Forensic Science International 217 (2012) 232.e1–232.e7

Contents lists available at SciVerse ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Forensic Anthropology Population Data

Age assessment by magnetic resonance imaging of the knee: A preliminary study

Fabrice Dedouit [a,b,c,*], Julien Auriol [b,c], Hervé Rousseau [b], Daniel Rougé [a,c], Eric Crubézy [c], Norbert Telmon [a,c]

[a] Service de Médecine Légale, Centre Hospitalier Universitaire Rangueil, Avenue du Professeur Jean Poulhès, 31403 Toulouse Cedex 4, France
[b] Service de Radiologie, Centre Hospitalier Universitaire Rangueil, Avenue du Professeur Jean Poulhès, 31403 Toulouse Cedex 4, France
[c] Laboratoire d'Anthropobiologie Moléculaire et Imagerie de Synthèse – AMIS UMR 5288 CNRS, 37 allées Jules Guesde, 31073 Toulouse Cedex, France

ARTICLE INFO

Article history:
Received 7 July 2011
Received in revised form 28 September 2011
Accepted 14 November 2011
Available online 5 December 2011

Keywords:
Magnetic resonance imaging
Forensic sciences
Anthropology
Age estimation
Knee
Transition analysis
Forensic anthropology population data

ABSTRACT

The authors developed an original magnetic resonance imaging (MRI) staging system for epiphyseal fusion of growth plate maturation of the knee and evaluated its reliability and validity for age assessment of living individuals. A total of 290 MRI scans of the knee were reviewed retrospectively in patients aged from 10 to 30 years old (138 males, 152 females). Five original MRI stages were defined to assess the degree of maturation of the distal femoral and proximal tibial epiphyses. Intra-observer variability was excellent and inter-observer variability was good, demonstrating the reliability and the validity of this original MRI staging system. In both sexes, the changes of growth plates (proximal tibial or distal femoral) were associated with age ($p < 0.001$). Our results agreed with classic data on skeletal maturation of the knee, with globally earlier maturation in females than in males, and also earlier maturation of the proximal tibial epiphysis than of the distal femoral epiphysis. MRI of the knee is an efficient non-invasive method of age assessment, without the disadvantage of X-ray exposure. Further studies with larger groups are needed to support our results.

1. Introduction

Forensic bone age estimation of living adolescents and young adults is becoming increasingly important in today's society because of the increase in migration. This forensic problem mostly relates to foreigners without valid identification documents, whose exact age needs to be established for asylum, criminal or civil proceedings [1–5]. The threshold age of legal responsibility is between 14 and 22 years old in most countries [1]. According to the recommendations of the International Study Group on Forensic Age Diagnosis (Arbeitsgemeinschaft für Forensische Altersdiagnostik, AGFAD), age estimations of living adolescents and young adults should firstly consist of a physical examination (including anthropometric data and signs of sexual maturation), secondly a radiograph of the left hand, and thirdly a dental examination (with recording of dentition status, and evaluation of an orthopantomogram) [1,2]. Some authors state that to establish whether an individual has reached the age of 21 years, an additional conventional X-ray or computed tomography (CT) scan of the medial epiphyses of the clavicle is recommended [2,6–11]. Ultrasound studies with forensic purpose of age assessment have already been performed, and concerned medial clavicular epiphysis and apophyseal ossification of the iliac crest [12–14]. Magnetic resonance imaging (MRI), another X-ray-free examination method, has already been successfully used to estimate the age of living young men and women for forensic purposes [15–20]. However, MRI is a radiological technique more objective and less operator-dependant than ultrasound. The regions of interest studied with MRI were mainly the clavicle and the wrist, areas that have also been exhaustively studied and documented with plain X-rays in the past [15–19]. Concerning the knee, rare MRI studies evaluated its potential forensic interest in bone maturation study [20–22]. One knee MRI study concerned only the proximal tibial epiphysis [20]. Use of an imaging modality with no radiation risk could have great advantages from forensic, legal and ethical standpoints. The aims of our study were firstly to develop an original MRI staging system of growth plate maturation and epiphyseal fusion of the knee for estimation of skeletal bone age in a population ranging from 10 to 30 years old, and secondly to evaluate the reliability and validity of the system.

2. Materials and methods

2.1. Sample

We retrospectively reviewed clinical knee magnetic resonance (MR) scans of living subjects of documented age, performed in the radiology departments of our institution (Toulouse, France), using a picture archiving and communication system (PACS) (McKesson Medical Imaging Group, Richmond, BC, Canada). The clinical

* Corresponding author at: Service de Médecine Légale, Hôpital de Rangueil, 1 Avenue du Professeur Jean Poulhès, TSA 50032, 31059 Toulouse Cedex 9, France. Tel.: +33 5 61 32 28 59; fax: +33 5 61 32 21 77.
E-mail address: fabded2@hotmail.com (F. Dedouit).

0379-0738/$ – see front matter © 2011 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.forsciint.2011.11.013

indication of the MRI examination was knee pain. We selected randomly and retrospectively 290 patients aged 10–30 years old. This large range was chosen because it included the different threshold age of criminal liability. The inclusion criteria consisted in:

- Absence of pathological modification of the knee: no epiphyseal tumor, direct acute trauma, infection, arthritis or dysplasia.
- No hormonal disturbance, nor general pathology (no past history of neoplasia, metastasis, radio or chemotherapy, and leukemia).
- Suitable MR scan parameters: visualization of the entire distal femoral and proximal tibial epiphysis, and availability of fast spin-echo proton density-weighted images.

2.2. MRI examinations

The examinations were performed with a 1.5-T whole body scanner (Intera, Philips Medical System, Amsterdam, The Netherlands). The extremities were imaged using transmit-receive extremity coil. A single MR imaging sequence was used to visualize the skeletal maturation of the knee. The technical characteristics were: fast spin-echo proton density-weighted images, TR 2500–4000 ms, TE 25–50 ms, slice thickness 3.5–4 mm, time for each acquisition: 4 min. The images consisted in two series of 23 images, with one acquisition in coronal plane and another one in sagittal plane.

2.3. Image analysis

Images were anonymised by deleting the names and documented ages of the patients. They were separately assessed by one radiologist (J.A.) and one forensic pathologist (N.T.), who were blinded to patient identification data, in order to evaluate inter-observer variability. The staging system was also evaluated after a 3-week interval by the first observer (J.A.) to estimate intra-observer variability.

2.4. MRI staging

The staging system was developed based on five MRI developmental stages. Both distal femoral and proximal tibial epiphyses were separately evaluated with these stages. Five growth plate patterns were designated as stages I–V. In most of cases, only the coronal series were used. The staging was performed after observation of all the 23 images composing the coronal acquisition. In cases of hesitation during one observation, the lower stage was retained, according to the principle "*in dubio pro reo*" which is the principle of benefit of the doubt used in criminal proceedings. The sagittal slices were also used in cases of hesitation, mostly to discriminate a stage II from a stage III, and also a stage III from a stage IV. However, this situation was rarely encountered.

2.5. Statistical analysis

Statistical analysis was performed with R 2.10. [23]. Cohen's kappa non-parametric test was used to evaluate intra- and inter-observer variabilities. We used analysis of variance (ANOVA) to determine for each sex, if the mean values of the different stage for the stage of the femoral and tibial epiphyses were significantly different. A descriptive statistical analysis was performed to determine for males and females the mean age, standard deviation and age range with a 95% interval of confidence. This was done separately for the distal femoral and proximal tibial epiphysis and for each bone stage, and for males and females. Finally, transition analysis was also performed separately for each sex and each epiphysis in order to determine the age-at-transition distributions. Transition analysis is a parameter method for modelling the passage of individuals from a given developmental stage to the next higher stage in an ordered sequence [24,25].

3. Results

3.1. Population

A total of 290 patients were included, consisting of 138 males and 152 females, with an age ranging from 10.1 to 30.9 years (male mean age 20.3 years, standard deviation 5.7 years; female mean age 20.5 years, standard deviation 6.0 years) (Table 1). The ethnic origin of the retrospectively selected patients was not taken into consideration because only the patient's name and date of birth were available in the PACS. The laterality of the knee was not taken in account.

3.2. MRI staging

The five growth plate patterns designated as stages I–V, were morphologically defined as follows:

- *Stage I*: continuous horizontal cartilage signal intensity present between the metaphysis and the epiphysis, stripe-like, with a thickness greater than 1.5 mm and a multilaminar appearance (Fig. 1a). The multilaminar appearance was seen as decreased signal intensity in the upper layer, increased signal intensity in the middle layer, and decreased signal intensity in the lower layer.
- *Stage II*: continuous horizontal linear cartilage signal intensity present between the metaphysis and the epiphysis, with a thickness greater than 1.5 mm, with increased signal intensity but without a multilaminar appearance (Fig. 1b).
- *Stage III*: continuous horizontal linear cartilage signal intensity present between the metaphysis and the epiphysis, with a thickness less than 1.5 mm, with increased signal intensity (Fig. 1c).
- *Stage IV*: discontinuous horizontal linear cartilage signal intensity present between the metaphysis and the epiphysis, with a thickness less than 1.5 mm, with discontinuous increased signal intensity (Fig. 1d).
- *Stage V*: no increased signal intensity between the metaphysis and the epiphysis (Fig. 1e).

Frequently, increased signal intensities were seen, but incomplete and peripheral, mostly bilateral, localised within the epiphysis and corresponding to vascular structures.

3.3. Intra- and inter-observer variabilities

Cohen's kappa nonparametric test revealed excellent *intra-observer reproducibility* ($k = 0.96$ for the distal femoral and the proximal tibial epiphysis), good *inter-observer reproducibility* for the distal femoral epiphysis ($k = 0.86$), and moderate inter-observer reproducibility for the proximal tibial epiphysis ($k = 0.63$).

3.4. Statistical and age-at-transition results

Tables 2a and 2b show minimum, maximum and mean age with their standard deviations, and the age range with a 95% confidence interval, separately for the distal femoral and proximal tibial epiphyses and for each bone stage. When the five epiphyseal stages were compared between age groups, significant differences were identified. The changes in growth plate pattern associated with age were seen for both proximal tibial and distal femoral epiphyses, in both men and women ($p < 0.001$). The percentage of individuals at each developmental stage in each age group and for each epiphysis is shown in Tables 3a and 3b. Tables 4a and 4b show the age at transition separately for the distal femoral and the proximal tibial

Table 1
Distribution of the population studied according to age and sex.

Age (years)	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Males	5	3	8	7	8	8	10	6	6	5	7	5	9	13	5	5	7	4	8	7	2
Females	8	4	5	12	6	11	5	6	7	11	3	11	4	11	10	5	7	3	8	7	8
Total	13	7	13	19	14	19	15	12	13	16	10	16	13	24	15	10	14	7	16	14	10