomical and physiological characteristics of the patient and the child's psycho-emotional state; however, it is not traumatic, is time-efficient, and minimizes cosmetic skin defects.

Conclusion

1. Osteosynthesis of unstable complex diaphyseal forearm fractures in children using elastic titanium nails demonstrates a high level of safety and reliability when performed in a specialised paediatric orthopaedic and traumatological department equipped with trained personnel, appropriate surgical instruments, necessary implants, and consumable materials. Under these conditions, Titanium Elastic Nail osteosynthesis can be considered a clinically justified method for stabilising unstable forearm fractures in children.
2. The complication rate associated with this method is low. In the majority of cases, complete restoration of the function of the injured limb can be achieved. The observed complications were generally mild, reversible, and did not lead to persistent functional impairment, angular or rotational deformity, limb shortening, growth disturbance, or the need for repeated reconstructive surgical intervention.
3. Removal of implants at 6–8 months after surgery is advisable when radiological examination confirms complete fracture union. The timing of implant removal should be determined individually, taking into account the degree of bone consolidation, the stability of remodelling, the absence of pain, the restoration of limb function, and the general clinical condition of the child.
4. The technique of osteosynthesis with elastic titanium nails for diaphyseal forearm fractures in children makes it possible to achieve satisfactory fracture stability and early restoration of limb function. This significantly shortens the period of hospitalisation, reduces the need for prolonged external immobilisation, facilitates earlier rehabilitation, and improves the child's quality of life in the postoperative period.

Thus, minimally invasive elastic titanium nail osteosynthesis may be recommended as an effective treatment option for unstable diaphyseal forearm fractures in children, provided that indications are properly determined, surgical technique is strictly followed, and postoperative clinical and radiological monitoring is ensured.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

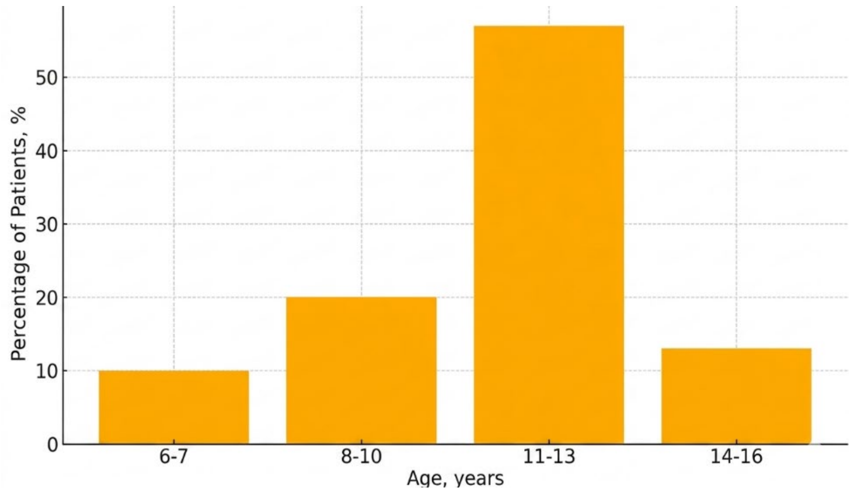

Figure 1. Disposition of operated children by Aige Group

Table 1. Timing of Metal Fixators Removal

Timing of Metal Fixators Removal (months)	Number of Patients	%
5	2	2.04
6	16	16.33
7	16	16.33
8	2	2.04
9	16	16.33
10	16	16.33
11	13	13.27
12	12	12.24
13	4	4.08
14	1	1.02
15	0	0.00