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Bone Maturation: A Literature Review

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Abstract

Bone maturation is the process of ossification development that takes place during childhood and adolescence as somatic growth occurs, and it allows determining the biological development of the patient in a more reliable way than chronological age. This analysis is performed through radiographs that show the modifications in the bones throughout growth, and although the process of change is similar for all bones, the specific events that occur are independent of chronological age. Therefore, the aim of this literature review was to describe the main indices of bone maturation because they play a crucial role in the planning and execution of effective orthodontic treatments, which underlines the need for a thorough understanding of this process in clinical practice.

Keywords: Bone maturation; Bone age; Bone maturation indicators

1. Introduction

Bone maturation is an essential biological process that involves the development and growth of bones over time, undergoing significant transformations in their structure and composition [1]. This process is not only crucial for skeletal growth, but also allows us to contrast the biological age of an individual with their chronological age, which is fundamental in various medical disciplines, especially in orthodontics as it allows professionals to predict the time of pubertal growth and estimate the rate of growth, which is vital for initiating treatments at the right time [2,3].

There are several indices to assess bone maturation, with the Cervical Vertebral Maturation Assessment (CVAM) method being one of the most widely used. This method is based on the morphology of the cervical vertebrae and has been developed and refined by researchers such as Baccetti and Franchi, who established specific criteria to classify the stages of maturation according to the morphology of the vertebral bodies [4,5]. However, there are other methods to assess bone maturation such as the hand and wrist index, proximal femur and pelvis, and palatal suture.

2. Theoretical framework

2.1. Concept

Bone maturation is the process which bones develop and grow over time, undergoing transformations in their structure and composition. This process is essential for skeletal growth and for comparing a person's biological age with their chronological age.[1,2]

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2.2. General

Bone maturation is essential in orthodontics to establish the biological age and predict the peak of growth, allowing treatments to be initiated at the right time. Its evolution depends on genetic, hormonal (such as growth and sex hormones) and environmental factors (nutrition, physical activity, sun exposure), and varies among individuals and ethnic groups. This maturation develops in stages that include cartilage formation, ossification, mineralization and bone fusion. In addition, there are differences in radiation exposure according to the bone assessment method used, being higher in the analysis of carpal bones than in the analysis of cervical vertebrae. [2, 3]

2.3. Bone maturation age

The analysis of bone age is the best indicator of physical maturation, it allows to determine the biological development of the patient, being a more reliable method than chronological age in the evaluation of growth and development of the human being. [2]

In order to identify the age at which bone maturity is reached, it is necessary to know several methods focused on the study of bone and the changes found throughout the years. During growth the bone presents modifications that can be evaluated radiographically. The process of change for each bone is the same. However, the events that occur in it are independent of chronological age.[2]

Factors influencing bone maturation

The speed and type of bone maturation are conditioned by the interaction of genetic and environmental factors.

Genetic factors determine the rate and order of maturation in each of the bones, with the genetic influence of sex, factors of autosomal origin and the specificity of the race, within the environmental factors it is affected by malnutrition and chronic diseases. [4]

2.4. Bone maturation indicators

2.4.1. Cervical vertebrae indicator

The method of Cervical Vertebral Maturation (CVM) method, based on the morphology of three cervical vertebrae, is a common approach for predicting the timing of pubertal growth, as well as for estimating growth velocity and growth ratio. [5]

In 1972, Lampariski, O'Reilly and Yanniello in 1998, Franchien in 2000 and Baccetti in 2002 proposed that cervical vertebrae that can be seen on a lateral skull radiograph are effective for growth assessment.

The CVM was developed by Baccetti, Franchi and Mcnamara in 2005. The evaluation criteria of this method are described according to the body morphology of the C2, C3 and C4 vertebrae and consist of six parameters for classification of maturation stages. [2]

2.4.2. Baccetti's method

When analyzing the morphological characteristics, two parameters that determine the 6 stages of maturation were taken into account.

Stage CS1

All the lower edges of the vertebrae are flat, C3 and C4 are trapezoidal in shape. The peak of mandibular growth occurs 2 years after this stage.[1]

Figure 1 Diagram of the CS1 maturation stage. [1]

Stage CS2

The lower border of C2 has a concavity. C3 and C4 remain trapezoidal in shape. The peak of mandibular growth begins 1 year after this stage. [1]

Figure 2 Diagram of the CS2 maturation stage. [1]

Stage CS3

The lower edge of C2 and C3 has concavity. The bodies of C3 and C4 may be trapezoidal or horizontal rectangular in shape. The peak of mandibular growth begins at this stage. [1]

Figure 3 Diagram of the CS3 maturation stage. [1]

Stage CS4

All the edges of the vertebrae show concavities. C3 and C4 show horizontal rectangular shape. The peak of mandibular growth ends at this stage or has ended one year before this stage.[1]

Figure 4 Diagram of the CS4 maturation stage. [1]

Stage CS5

All the inferior borders of the vertebrae present concavity. At least one of the bodies of C3 or C4 is square in shape. If not square, the body of the other cervical vertebra remains horizontal rectangular. The peak of mandibular growth has ended 1 year before this stage. [1]

Figure 5 Diagram of the CS5 maturation stage. [1]

Stage CS6

All vertebral bodies show obvious concavity. At least one of the bodies of C3 and C4 shows vertical rectangular shape. The peak of mandibular growth has ended 2 years before this stage.[1]

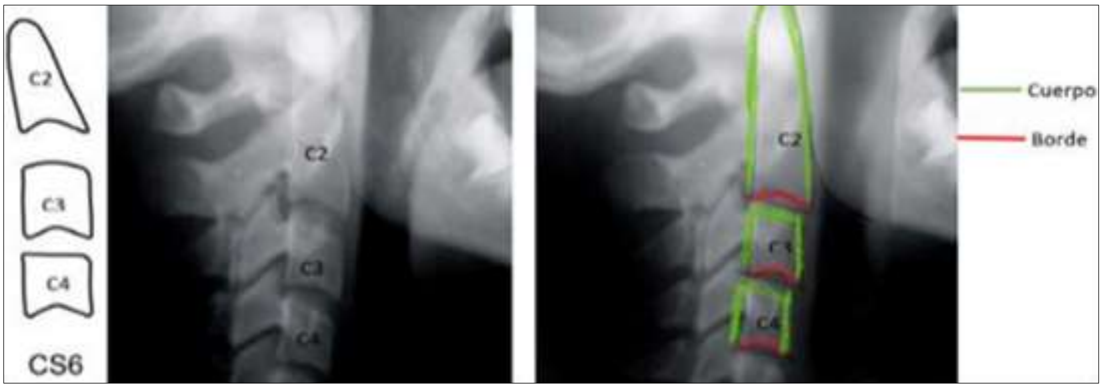


Figure 6 Diagram of the CS6 maturation stage. [1]

In this method the point of greatest mandibular growth occurs between CVMS II and CVMS III. [1]

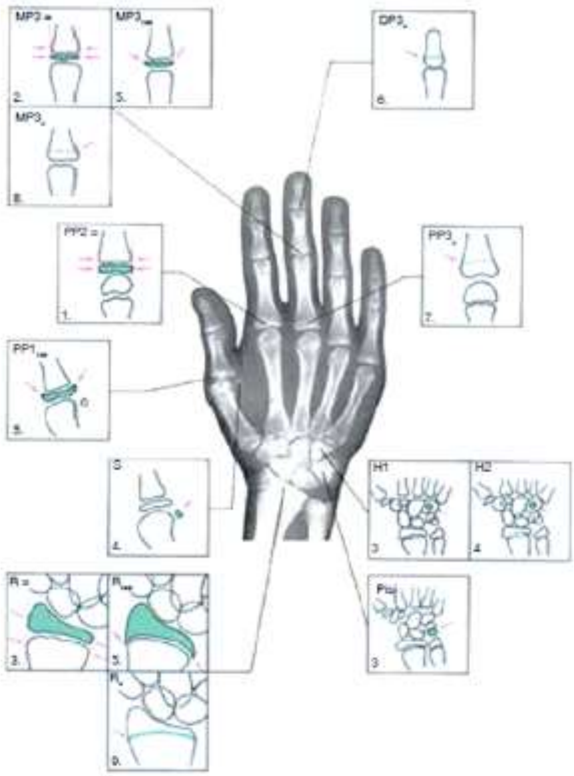
2.4.3. Hand and wrist indicator

Hand and wrist radiography is widely recognized as an effective method for assessing skeletal development. Numerous studies have used this technique to analyze bone maturation, using an index that is based on the timing and sequence of appearance of carpal bones, as well as specific ossification events.[6]

Björk Method

This method is used between 9 and 17 years of age and classifies the maturation process of the hand in 9 stages, for which 14 ossification points are analyzed, each stage representing the level of skeletal maturity evaluated according to the ratio between epiphysis and diaphysis. [6]

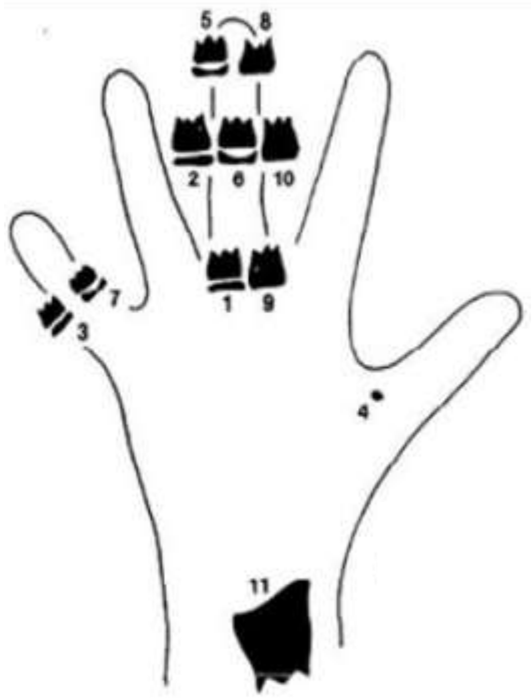
Table 1 Schematic of the Björk method [7]

State	Characteristics	Graphic
PP2	The epiphysis of the proximal phalanx of the index finger shows the same width as the diaphysis. Occurs approximately 3 years before the peak of pubertal growth.	
MP3	The epiphysis and diaphysis of the middle finger are equal, occurring just before the onset of the pubertal growth spurt.	
Pisi	Visible ossification of the pisiform bone.	
H1	ossification of the hamular process of the hamatum	
R	Radius with the same width of the epiphysis and diaphysis	
S	First mineralization of the ulnar sesamoid bone	
H2	Progressive ossification of the hamular process of the hamatum marks the beginning of growth spurt	
MP3cap	The diaphysis is covered by cap shaped epiphysis.	
PP1cap	The epiphysis completely surrounds the diaphysis of the proximal phalanx of the thumb.	
Rcap	The epiphysis completely surrounds the diaphysis of the radius.	
DP3u	Visible union of the epiphysis and diaphysis of the distal phalanx of the middle finger.	
PP3u	Visible union of the epiphysis and diaphysis of the proximal phalanx of the middle finger.	
MP3u	Visible union of the epiphysis and diaphysis of the middle phalanx of the middle finger.	
Ru	Complete ossification of the epiphysis and diaphysis of the radius.	

Fishman Method

Developed in 1987, it evaluated 11 maturation indicators located in the epiphyses and diaphysis of the thumb, third finger, fifth finger and radius.[2]

Table 2 Schematic of Fishman method [2]

State	Characteristics	Graphic
SMI1	In the middle finger the epiphysis shows the same width as the diaphysis.	
SMI2	In the middle phalanx of the middle finger the epiphysis shows the same width as the diaphysis. It appears during the onset of prepubertal growth velocity.	
SMI3	In the middle phalanx of the fifth finger the epiphysis shows equal width to the diaphysis.	
SMI4	The adductor sesamoid of the thumb becomes visible. It becomes visible during the period of very rapid growth velocity.	
SMI5	In the distal phalanx of the middle finger, the formation of the epiphysis over the diaphysis is observed.	
SMI6	In the middle phalanx of the middle finger, a covering of epiphysis over the diaphysis is observed.	
SMI7	In the middle phalanx of the fifth finger, the formation of an epiphysis over the diaphysis is observed. Maximum growth velocity.	
SMI8	In the distal phalanx of the middle finger, fusion of the epiphysis over the diaphysis is observed. Time interval of growth rate deceleration.	
SMI9	In the proximal phalanx of the middle finger, fusion of the epiphysis over the diaphysis is observed.	
SMI10	In the middle phalanx of the third finger, fusion of the epiphysis and diaphysis is observed.	
SMI11	Fusion of the epiphysis and diaphysis is observed in the radius, at this stage growth is complete.	

2.4.4. Other types of indicators

Pelvis and proximal femur indicator

Skeletal growth of the pelvis and proximal femur occurs as a result of multiple secondary ossification centers, which appear and close at different times during bone maturation. This process involves the formation and fusion of ossification centers in the bones that make up the pelvis, including the ilium, pubis, and ischium. [8]

According to Parvaresh, the known secondary ossification centers of the pelvis are the iliac crest (IC), the anterior superior iliac spine (ASIS), the anterior inferior iliac spine (AIIS), the posterior superior iliac spine (PSIS), the pubic symphysis (SP), and the ischial tuberosity (IT). On the other hand, there are the proximal femoral secondary ossification centers that are the femoral head (FH), the greater trochanter (GT), and the lesser trochanter (LT). [9]

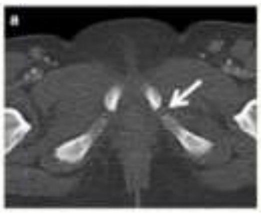
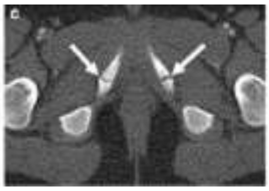
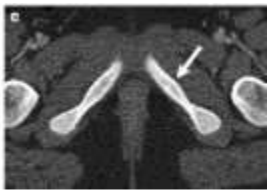
Cone beam computed tomography (CBCT) analysis is the most accurate to verify this maturation center, thus validating that women mature earlier than men, which is linked to overall skeletal development. It is important to consider sex differences in skeletal development because these differences may influence the timing and pattern of ossification of secondary ossification centers. [9] [10]

On the other hand, in a study conducted by Grissom 2018, six ossification centers were reviewed: ischiopubic synchondrosis, triradiate cartilage, ischial process, sacrum, iliac crest process, and pubic symphysis. Grading each of these ossification centers (except the iliac crest process) on a numerical scale based on absence, progressive ossification, and fusion of fragments. For the iliac crest process, only the absence and degree of fusion was graded using the Risser classification.[10]

Ischiopubic synchondrosis

The cartilage of the ischiopubic synchondrosis does not ossify in fragments and is best seen on axial images.[10]

Table 3 Classification of ischiopubic synchondrosis [10]

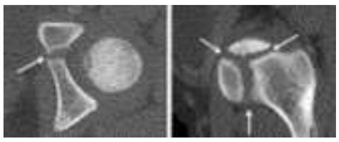
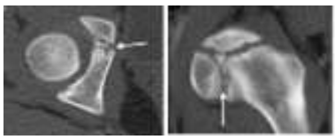
Numerical scale	Meaning	Images
0	Non-ossified synchondrosis	
1	Narrow synchondrosis	
2	Fused synchondrosis	

Triradiate cartilage

Triradiate cartilage is a Y-shaped synchondrosis between the three primary ossification centers of the hip joint (ileum, ischium, and pubis), best assessed on sagittal images, but also on axial and coronal images.

During maturation, small fragments of secondary ossification are first seen in the center of the triradiate cartilage. These then increase in size and disperse throughout the triradiate cartilage, followed by coalescence and finally complete fusion. Assessment of this is also given on a grading scale.[10]

Table 4 Classification of triradiate cartilage [10]

Numerical scale	Meaning	Images
0	Non-ossified synchondrosis	
1	Small fragments	
2	Coalescing fragments	

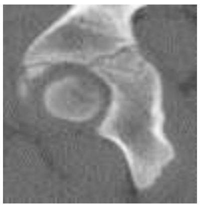
3	Fused	 

Ossification is also seen in three secondary centers within the peripheral acetabular cartilage. These appear at the same time when the triradiate fragments are viewed. When they fuse with the primary ossification center, they add depth to the acetabular cup. [10]

Ischial process

When ossification begins, a small fragment is first seen on the cephalic aspect of the cartilaginous process. The fragments enlarge and eventually fuse with the ischium. They are best seen on axial and sagittal images on a scale of 0 to 2 [10]

Table 5 Classification of Ischial Process [10]

Numerical scale	Meaning	Images
0	Unassessed process	
1	Fragmented process	
2	Fused process	

Sacrum

The secondary ossification centers (epiphyses) of the sacrum develop along the lateral aspect. They appear linear and fragmented, and then unite and fuse with the sacral body. [10]

Table 6 Classification of the Sacrum [10]

Numerical scale	Meaning	Images
0	Without ossified epiphysis	 
1	Ossified epiphyses with or without partial fusion	 

2	Fused epiphyses	

No ossified epiphyseal fragments were observed in stage 0 or stage 2. In order to differentiate between grade 0 and grade 2, the transverse distance at the anterior sacroiliac joint is measured (using the narrowest side), 1 cm below the upper margin of the sacral base (S1). Note that grade 0 shows a thin, sharp linear cortex along the lateral surface of the sacrum, while grade 2 shows a thickened and lobulated cortical margin.[10]

Iliac crest process

The ileum is a primary ossification center with a cartilaginous upper process. The Risser staging system is used to grade skeletal maturity based on the development and fusion of secondary ossification centers. [10]

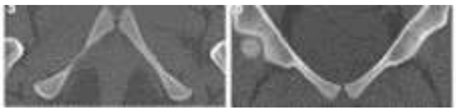
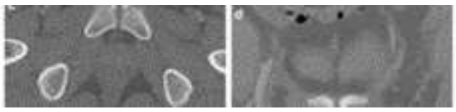
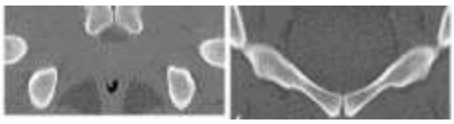
Table 7 Classification of the iliac crest [10]

Numerical scale	Meaning	Image
0	Unassessed process	
1	One-quarter ossified	
2	Half ossified	
3	Three-quarters ossified	
4	Completely ossified but not fused to body of ileum	
5	Ossified and fused to ileum	

Pubic symphysis

The pubic symphysis is a cartilaginous joint consisting of a fibrocartilaginous disk between the medial aspect of the adjacent pubic bones. These grow into and become incorporated into the pubic bones. The components of the pubic symphysis are best seen on axial and coronal images and are graded on a scale of 0 to 2. [10]

Table 8 Classification of the pubis [10]

Numerical scale	Meaning	Images
0	Absence of ossification	
1	Fragmented ossification	
2	Fusion	

Palatal suture indicator

The median palatal suture (MPS) is a cranial joint, located along the midline of the bony palate, between the palatine processes of the maxilla and the horizontal plates of the palatine bones. [11]

According to Ennes et al. it can be classified according to the degree of ossification by means of a total occlusal radiograph of the maxilla, identifying the location and extension of the bridges that comprise the three regions of the median palatal suture. [12]

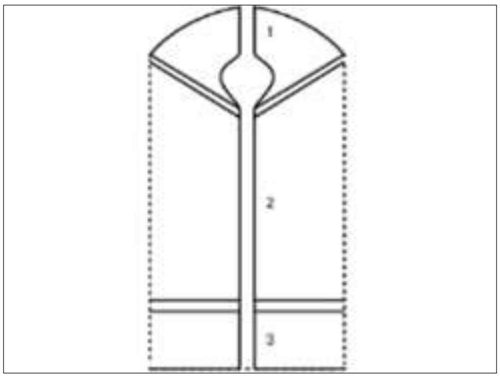


Figure 7 Ossification bridges 1) anterior segment; 2) middle palatine segment; 3) posterior palatine segment

The length of each bridge can be measured with a millimeter ruler on the complete occlusal radiograph. There are scores to determine the presence and extent of ossification bridges, with established scores of: 0, 1, 2 and 3. [12]

- Grade 0: corresponding to the absence of ossification bridges
- Grade 1: presence of bridges with an extension of between 1 and 3 mm
- Grade 2: presence of bridges with an extension between 3.1 and 6 mm
- Grade 3: presence of bridges with an extension greater than 6.1 mm

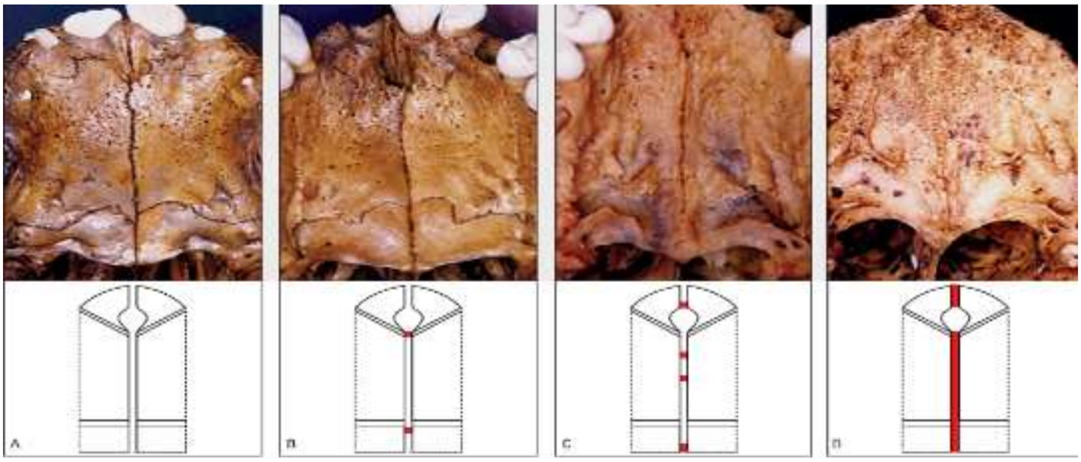
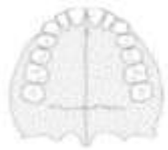
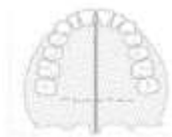


Figure 8 Degree of ossification of the midpalatine suture [12]

The presence of ossification bridges in the suture may be an indicator of maturation and radiographically these bridges may appear as areas of greater bone density that connect the margins of the suture, so the identification of these bridges may indicate a greater degree of maturation. [12]

Another way to verify the maturation of the SPM is by the Angeleri method using CBCT, in this method five stages are described. [11]

Table 9 Angeleri method [11]

Stage	Definition	Characteristic	Images
A	Suture without ossification.	Straight sutural line of high density, with little or no interdigitation.	
B	Partial ossification.	Scalloped appearance of high-density sutural line.	
C	More advanced ossification	Two parallel, scalloped, high-density lines that lie next to each other, separated in some areas by small, low-density gaps.	
D	Almost complete ossification	Complete fusion at the palatine bone, with no evidence of a suture.	
E	Completely ossified suture	Anterior fusion in the upper jaw.	

3. Conclusion

It is important to know the stages of bone maturation and its relationship with growth, for an adequate management of the patient and to obtain an adequate treatment plan. There are several methods, among them the skeletal ones are the most used, such as the analysis of vertebrae, hand and wrist, among others.

Accurate assessment of the correlation between chronological age and cervical bone maturation allows for more accurate planning of dentomaxillary orthopedic treatments. By identifying the ideal time for intervention, orthodontic and orthopedic therapies can be implemented during critical phases of the patient's growth, facilitating the correction of malocclusions and dentomaxillary problems more efficiently.

Analysis of skeletal growth of the pelvis and proximal femur, as well as evaluation of the palatine suture, are essential for a thorough understanding of human skeletal development. Identification and classification of ossification centers in both the pelvis and femur facilitate differential analysis of maturation between men and women; in fact, this influences the chronology of bone development. It should be emphasized that cone beam computed tomography (CBCT) and occlusal radiographs allow for a precise and detailed evaluation of these bone maturation identification processes.

Knowledge about the ossification of specific structures, such as the ischiopubic synchondrosis and the triradiate cartilage, generates important information about physical development at different stages of life. Likewise, classification of the palatine suture and its degree of ossification are indicators of maturation that may have clinical implications in dentistry and especially in the area of orthodontics.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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