Review article

Management of growth arrest: Current practice and future directions

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ABSTRACT

Introduction: Premature growth arrest can pose a challenge to the orthopedic surgeon. Various options for treating physeal arrest exist.

Methods: Systematic searches were conducted on PubMed/Medline, ScienceDirect, OVID, and Cochrane Library. Secondary searching was performed, where certain articles from reference lists of the selected studies were reviewed that were not found in the primary search.

Results: This review article discusses the different methods of management for premature growth arrest.

Conclusions: The use of mesenchymal stem cells provides a promising alternative treatment modality.

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1. Introduction

Physeal injuries complicate 18–30% of pediatric fractures. Growth arrest occurs in 5–10% of cases in those with physeal fractures. The incidence of growth arrest is quite variable depending on physeal location, type of injury, and treatment received.^{1–2} Premature growth arrest is characterized by an unexpected discontinuation of longitudinal and/or appositional bone growth secondary to an insult to the growth plate prior to skeletal maturity. Growth arrest is frequently posttraumatic; however, other etiologies include congenital conditions (e.g. Blount's disease), infection, neoplasm, irradiation, metabolic/hematologic abnormalities, ischemia, disuse, and iatrogenic injury.³ The most frequently injured physis is the distal radius.¹ According to Mizuta, the physis of upper limb is more frequently injured than those of lower limb in a ratio of 3:1.¹ The outcome of premature growth arrest is based on skeletal age, location and extent of the associated physeal bar. A central physeal bar results in cessation of longitudinal growth, and subsequently a limb length discrepancy (LLD). A peripheral physeal bar may result in both a limb length discrepancy as well as angular deformity.

There are many current treatment strategies that focus on either restoring the propensity for growth, such as surgical removal of physeal bars with or without placement of interpositional material, or mitigating the resulting complications of the arrest, encompassing deformity correction.⁴ The goal of this review is to present a concise summary of the current practice and future directions in management of premature growth arrest.

2. Epidemiology of growth arrest

Injury to the reserve or proliferative zone of the physis may produce irreversible damage to the growing cells, resulting in growth disturbance. Physeal cartilage is exceptionally susceptible to injury for many reasons. Compared to adult articular cartilage, physeal cartilage is more susceptible to stress forces. The physis may be 2–5 times weaker than the surrounding fibrous tissue, so growth plates fail before ligaments, opposite to adult fracture patterns. Physeal cartilage is also more prone to tension and shear forces than adjacent bone.^{5–7} Fracture involving the growth plate was first described in 1963 by Salter and Harris, and the described Salter-Harris classifications system is the most widely used.⁸ Fig. 1.

3. Anatomy of physeal injury

Type 1 fracture involves extension through the hypertrophic zone of the physis Fig. 2. In these fractures, the physeal germinal

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Fig. 1. Salter Harris classification.

cells remain with the epiphysis and the calcified layer with the metaphysis. Type II injuries account for more than half of all physeal fractures and are the most common physeal injuries. Type II injuries extend through the hypertrophic zone and exit through a portion of the metaphysis, generating the characteristic triangular metaphyseal Thurston-Holland fragment.⁹ As long as no vascular compromise exists and the germinal cells are retained with the epiphysis, the prognosis for the first two types of fractures is often good, with minimal incidence of growth disturbance.^{10–16}

Unlike Type I and II fractures, type III and IV fractures involve the reserve zone and as a result present with an increased risk of irreversible growth arrest. This may be a result both of injury to the germinal cells of the physis as well as resulting physeal bar formation, tethering the epiphysis to the metaphysis. Physeal injuries are more common with increasing age, and it is more pronounced in boys,¹ due to increased vigor of activities, and relative weakness of the physis near puberty. The peak incidence of physeal fractures is 11 years for girls, and 12 years for boys. Type III injuries are more common in older children and generally convey a moderate prognosis if the vascular supply to the epiphyseal fragment is not compromised, there is no displacement of the fracture, and there is no injury to the germinal center. While the displacement may be evaluated on radiographs, the impact of the degree of displacement on prognosis is not well-understood. Furthermore, integrity of the vascular supply and ultimate injury to the germinal center cannot be easily assessed. While type III fractures do not always necessitate surgery, restoration of the articular surface is imperative. Type IV injuries inevitably damage the germinal layer and require surgical intervention to align the physis as well as the articular surface. Type V fractures are the most severe class and occur due to a crush injury to the germinal physeal layer. This commonly results in growth arrest; however, type V fractures are perhaps the most difficult to diagnose acutely and may only be evident once a patient has been followed longitudinally. Any insult to the reserve zone and germinal chondrocytes may result in premature growth arrest. Trauma, congenital conditions (e.g. Blount's disease), infection, neoplasm, irradiation, metabolic/hematologic abnormalities, ischemia, disuse, and

iatrogenic injury have all been described as etiologies of growth arrest.¹⁷ Prolonged ischemia such as in septic shock or vascular injury to the limb may result in damage to or loss of the reserve layer of the physis.¹⁸ Infection of the spongiosa often spares the reserve zone¹⁹; however, septic arthritis or subperiosteal abscess can directly compress the epiphyseal vasculature resulting in ischemic necrosis of the germinal chondrocytes of the reserve zone.²⁰ Iatrogenic injury due to trans-physeal fixation techniques is well described.²¹

4. Presentation and evaluation

A thorough history and physical examination is critical. In the setting of trauma, poor prognostic indicators include high-grade Salter-Harris fractures (Type III or IV), high-energy trauma, numerous reduction attempts, poor final reduction, characteristically distal femur and tibial fractures, and greater initial displacement.²²

Radiography remains the best method to evaluate physeal injuries.²³ After physeal injury has been established, repeat radiography is recommended every 3 months until normal growth has been documented for at least 6 months. CT and MRI can elucidate more information concerning size, location, and shape of associated physeal bars^{23,24}; however, CT is not a first-line tool due to its limited effectiveness in the evaluation of soft tissues and concern of radiation exposure.²⁵ Although both CT and MRI are useful for detecting and determining size of bony bridge, MRI has the added benefit of providing various sequences allowing for additional information concerning abnormalities in cartilage (ex. non-ossified cartilage bar requiring further intervention) and surrounding soft tissue injury.²⁵ MRI has no risk of radiation exposure. Three-dimensional MRI may also be used for evaluating growth plate injury and allows for accurate measurement of the physeal bar.²⁴ The best sequence for preoperative physeal bridge imaging is thought to be fat-suppressed 3D spoiled gradient echo-weighted MRI.²⁶ Recently, the use of intraoperative computer-assisted navigation has been used to adequately identify the bony bar.²⁷

Fig. 2. Physeal injury type1 (extension through the hypertrophic zone of the physis).

5. Management

The ultimate goals of treatment are to restore limb length and mechanical alignment, mobilize adjacent joints, and correct deformity without subsequent cosmetic or functional deficiency. Several treatment options exist, each with their own advantages and disadvantages. The general management strategies include **physeal bar excision**, **epiphysiodesis**, **chondrodiastasis**, and **limb lengthening or deformity correction with circular fixation**, or a **combination of these techniques** (Table 1).

Table 1

Treatment options for growth arrest.

1- Physeal bar resection
1- Epiphysiodesis
2- Chondrodiastasis
3- Limb lengthening and deformity correction

5.1. Physeal bar excision

Younger children with significant physeal growth remaining may respond well with bar resection; however, gaining access to the bar and ensuring complete resection may be difficult. Physeal bar resection is primarily used when there is tethering of the growth plate, and resection can restore normal growth of the epiphysis if physeal arrest is detected early and deformity has not developed. Most authors agree that the indications for physeal bar resection include: a documented existing or developing deformity with at least 2 years of growth remaining, 25–40% of the physis is affected, and at least 1 year free from drainage if the physeal bar was secondary to infection.²⁶ If the patient has a significant angular deformity, a corrective osteotomy can be considered, as spontaneous correction is unpredictable.¹⁹ The indication for concomitant osteotomy varies by author from an angular deformity of greater than 10° to greater than 25°. The decision to perform a corrective osteotomy with partial bridge resection should be based on the severity of the deformity, the area of physeal bridge, and the patient's remaining growth potential (Table 2). The goal of treatment with this modality is to remove the bony/fibrous bar and to fill the defect with a material that prevents recurrent bony bar formation. The surgical approach to bar resection is important, as the bony bridge needs to be completely resected with the least trauma to surrounding tissues as possible. The bridge must be well visualized and identified for acceptable resection. With computer-assisted guidance, information from CT images allow for highly accurate real-time 3D monitoring of the bony bridge as an alternative to fluoroscopic visualization. Techniques for removal of the bar depend upon the location of the bridge. Peripheral bridges are approached directly, with excision of the overlying periosteum from the junction of the bridge and the intact periosteum across the extent of the bridge. Central bridges can be approached either through a metaphyseal window or through a metaphyseal osteotomy adjacent to the bridge, with curettage of the cancellous bone down to the bridge. A high-speed burr is used to completely remove the physeal bridge once it has been located.²⁶ To prevent thermal damage to the bone, alternating burring, irrigation, suction, and arthroscopy is used during excision of the physeal bridge.^{28,29} The surgical field must be dry for proper arthroscopic visualization to avoid any obscuring effects of blood in the irrigation fluid.²⁸ After excision of the bridge, insertion of metallic markers on either side of the physis is essential for subsequent follow up to differentiate growth of the affected physis from overgrowth of the physis at the other end of the same bone. Different marker types such as transverse small Kirschner wires, small vascular clips, and small bone anchors without sutures have been used with some success, but the preferred markers are titanium Kirschner wires as they are MRI compatible. The markers should be inserted into the cancellous bone parallel to the physis in the plane of deformity, and in the ossified center of the epiphysis, not in the cavity created by the recent excision²⁶ (Table 3). It is essential in all bridge excisions to visualize complete resection of the bony bridge to prevent recurrence of bony deformity. Traditionally, a small dental mirror was used to visualize the bony bridge^{26,28}; however, anatomical issues described by Birch et al., including the obstruction of view to the physis due to muscles, tendons and joint capsule, make visualization of the physeal bar very difficult.³⁰ More recently, the arthroscope has been reported to have better visualization in central physeal bridge resection, while also allowing for a smaller size of the metaphyseal window.^{31,32} Using this technique, Marsh and Polzhofer²⁸ reported excellent results in 70% (21/30) of patients, good results in 17% (5/30), and poor results in 13% (4/30). These authors stated that the inherent light source of the arthroscope and ability to magnify images provides the best

Table 2

Indications for bar resection.

- 1- Bar size 25–40%
- 2- >2 years of growth remaining, we calculate the bone age by x ray of left hand
- 3- At least one year free from drainage if the physeal bar was secondary to infection

Table 3

Tips for bar resection.

- 1- Mapping the location of physeal bar using CT/MRI
- 2- Metaphyseal window for central bar—direct approach for peripherally located bar
- 3- Consider arthroscopy for visualization with minimal morbidity
- 4- Use dry scope/c arm/dental mirror/computer navigation to check complete resection of bar
- 5- Interpositional graft: fat graft/artificial dura/cranioplast cement/Polymethylmethacrylate (PMMA)
- 6- Marker to monitor the resumption of growth (Kirschner wires, small vascular clips, and small bone anchors without sutures)
- 7- Concomitant osteotomy depending on the degree of deformity

visualization with minimal morbidity. Moreta reported excellent results in 40% (2/5) of patients, good results in 20% (1/5), and poor results in 40% (2/5).³² Moreta attributed the poor outcomes to high energy trauma mechanisms and incorrect initial treatment or delayed physeal bridge resection. Surgeons managing physeal arrest using physeal bar resection should consider utilizing the arthroscope as it can assist in this already technically demanding technique and may lead to higher success.³²

To prevent physeal bridge reformation, interposition material should be used to fill the cavity left by the physeal bar excision, preventing contact between the adjacent metaphysis and epiphysis. Polymethylmethacrylate (PMMA) has been used as interpositional graft; however, PMMA alone generates heat and causes more damage to the growth plate.¹⁶ Instead better options exist to facilitate remaining growth: cranioplast cement; artificial material, like dura, to avoid reformation of the growth bar; or autogenous fat may be used as interpositional graft. Interpositional fat, while advantageous because it is autogenous, does have some drawbacks as it does not provide structural support to the weakened bone and requires postoperative immobilization, and it is associated with poor hemostasis in the bone cavity.²⁶ Osterman compared interpositional bone wax, fat, and cartilage after physeal bar resection in rabbits. His study reported heterogeneous cartilage transplant yielded the best results in terms of maintenance of longitudinal growth and prevention of angular deformity. The study also discussed how fat grafts can be used successfully but carry the risk of partial necrosis and displacement, leading to hematoma formation and bony bridge recurrence.³³

There is a good prognosis for physeal arrests less than 10% of the growth plate while physeal arrests greater than 25% of the growth plate carry a poor prognosis.³⁴ Williamson and Staheli conducted 29 primary physeal bar resections in 28 patients. Each patient was followed up for 2 years and 65% (11/28) showed excellent, 12% (2/28) fair, and 23% (4/28) poor results. These authors achieved an overall mean growth of 83% using physeal bar resection.³⁵

5.2. Epiphysiodesis

If physeal bar >50%, excision is not viable due to the bony bridge size, epiphysiodesis can be used to prevent the occurrence of disabilities such as gait abnormalities and abnormal loading on

joints.³⁶ A combination of ipsilateral epiphysiodesis to prevent progressive angular deformities, and contralateral epiphysiodesis to prevent limb length discrepancy (LLD) can be performed. Central physeal arrest has been best managed with contralateral epiphysiodesis.³⁷ In patients with LLD, epiphysiodesis is indicated when the projected discrepancy at bone maturity is between 2 and 5 cm, as LLD less than 2 cm is likely to be asymptomatic and LLD greater than 5 cm will require a limb lengthening procedure of the short limb (Table 4).^{36,38}

Epiphysiodesis is a relatively simple technique that can consistently produce a full physeal arrest. The success of the procedure is largely determined by its timing with the patient's bone maturity to avoid under or overcorrection. Commonly used methods to predict remaining bone growth include: the modified and original Anderson-Green Growth Remaining charts, the Menelaus arithmetic method, the Moseley straight-line graph method, and the Paley multiplier method.^{38–39} While none of the methods are accurate in predicting the final LLD at maturity with surgery, a combination of multiple methods of calculation, repeated measurements, and comparison with the patient's growth pattern and Tanner stage can be used to optimize timing of surgery.³⁴ There are multiple operative techniques to epiphysiodesis. The original technique described by Pheister was an open procedure in which a 1 cm block of cortical bone containing the physis and adjacent metaphyseal and epiphyseal bone was excised. The physis was then curetted and the bone block was reinserted in a reversed 180-degree position, creating a permanent physeal arrest.⁴⁰ This technique has since been abandoned in favor of a minimally invasive percutaneous approach. Permanent methods of percutaneous epiphysiodesis include ablation of the physis with drilling and curettage. Reversible methods of epiphysiodesis include physeal stapling (Blount's staples), guided growth plates (ex. The 8-plate of Orthofix, the Peanut plate of Biomet, PediPlates of OrthoPediatrics, and the Hinge-Plate [Pega-Medical, Quebec, Canada])⁴¹ Fig. 3, and transphyseal screws (PETS) placed obliquely across the physis.⁴² Independent studies of each of these techniques show satisfactory growth arrest and generally low rates of complications.³⁶ The more common complications of epiphysiodesis include infection, recurrent deformity, hardware malfunction, and failure of physeal arrest.^{36,41,43} A study by Stevens and Klatt found a 45% incidence of staple migration in 53 staplings,

Table 4

Indications for epiphysiodesis.

- 1- Physeal bar >50%
- 2- Projected LLD between 2 and 5 cm
- 3- Central physeal arrest → contralateral epiphysiodesis
- 4- Peripheral physeal arrest → ipsilateral epiphysiodesis w/contralateral epiphysiodesis

Fig. 3. Peanut Plate of Biomet.

and no reported hardware malfunction in 15 eight-platings, suggesting that eight-plates are preferred over staples.⁴¹

5.3. Chondrodiastasis

Physal distraction, or chondrodiastasis, is another method for correction of deformities caused secondarily by physal bar. This method involves the use of external fixation and progressive lengthening to provide a force directly at the site of the growth plate, allowing distraction and accompanying regenerate bone to correct any limb length/angular deformities. The physal bar can be broken intraoperatively by overdistracted or by twisting after frame application. With the overdistracted technique, the patient is able to feel the bar breaking, which may cause them discomfort. The external fixator is anchored above and below the physis and incrementally adjusted at a slow and controlled rate that allows for preservation of the epiphyseal cartilage. Both unilateral and Ilizarov type circular external fixator apparatuses have been successfully used to correct limb length discrepancy and angular deformity.^{44,45} Zarzycki described a few occurrences of axial deviation associated with the unilateral external fixators, and therefore suggested that the Ilizarov technique was the preferred method.⁴⁵ Because this technique uses the growth plate as the zone of least resistance, no osteotomies are required, physal bar excisions are not necessary, and the vascular supply to the regenerative tissue is fully retained. This procedure is controversial as there does not seem to be a consensus in the current literature regarding the relationship between physal distraction and premature fusion of the growth plate.

Bjerkreim reported premature cartilage fusion in all 10 of his upper tibial physal distraction patients,⁴⁶ and Eydelshetyn et al. reported 4 cases of premature cartilage fusion in 33 of his patients.⁴⁷ Meanwhile, Zarzycki et al. reported no instances of premature cartilage fusion in their studies of 40 physal distraction procedures,⁴⁵ and Givon reported three cases of successful bilateral proximal tibial hemichondrodiastasis in patients between the ages of 3 and 7.⁴⁸

De Bastiani discussed that in children who underwent limb elongation at younger than 10 years old, the lengthened limb grew at a slower rate than the normal limb, suggesting that the issue

may not be premature growth plate fusion but instead reduced growth plate function.⁴⁹ Because of this, most authors suggest reserving chondrodiastasis for adolescents approaching skeletal maturity who have a highly predictable limb length discrepancy.^{44,46,47,49}

Langlois reported a mean length gain of 4.75 cm and a mean angular correction of 22.2° in a study of 20 chondrodiastasis and hemichondrodiastasis procedures.⁴⁴ Zarzycki et al. reported an average lengthening of 4.6 cm in 24 patients who underwent femoral physal distraction and 4.7 cm in 16 patients who underwent tibial physal distraction.⁴⁵ The rate of distraction is easy to control, patients can bear weight early, and there is minimal impact on patient quality of life immediately post-operation.⁴⁹ Complications associated with chondrodiastasis include pin tract infection, osteolysis at the site of direct trauma from fixation screws, axial deviation, and joint immobilization.^{44,45,49}

5.4. Deformity correction: gradual vs acute correction

Deformity correction can correct any subsequent angular deformities, while the lengthening can correct short stature and leg length discrepancies. Techniques to lengthen include unilateral external fixation for simple lengthening over short/medium distances, circular fixators for three-dimensional complex deformities, mechanical or motorized intramedullary nails, and lengthening over nail, which combines external fixation with intramedullary nailing.⁵⁰ Taylor Spatial Frame (TSF, Smith & Nephew, Memphis, TN), a modified Ilizarov apparatus that combines a rigid hexapod fixation system with a web-based software program, was introduced to treat more complex limb deformities. In a study conducted by Manner et al., the aim of deformity correction was achieved in 90.7% (117/129) of patients in the TSF treatment group, compared to 55.7% (44/79) of patients in the IRF treatment group. Kucukkaya studied the effectiveness of the TSF in complex limb deformities, including rotational/translational deformity and nonunion with excellent clinical results. In 13 tibial and 5 femoral segments, the mechanical axis reached normal limits, and complete consolidation was achieved in all osteotomized segments.⁵¹

5.4.1. Case 1

A 13-year-old girl with history of trauma to the right lower extremity 3 years earlier (Fig. 4A). The patient started to notice gradual deformity of the right knee (hyperextension of the knee or knee recurvatum) (Fig. 4B). Radiographs of both knees show the closure of the anterior part of the physis of the proximal tibia in the right knee (Fig. 4C), while the growth plate is still open (active) in the left knee (Fig. 4D). This premature closure of the right proximal tibial physis was due to type V physeal injury of the proximal tibial physis that result in partial closure of the anterior part. As the tibia continued to grow from the posterior part only, the deformity developed. Posterior proximal tibial angle on the affected side was 117 and 82 on the normal side. Proximal tibial osteotomy was performed with application of the ring type of external fixator (Fig. 4E). Gradual correction was obtained. Final radiographs show healing of the osteotomy and correction of the proximal posterior tibial angle to 84 (Fig. 4F,G).

5.4.2. Case 2

11 years old boy, had distal ulnar physeal arrest due to previous injury. Patient had wrist deformity with subluxation of the distal radioulnar joint. Proximal ulnar osteotomy was performed with application of uni planar fixator. Gradual lengthening of 1.7 cm was obtained with correction of the wrist deformity and reduction of the distal radioulnar joint (Fig. 5A–C).

Motorized intramedullary nails have been introduced as a method to provide bone fragment stabilization and lengthening

without the need for external fixation. Several devices have been developed like the Fitbone (Wittenstein, Igersheim, Germany), Albizzia (Depuy, Villerbuane, France), Intramedullary Skeletal Kinetic Distractor [ISKD] (Orthofix, Inc., McKinney, Texas), and the PRECICE nail (Ellipse Technologies, Irvine, California). The only devices approved by the US FDA are the ISKD and PRECICE nail. The ISKD is made of unidirectional telescopic distraction rods that are activated by rotation of the limb segment, while the PRECICE nail is controlled by a handheld external electromagnetic activator, and can be lengthened or shortened depending on the goals of treatment.⁵² The ISKD has been documented to have significant complications secondary to poorly controlled distraction.⁵³ Paley described high rates of accuracy of distraction with the first generation PRECICE nail, with very few reports of mechanism breakage or failure.^{54,55} After some changes in the nail design, the PRECICE 2 was released in November 2013, and there have been no further failures of distraction in over 150 cases.⁵⁶

Feldman et al. compared the accuracy of correction of tibia vara using acute intraoperative correction versus gradual postoperative correction. The study compared 14 patients whose tibia vara was corrected acutely and held using an EBI external fixator to 18 patients whose tibia vara was corrected gradually using Taylor Spatial Frame and 6-axis deformity analysis. The results showed that gradual correction of limb deformity appears to achieve more successful and accurate results compared to acute correction.⁵⁷

Complications associated with distraction lengthening include muscle contractures due to distraction-generated tension or pin

Fig. 4. A: AP and Lateral x-rays of the original injury (fracture midshaft femur). B: Knee valgus and recurvatum 3 years after the initial injury. C: Yellow arrow represents the closure of the anterior tibial physis. The posterior proximal tibial angle on the affected RT side is 117. D: Red arrow represents the anterior tibial physis still intact on the unaffected side. The posterior proximal tibial angle on the unaffected side is 81. E: High tibial osteotomy with application of TSF. F: AP and Lateral 3 months postoperative x-rays showing the gradual correction of the deformity. G: AP and Lateral 6 months postoperative x-rays showing the final correction of the deformity with removal of the TSF and application of a cast.

Fig. 4. (Continued)

transfixation of the muscles and tendons, joint subluxation, axial deviation, neurologic and vascular injuries, premature or delayed consolidation, pin site infections, and fracture through the regenerate.⁵⁸

6. Future directions of treatment

The future of treatment of physeal bars aims at finding treatment options that allow for complete regeneration of physeal cartilage defects and avoidance of limb length/angular deformity. Many different aspects of achieving this ultimate goal are currently under investigation utilizing animal models.

The use of mesenchymal stem cells (MSC's) in growth plate injuries has been widely studied in animal models. MSC's can easily be harvested from many tissues including adipose tissue, muscle, synovium, and periosteum. Due to their multipotent nature, MSC's have the ability, when under the proper stimuli, to differentiate into many different musculoskeletal cells, including chondrocytes.

Much research has been performed to evaluate the proper source, environment, and placement that could allow regeneration of chondrocytes in place of physeal bars. Hui et al. found that MSC's derived from bone marrow and periosteum were most effective at differentiating into physeal chondrocytes and correcting tibial limb length deformities in New Zealand white rabbits.⁵⁹ Both allogeneic and autogenic transplantations of MSC's for treatment of physeal defects in rabbits have been found to be efficacious, with no significant differences between the two grafts.⁶⁰ Additionally, Foster et al. showed that in some cases transferred chondrocytes could prevent bony bridge formation in the sheep model.⁶¹ These findings were supported by Chen et al., who used cultured MSCs from periosteum and showed significant reduction in growth arrest of the rabbit tibia.⁶²

Current research with MSC's involves the use of scaffolds to provide an infrastructure for the cells to colonize and become a bioactive vehicle. Many different scaffolds have been studied including Gelfoam, agarose, sodium hyaluronate and type I

Fig. 5. A: AP, Oblique, and Lat x-rays of the hand and wrist joint showing ulnar shortening due to physal injury. B: Osteotomy with application of uni planar external fixator to correct the shortening. C: Anteroposterior and lateral radiographs demonstrating lengthening of the ulna with consolidation of the regenerate.

collagen, chitin, and type I collagen with chitosan micro and nano fibers. No significant differences in outcomes have been observed due to the type of scaffold alone. Although many in vivo ovine, porcine, and rabbit studies have shown good results in the ability to treat physal defects with MSC's, many of the accessory details of the stem cell cultivation and transplantation process are still being actively studied. These details include determining the optimal density of MSC's based on the physal bar's qualities (size, location, etc.), role of TGF β and FGF in pre-differentiation and proliferation of MSC's, the best material and pore size of scaffolds, and the prochondrogenic effects of dynamic compression and hypoxia on MSC's proliferation.⁶³

7. Summary

Early recognition of physal arrest is critical in order to ensure timely and effective management. Surgical intervention depends on several factors including skeletal age, growth potential remaining, and qualities of the physal defect. Although many different surgical techniques are currently utilized, including image-guided and arthroscopic physal bar excision, chondrodiasis, epiphysiodesis, and limb lengthening, none of these can regenerate the damaged physal tissue. Future directions involve utilizing mesenchymal stem cells to replace and regenerate defects caused by insult to the growth plate and physal bars.

Conflicts of interest

The authors have no conflict of interest to report.

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