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Review article

Bone age determination based on the study of the medial extremity of the clavicle

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Abstract. The development of the medial clavicular epiphysis and its fusion with the clavicular shaft have been a subject of medical research since the second decade of this century. Computed tomography provides the imaging modality of choice in analyzing the maturation process of the sternal end of the clavicle. In a retrospective study, we analyzed normal development in 380 individuals under the age of 30 years. The appearance of an epiphyseal ossification center occurred between ages 11 and 22 years. Partial union was found from age 16 until age 26 years. Complete union was first noted at age 22 years and in 100 % of the sample at age 27 years. Based on these data, age-related standardized age distributions and 95 % reference intervals were calculated. Compared to the experience recorded in the relevant literature, there are several landmarks that show no significant change between different ethnic groups and different periods of publication; these are the onset of ossification, the time span of partial union, and the appearance of complete union. Despite the relatively long time spans of the maturation stages, bone age estimation based on the study of the development of the medial clavicular epiphysis may be a useful tool in forensic age identification in living individuals, especially if the age of the subject is about the end of the second or the beginning of the third decade of life (e. g. in determining the applicability of adult or juvenile penal systems). Another possible use is in identifying human remains whose age is estimated at under 30 years.

Key words: Clavicle – Medial clavicular epiphysis – Computed tomography – Bone age determination

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Introduction

The clavicle is a long bone with a medullary cavity and the first fetal bone to undergo primary ossification. However, unlike other long bones, it initially does this by membranous ossification without prior endochondral ossification. There are two primary ossification centers, one medial and one lateral, which appear during the 5th and 6th weeks of intrauterine life and normally coalesce during fetal life [1, 2]. Cartilaginous growth areas (epiphyses) develop at both the acromial and the sternal end of the clavicle, transforming the developmental pattern to a combination of endochondrial longitudinal ossification and membranous diaphyseal/metaphyseal ossification. However, the most active growth throughout postnatal development remains diaphyseal membranous ossification [2].

A secondary epiphyseal ossification center appears at the medial end of the clavicle during adolescence. The analysis of its development and its fusion with the clavicular shaft has been at the center of interest since the second decade of this century [3–6]. Based on large, systematic studies, it has been shown that the relative timing of the epiphyseal development of the medial clavicle and its union with the clavicular shaft may be used in estimating the age of osseous remains. These data suggest that detailed knowledge of the maturation of the medial clavicle could be a useful adjunct in the forensic age identification of living or dead individuals [7, 8].

In our own department, we have observed an increasing need over the years for age identification of living individuals. In the vast majority of cases, the suspected age range was between late adolescence and the third decade of life. In addition to conventional radiographs of the left hand and the pelvis, we used the stage of epiphyseal development of the medial clavicular epiphysis, determined by computed tomography (CT), for age estimation [9].

The purpose of this article is to present our reference population for the stages of epiphyseal maturation and union of the medial clavicle determined by CT and to compare these data with those obtained from the anatomical, anthropological, and radiological literature. Another objective is to assess the extent to which this method can be used for age estimation in living individuals, and thus to define its potential role in forensic age identification.

Examination methods and technical considerations

There are several examination techniques for imaging the sternal end of the clavicle in the living individual. Conventional radiographs, which were the basis of analysis in some comprehensive studies (Table 2) [5–8, 10–12], are often suboptimal because of overlapping ribs, vertebrae and mediastinal shadows [13–15]. In some cases these structures even prevented the exact determination of the stage of medial epiphyseal development [10, 11]. Conventional multidirectional tomography may be helpful, but it is time-consuming and the images often lack clarity.

Computed tomography eliminates many of the problems associated with conventional radiography and tomography. The cumulative exposure to radiation is lower than in tomography, and it provides vastly better anatomic pictures. In addition, it visualizes soft tissue structures [15, 16]. Compared to standard CT, spiral CT technique offers several advantages, the most important being the short examination time, which increases its acceptance by the patient. With spiral CT, it is possible to acquire continuous data during a single breath-hold, thereby avoiding respiratory motion artefacts. However, with the examination of smaller volumes by spiral CT, a higher volume-dose index is to be expected in comparison to that of standard CT [17]. This problem can be solved by using pitch factors greater than 1. For imaging of the sternoclavicular joints with spiral CT technique, we consider a 3.0-mm collimation, a table speed of 4–5 mm/s (pitch 1.3–1.7), and a 3.0-mm reconstruction increment sufficient. For better assessment of bony structures, a high-resolution reconstruction algorithm is recommended [16].

The sternoclavicular joints are also amenable to magnetic resonance (MR) imaging [18]. Up until now, no data exist concerning the MR appearance of the different stages of the development of the medial clavicular epiphysis. However, with regard to forensic, legal and ethical aspects, the use of a radiation-exposure-free imaging modality would be of great advantage [19].

The Mainz reference population

Due to an increasing need for age estimation of living individuals in the course of criminal procedures, we began to examine the maturation of the medial clavicular epiphysis by CT as an adjunct to X-ray examinations of the hand and pelvis.

In order to perform a systematic analysis of medial clavicular development, the CT examinations of the chest or shoulder girdle from a 7.5-year period (September 1989 to March 1997) were retrospectively reevaluated by an experienced radiologist. Basic conditions for further analysis were patient age of under 30 years lack of bone development disorders, and sufficient documentation of the sternoclavicular joint region. The latter had to allow assessment of the medial clavicular epiphysis in a bone window setting (1500/300 HU), independently from the originally chosen reconstruction algorithm. All CT examinations were performed on scanners of the third or fourth generation (Somatom DRH, Plus and Plus S, Siemens, Erlangen, Germany; Picker PQ 2000 and 5000, Picker International, Cleveland, Ohio, USA). The CT data were acquired by using either a conventional standard mode or a spiral mode with varying pitch factors (1–2), according to the examination protocol used for the specific indication. Effective slice thickness of the sternoclavicular joint region was 8 mm in 202 cases (53.2 %), 5 mm in 88 cases (23.2 %), and 4 mm in 54 cases (14.2 %). In 36 cases (9.5 %), slice thickness was either 1, 2 or 3 mm.

The indications for the CT examinations were a tumor in 192 cases (50.5 %), trauma of the thorax or the shoulder girdle in 69 cases (18.2 %), followed by infectious diseases in 34 cases (8.9 %). In 85 cases (22.4 %), the indications for CT varied: for example, determination of the scoliosis angle in patients with kyphoscoliosis ($n = 13$), diseases of the heart or great vessels ($n = 12$), acute or chronic recurrent pulmonary embolism ($n = 11$), pneumothorax ($n = 10$), and interstitial lung diseases ($n = 9$).

In accordance with the studies by Owings Webb and Myers Suchey and by Jit and Kulkarni [8, 12], the stages of maturity and union of the medial clavicular epiphysis were categorized as follows: Stage 1 refers to nonunion without ossification of the epiphysis. Stage 2 describes nonunion but with detectable ossification of the epiphysis. Stage 3 was defined as partial union, and stage 4 as complete union of the ossified epiphysis with the clavicular metaphysis. Osseous union was considered partial until there was complete bony attachment of the whole epiphysis to the metaphysis, documented by CT.

The age of the individuals at the time of the CT examination was known in all cases. Age was handled in strictly chronological terms: thus, age 15 years refers to persons having reached their 15th but not their 16th birthday.

Based on the assumption of normal empirical distributions of the developmental stages, statistical analysis comprised the calculation of stage-related standardized age distributions that allow for determination of a 95 %-confidence interval for each developmental stage. At the same time, the probabilities were calculated as having a certain maturation stage at a given age.

To date, the CT scans of 380 patients under the age of 30 years have been available for further analysis. The sample consists of 229 males (60.2 %) and 151 females (39.8 %). Analogous to standard X-rays of the left hand, the age distribution of the whole sample in dependence on the developmental stage of the left medial clavicular epiphysis is given in Table 1: nonunion without ossification of the medial epiphysis (stage 1) could be observed

Table 1. Age distribution of individuals by the stage of maturation of the medial clavicular epiphysis (n = 380)

Age (years)	Stage 1 n (%)	Stage 2 n (%)	Stage 3 n (%)	Stage 4 n (%)	Total
0–4	18 (100 %)	–	–	–	18
5–9	22 (100 %)	–	–	–	22
10	7 (100 %)	–	–	–	7
11	7 (83 %)	1 (17 %)	–	–	7
12	5 (100 %)	–	–	–	5
13	8 (73 %)	3 (27 %)	–	–	11
14	5 (38 %)	8 (62 %)	–	–	13
15	2 (11 %)	16 (89 %)	–	–	18
16	1 (5 %)	16 (84 %)	2 (11 %)	–	19
17	–	9 (69 %)	4 (31 %)	–	13
18	–	10 (59 %)	7 (41 %)	–	17
19	–	5 (25 %)	15 (75 %)	–	20
20	–	1 (5 %)	21 (95 %)	–	22
21	–	–	15 (100 %)	–	15
22	–	1 (6 %)	14 (88 %)	1 (6 %)	16
23	–	–	12 (55 %)	10 (45 %)	22
24	–	–	6 (30 %)	14 (70 %)	20
25	–	–	5 (15 %)	29 (85 %)	34
26	–	–	2 (7 %)	25 (93 %)	27
27	–	–	–	17 (100 %)	17
28	–	–	–	23 (100 %)	23
29	–	–	–	13 (100 %)	13
Total	75 (20 %)	70 (18 %)	103 (27 %)	132 (35 %)	380

until age 16 years (Fig. 1). The appearance of an ossification center in the medial epiphysis (stage 2) occurred between ages 11 and 22 years (Fig. 2). Partial union (stage 3) was found from age 16 until age 26 years (Fig. 3). Complete union (stage 4) was first noted at age 22 years and in 100 % of the sample at age 27 years (Fig. 4). Determination of the maturation stage by CT is a simple method; the only possible diagnostic pitfall being the persistence of the medial epiphyseal ossification center that was once reported in a case report [20].

Differences in development between the left and right medial clavicular epiphyses were noted in six cases (1.6 %). However, this did not lead to any statistically significant discrepancy in the maturation process between both sides. There were no statistically significant differences in epiphyseal development between males and females and, in view of the limited sample size, the results were not considered separately.

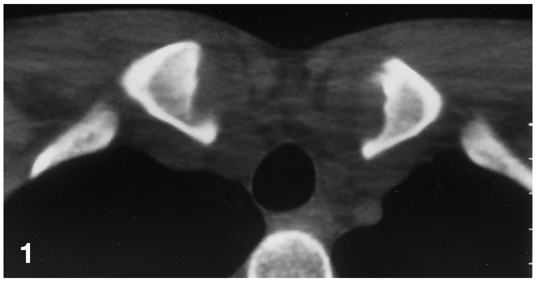
In Fig. 5, the probabilities of a certain maturation stage concurring with a given age are represented. At the same time, they enable the determination of a 95 % reference interval for each developmental stage: since the mean age of appearance of the ossification of the medial epiphysis (stage 2) was 16.1 years and the standard deviation 1.9 years, the 95 % interval extends from 12.3 to 19.9 years. For stage 3, the interval extends from 16.5 to 25.5 years with a mean of 20.9 years and a standard deviation of 2.2 years. For stage 1, it extends from 0 to 16 years, and for stage 4 it begins with age 22 years.

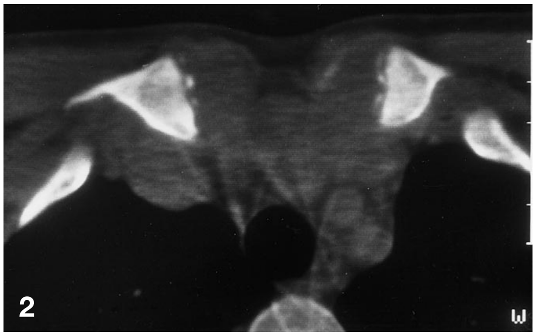
Comparison with other studies

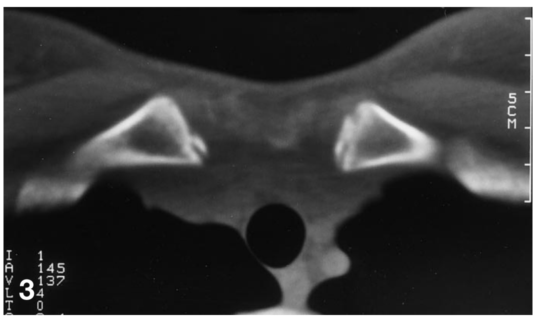
The postnatal development of the clavicle and especially of the medial clavicular epiphysis has been under investigation for a long time [3–8, 10–12]. In Table 2, the most comprehensive studies from the literature currently available are summarized. In comparing these data with those of our population, several points need to be commented on.

Despite different ethnic groups and publication periods, the time span of the appearance of the secondary ossification center (beginning between age 11 and age 13 years), shows no significant difference in all the samples but two. In the group studied by Owings Webb and Myers Suchey [8], there is a marked delay in appearance of the ossification center. This may be due to a methodological problem, namely that the onset of calcification of the medial epiphysis may be more difficult to detect by anatomical section than by radiological methods (radiographs or computed tomography). Flecker mentioned in his studies [6, 10] that, due to overlaying soft tissues and bony structures, an exact staging was not possible in many of his individuals. Thus, the longer time of appearance of secondary ossification only reflects his problems in the exact staging of the maturation of the medial clavicular end.

There are also no apparent differences concerning the onset of partial fusion of the medial epiphysis in all the studies (age 16 to 19 years). However, this developmental stage lasts considerably longer in the studies by McKern and Stewart [7] and by Owings Webb and Myers Suchey [8]. Again, one may speculate whether this reflects another methodological problem. Persistent small grooves or notches seen during anatomical preparation may be classified as partial fusions, whereas radiographic studies may yield complete fusion of the epiphysis with the clavicular shaft [21]. However, to date no comparative study exists that deals with this problem.







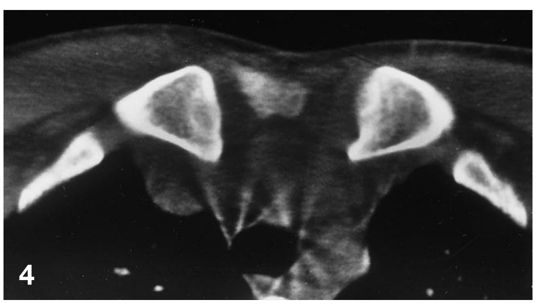


Fig. 1. Stage 1 without ossification of the medial clavicular epiphysis: male, 12 years

Fig. 2. Stage 2 with ossification of both medial clavicular epiphyses without apparent fusion with the metaphysis: male, 15 years

Fig. 3. Partial fusion (stage 3) with the clavicular metaphysis: female, 22 years

Fig. 4. Complete fusion (stage 4) with the clavicular shaft: female, 28 years

Analogous to the time span of the appearance of the secondary ossification center, there seem to be no significant discrepancies in the onset of complete fusion, with one exception. In his study of 654 Bengalis, Galstaun [11] reported the beginning of complete fusion at age 19 years. However, he did not differentiate partial and complete fusion (stages 3 and 4) in his study.

To summarize experience from our study and that of the literature, there seem to be no significant discrepancies in the essential parameters of the maturation process of the medial clavicular epiphysis. This is a very important fact, since the studies are from different eras of this century and therefore reflect distinct nutritional customs and varying intake of proteins and vitamins in daily food, as well as the ingestion of hormones (e. g. oral contraceptive usage). Furthermore, these data were collected from different ethnic groups and socioeconomic classes.

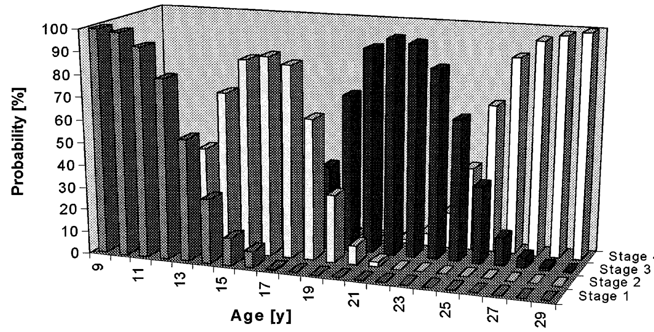


Fig. 5. Calculation of stage-related standardized age distributions and 95 %-reference intervals

Discussion

Today there is an increasing demand for age estimations in living individuals. The questions associated with these age estimations concern general criminal responsibility (age over 14 years) or the applicability of the adult or juvenile penal system (in Germany, age over 21 or under 18 years) in juvenile delinquents. Often we have to examine young asylum seekers without identification or with false identity papers who have been convicted of an offense. Usually the age estimations are required to help in differentiating between two or more possible ages or birth dates [19].

The principal methods available for age determination in living subjects are those of radiology, tooth morphology, and biochemistry. These methods differ widely with respect to potential, limits and risks [19, 21]. All significant age determination methods require medical intervention or examinations that are not usually medically indicated. This poses a number of questions of a legal and ethical nature that have to be answered in the specific sociopolitical situation. The most important are whether a physician may be in conflict with the law in applying age determination methods and whether these methods can legally be applied in living persons without their consent. These questions must be decided in each individual case on the basis of the appropriate regulations and the principles of medical ethics. Detailed knowledge of the available methods and their potential and limits is of utmost importance [19].

In the Federal Republic of Germany, the application of radiological methods for age identification in living individuals must be in accordance with the medical X-ray code (Röntgenverordnung, "RÖV"). Generally, ra-

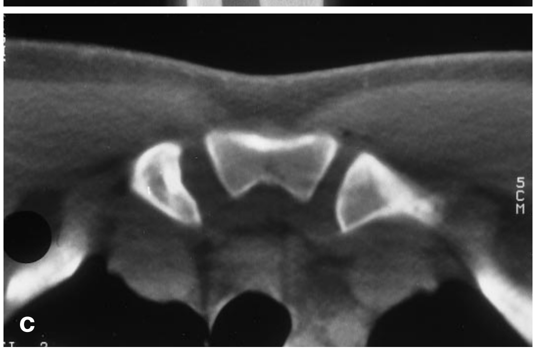


Fig. 6 a–c. Asylum seeker accused of rape. All test regions demonstrate complete skeletal maturation. **a** A. p. radiograph of the left hand and wrist; **b** a. p. radiograph of the pelvis; **c** CT of the sternoclavicular joints

diological methods that are associated with radiation exposure are only indicated in legal and ethical respects if they can be of help in the detection or treatment of diseases. According to § 24 of the RÖV, examinations for age determination can only be carried out if they are ordered in the course of a criminal procedure by a judge (§ 81 a, code of criminal procedure). If applied, they should be of help in clarifying the above questions [19].

Age estimations in childhood often still rely on the relatively old standards of the hand and wrist published by Greulich and Pyle [22] and are completed by determination of tooth development. The 95 % confidence interval for hand X-rays is about ± 2 years [19, 23–25]. During adolescence and the third decade of life, the assessment of the appearance and fusion of the epiphyses of long bones and the pelvis is of increasing importance. However, the process between ossification of an epiphysis and final closure normally lasts several years. This emphasizes the importance of defining the exact stage of development for each epiphysis and of knowledge of the range of variation for the timing of union [26–28].

The McKern and Stewart study [7] showed that not all epiphyses are of equal value in estimating age. Among the best indicators were the epiphyses of the proximal humerus, distal radius, femoral head, iliac crest, and medial clavicle. Based on these findings, the test regions for age estimations in our department are the hand and wrist, the pelvis, and the medial end of the clavicles. Thus, in addition to a. p. radiographs of the hand, wrist, and pelvis, we routinely perform CTs of the sternoclavicular joints when age estimations for individuals in adolescence or the third decade of life are required. The aim of these age estimations is to determine the most probable age of young delinquents without any identity papers who claim to have different birth dates during criminal procedures.

The following case may demonstrate the usefulness of bone age determination in such instances. A young asylum seeker from Albania was accused of rape. At several offices, he gave different birth dates ranging between March 1959 and November 1970. During the lawsuit, he pretended to have been born on 11 November 1975, so that his age would have been 20 years at that time. As a consequence, he would have been punished according to the juvenile penal system. Bone age determination performed using the above-mentioned test regions. This showed that his skeletal maturation was complete (Fig. 6). According to Fig. 5, the probability of his being 20 years old with stage 4 of epiphyseal development of the medial clavicle was under 0.1 %. This resulted in the adult penal system being applied in the further criminal procedure.

Conclusions

The development of the medial extremity of the clavicle can easily be assessed by computed tomography. In order to establish a reference population, we retrospec-

Table 2. Survey of the most comprehensive studies dealing with the development of the medial clavicular epiphysis

Study group (year)	Sample size	Males	Females	Age (years)	Ethnic group	Method	Ossification of medial epiphysis (age in years)	Partial union (age in years)	Complete union onset (age in years)	Complete union in 100 % of the sample (age in years)
Todd, D'Errico (1928)	166	130	36	17–29	White, Black, USA	Anatomic preparation	n. d.	19–27	22	28
Flecker (1933)	437	206	231	11–26	Australasians	Chest X-rays[a]	11–26	n. d.	22	26
Galstaun (1937)	654	446	209	12–25	Bengalis	Chest X-rays[a]	12–19	n. d.	19[b]	25[b]
McKern, Stewart (1957)	374	374	–	17–31	White, USA, death during Korean war	Anatomical section	n. d.	18–30	23	31
Jit, Kulkarni (1976)	684	391	193	11–30	North Indians	Chest X-rays	11–19	18–24	22	25
Owings Webb, Myers Suchey (1985)	859	605	254	11–40	White, Black, Latin Americans, USA	Anatomical section	16–21	17–33	21	34
Present study (1997)	380	229	151	0–29	White, Europe	Thoracic CT	11–22	16–26	22	27

[a] no documentation of X-ray findings
[b] no differentiation between partial and complete fusion
n. d. no data available

tively analyzed normal development in 380 individuals under the age of 30 years. The ossification of the medial clavicular epiphysis and its complete union with the clavicular shaft normally lasts several years. The data collected allow exact staging of the development and provide the range of variation for the timing of union. However, several limitations associated with our reference population remain. The number of individuals is limited, and it remains unclear whether greater sample size will lead to an increase in the age periods of the developmental stages. Despite the experience available from the literature, the transfer of our data to other ethnic groups with different nutritional habits should be made with caution. Nevertheless, bone age determination based on the study of the development of the medial clavicular epiphysis may be a useful adjunct in forensic age identification in living individuals. This method is also indicated for the identification of human remains whose age is estimated at between 15 and 30 years.

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Book review

European Radiology

Novelline, R. A.: Squire's Fundamentals of Radiology, 5th edn. Cambridge, Massachusetts: Harvard University Press 1997. 640 pp., 1269 halftones, 85 line illustrations, (ISBN 0-674-83339-2), £ 46.50.

As a result of wide popularity, this excellent textbook reaches its fifth edition. The book appears to have been and to be the "vademecum" of thousands of medical students, but its content is also devoted to doctors of sciences other than radiology, who use imaging as an essential tool for diagnostic workup of patients.

The 25 years' experience of the textbook can clearly be recognized through its 20 chapters covering all fields of diagnostic imaging. The significant advances in imaging technology have brought a great number of new diagnostic images to this edition and new subjects, such as interventional radiology, have been included. Another important new feature of the book is body anatomy, explained either by plain films or by cross-sectional images. All diagnostic problems are presented in a very practical and essential way, tailored to students who will certainly be doctors but may not become radiologists. The reasoning of the author as a non-radiologist but with the radiologist's eyes is the most captivating feature of the textbook. This aspect can only be explained by Squire's and then Novelline's great experience in teaching medical students.

The first three chapters of the book are devoted to fundamentals of diagnostic imaging, like basic concepts on radiodensity and imaging techniques. This section is completed by the new extensive chapter on radiological anatomy. Chapters 4 to 10 of the textbook deal with chest-contained structures. This section is opened by a short introduction on "How to study" the chest, properly explaining to the student the many aspects of reading rays of this region. Going through the other chapters, the student faces the problems of the lesions affecting the lungs, the diaphragm, the pleural space, the mediastinum, and the heart.

Chapter 11 is introductory to the study of the abdomen and it is followed by three chapters dedicated to bowel gas patterns, free fluid and free air, to contrast study and CT of the gastrointestinal tract, and to abdominal organs. Condensing all abdominal diseases into four very clear and complete chapters has certainly required great efforts and ability. The chapter on the musculoskeletal system starts with a short introduction on "How to study radiographs of bones". In about 50 pages the essentials of bone abnormalities are fully discussed and summarized.

"Men, Women and Children" is one of the most interesting chapters of the book: obviously, it does not deal with a complete survey, but it covers the most common diseases related to sex (male, female) or young age.

The vascular system and the central nervous system are taught with an extremely wide series of cross-sectional images and with excellent angiographic reproductions. The new chapter on interventional radiology explains to the student the great role that this branch is playing in patient treatment. The text and figures clearly and exhaustively illustrate the many facets of interventional procedures. A short chapter on "Pathological Change over Time and Multisystem Disease: TB and AIDS" closes the textbook. Novelline's work confirms the high appreciation that the textbook received in its first four editions. The text is always clear, explaining the most difficult diagnostic situations in practical language. Some of the images presented are "unknown" diagnoses, so that the student is stimulated to give a personal solution. The keys to the tests are given at the end of the book, in a separate section.

Finally, the quality of all images and captions is excellent, mainly from the teaching point of view. In fact, I was unable to find any misleading image or caption.

Although the book is primarily devoted to medical students, its characteristics make it suitable also for first-/second-year residents in radiology. The book is definitely to be recommended to all doctors willing to know more about modern diagnostic imaging. Its size and reasonable price make this volume highly cost-effective.

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