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Sonographic Monitoring During Distraction Osteogenesis

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Abstract

Distraction osteogenesis is a method of bone healing and regeneration widely used to correct bone malformations, shortenings, and other bone defects. Despite its benefits, it is a long-duration therapy with considerable physical and psychological morbidity. Treatment optimization is fundamental and monitoring techniques are being studied. This chapter discusses monitoring methods with a focus on ultrasound evaluation of distraction osteogenesis.

Keywords: sonographic monitoring, distraction osteogenesis, bone regeneration

1. Introduction

The distraction osteogenesis is a method of bone regeneration and fixation that was established by Ilizarov around the 1950s, causing revolution in the reconstruction and deformity correction surgeries [1]. The technique consists of a controlled bone fracture (osteotomy) and, after the formation of the soft callus (latency period), continuous traction of bone fragments in opposite directions, using an external fixator (lengthening phase), until the desired extension is reached, then fixing it until consolidation (neutral fixation/consolidation phase). This process does not use grafting and allows to cover extensive bone defects with newly formed bone (regenerated) or to remodel malformed structures. Nowadays it is applied in multiple ortho-

pedic and maxillofacial surgeries. However, it is a long-duration therapy and the patient may remain in use of an external fixator for a period of up to 20 weeks.

The treatment duration generates great physical and psychological morbidity. Its importance was recognized by Ilizarov himself when he postulated: “keeping the apparatus for longer than necessary is as damaging as removing early” [2]. Therefore, the optimization of therapy is fundamental to reduce the complications and ensure its success. For that reason, the distraction osteogenesis monitoring must be realized. Several methods are available, with some being more suited to each phase. The histological characteristics of the regenerated tissue in each phase are fundamental for the comprehension of the monitoring methods, as we see later.

1.1. Latency period

Latency period consists in the physiological tissue repairing response initiated immediately after the osteotomy. The lesion unleashes an inflammatory reaction with clot formation

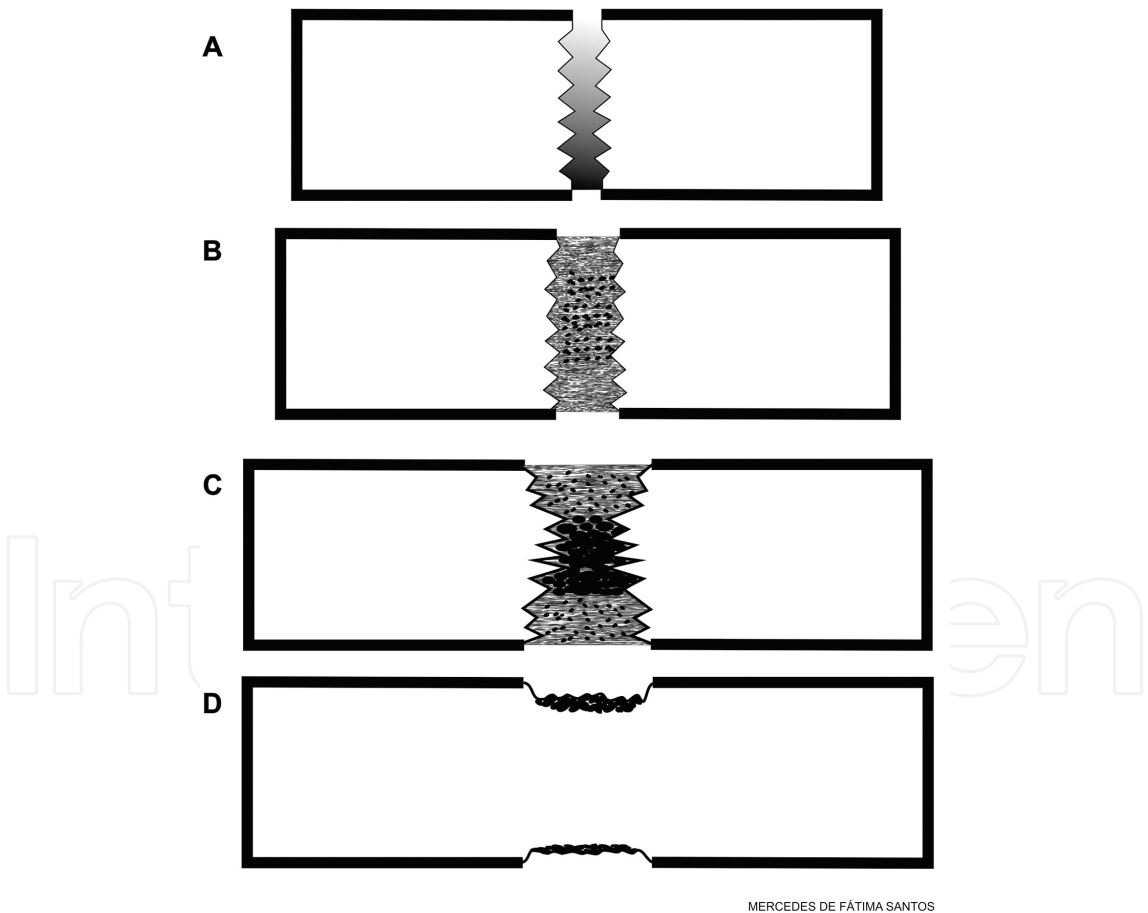


Figure 1. Distraction osteogenesis scheme. (A) Osteotomy, (B) gap increase with ossification centers (black dots), (C) progressive gap increase, confluence of ossification centers, and peripheral bone formation and (D) hard callous bridging the gap with mild corticalized margins and central invagination.

between and around the osteotomy segment and cytokine activation, growth factors, and mesenchymal cellular aggregation. A granulation tissue is formed, consisting of extracellular matrix rich in fibrin, collagen, neutrophils, fibroblasts, and cells with osteogenic potential [3]. This set is called soft callus (see **Figure 1**).

The goal of this phase is the formation and maturation of the soft callus, with sufficient neovascularization to stimulate ossification. Classically, its duration is established around 5–7 days. There is no need for monitoring in this phase.

1.2. Lengthening phase

After the latency phase, the distraction apparatus is activated and the soft callus is strained initiating several osteogenic processes. The straining produced in the longitudinal axis alters the cellular expression in the soft callus. At the gap center, high strain forces inhibit cellular differentiation and stimulate its proliferation. In the extremities, strain forces are milder, thus allowing cellular differentiation. Therefore, the callus center has high cellular density composed of precursor mesenchymal cells (fibroblasts and pre-osteoblasts), while the extremities are paucicellular and composed mostly of osteoblasts. Hence, the osteogenesis process occurs from the deeper region of the extremities toward the center and surface [3, 4].

The formation of bone tissue is modulated by the rate of distraction and its rhythm. The first is the total length gain in a day, which varies from 0.5 to 1.0 mm/day; the second refers to the number of daily activations to reach the desired length, varying from two to four activations per day. Excessive traction tends to stimulate the formation of cysts and fibrous tissue, reducing the resistance of the regenerated tissue; on the other hand, less traction leads to precocious consolidation, making it impossible to achieve the desired length [5].

1.3. Consolidation phase (neutral fixation)

Reaching the desired length, the external fixator is locked, fixing the bone extremities and ensuring proper support during the consolidation period. The apparatus must remain in position until the regenerated tissue is sufficiently consolidated to avoid complications such as deformations or post-distraction fractures. The duration of this period is usually defined as the number of the days of the lengthening phase multiplied by two (lengthening phase $\times$ 2). This rule, however, does not avoid the occurrence of complications, making other parameters of evaluation necessary.

2. Monitoring methods

Several complementary methods can be used to follow the evolution of the procedure, each one with advantages and disadvantages, depending on the phase of the process.

2.1. Ionizing radiation

X-ray, dual energy X-ray absorptiometry (DEXA) and computed tomography can be utilized for the evaluation of the bone callus. However, the necessity for a serialized evaluation, exposure to ionizing radiation, metallic artifacts susceptibility, and the high cost and more restricted availability of computed tomography and DEXA limit the utilization of these methods.

The X-ray is the most used, because it allows proper evaluation of the bone extremities and distraction distance (gap). Using the “three cortical rule,” where the visualization of at least three corticals with 2 mm thickness on orthogonal views is necessary, the removal of the external fixator is indicated [6, 7]. Yet, it was observed that this method is subject to great observer variation, not being more accurate than random chance [8]. Other limitations are related to the initial stages where radiography is incapable of evaluating soft tissue.

Studies valued the role of DEXA in the evaluation of the regenerated tissue, from the lengthening stages until its attempt to objectively define the best moment to remove the external fixator. Some research parameters include the relation between the regenerated bone mineral density and contralateral limb, and also the percentage of the weekly increase of bone mineral density [9, 10]. Despite promising results, there is still no standardization of these parameters.

The quantitative computed tomography (QCT) sums the quantitative evaluation with high-resolution images of regenerating bones, presenting better correlation than the DEXA and allowing a global evaluation to the assistant doctor. However, high cost, little availability, and great exposure to radiation (more than the other methods) limit its application [1].

2.2. Ultrasonography

Recently, the role of ultrasonography in the monitoring and distraction has been target of several studies. Several characteristics make this a method of interest, as it does not use ionizing radiation, it is widespread, and it is not subject to artifacts related to external fixators. The top advantage is the possibility of characterization of soft tissue and precocious detection of complications like cysts and collections.

For the ultrasonographic evaluation, linear transducers for high resolution must be used (5–12 MHz). The osteotomy is evaluated with beams perpendicular to the bone corticals, longitudinally and transversely along the bone axis. In the initial evaluation, the ultrasonography identifies the osteotomy corticals as hyperechoic surfaces, with posterior acoustic shadow and acute margins. Between them is located the soft callus, defined as a hypoechoic area with great penetration of the ultrasonographic beam [11]. (see **Figure 1**)

In the first weeks, the appearance of echogenic outbreaks longitudinally oriented in the interior of the “gap” is noticed. In the cross-sectional assessment, there is a “cut wire” aspect. Between 2 and 4 weeks, the first individualized ossification center starts to be identified. Over time, there is an increase in number and size of those centers with the tendency to confluence on the longitudinal axis. Gradually, there is loss of penetration power in the callus and rounding of

the edges of osteotomies. After 6–8 weeks, it is defined a cortical margin with mild central invagination and thickness markedly reduced in relation to the osteotomies corticals [12].

With the progression of the corticalization, the ultrasound beams are gradually more reflected, thus losing the correlation between the method and characterization of changes in the stiffness and strength of the regenerated tissue (attenuation $\times$ reflection) [13]. Eventually, the beams' reflection will be full, preventing the evaluation continuity with this method. Therefore, ultrasound assessment is limited in the final stages of consolidation and there are no studies in literature investigating its role establishing enough bone healing for the apparatus removal [1].

The ultrasound appearance during the entire process was compared with tissue density measurement with computerized tomography, evidencing an exponential increase in bone density through the consolidation time [14], but no objective ultrasound parameter was proposed as a follow-up measure. Ultrasound evaluation itself is mainly subjective and prone to multiple variables as transducer position and measurement site [15]. Troulis et al. proposed the use of through-transmission method, in which the beam penetration depth in the soft callus is used as the stiffness indicator. But in his work through transmission was compared with the surgeon's intraoperative bone stiffness evaluation, which was also subjective [16]. The lack of objective parameters to assess bone mass index limits its application as a monitoring method.

Quantitative acoustic parameters (ultrasonometry) and its correlation with soft callus properties have been studied. Velocity propagation across the gap correlates with bone healing [17], while speed of sound, acoustic reflection, and attenuation correlate with trabecular bone mass index [18] and acoustic backscattering relates to trabecular microstructure [19]. Strong association between the penetration depth within the gap and maximum load and torsional stiffness of the consolidated callus has been shown. With noninvasive, radiation-free, objective data, follow-up protocols can be studied and early therapy modifications (distraction rate, medications) may optimize the distraction and consolidation processes.

3. Conclusion

The monitoring of the osteogenesis distraction is fundamental to avoid complications and reduce the time of use of the external fixator. Several methods are available, each one presenting advantages and disadvantages. The ultrasound seems like an excellent method in the initial evaluation of distraction; however, it is incapable of orienting objectively the moment of removal of the external fixator. The methods using ionizing radiation present several possibilities, but lack in objective and standard data limits its application. Considering these factors, a multimodal evaluation of the progression of the treatment, conciliating clinical expertise, and the rational use of the available complimentary exams for the optimization of the treatment must be used.

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