Developmental anatomy of the atlas and axis in childhood by computed tomography

Clinical article

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Object. The CT modality plays a central role in the diagnosis of cervical spine fractures. In childhood, radiolucent synchondroses between ossification centers can resemble fractures, and they can be the sites of fractures as well. Recognition of cervical spine fractures in children requires familiarity with normal developmental anatomy and common variants as they appear on CT scans.

Methods. A convenience sample of 932 CT scans of the cervical spine accessible on the picture archiving and communications system (known as PACS) at a single children’s hospital was examined. Scans were excluded from further analysis if they did not include the atlantoaxial region or were otherwise technically unsatisfactory; if the patient carried the diagnosis of a skeletal dysplasia; or if there were developmental lesions noted at other levels of the spine. No more than 1 scan per patient was analyzed. Synchondroses were graded as radiolucent, not totally radiolucent but still visible, or no longer visible. Their locations and symmetries were noted. The presence or absence of the tubercles of the transverse ligament was noted as well.

Results. After exclusions, 841 studies of the atlas and 835 studies of the axis were analyzed. The 3 common ossification centers of the atlas arose in the paired neural arches and the anterior arch, but in as many as 20% of cases the anterior arch developed from paired symmetrical ossification centers. The 5 common ossification centers of the axis arose in the paired neural arches, in the basilar center, in the dentate center (from which most of the dentate process develops), and in the very apex of the dentate process. The appearance of each synchondrosis was noted at sequential ages. The tubercles for the transverse ligament generally did not appear until the ossification of the synchondroses of the atlas was far advanced. Anomalies of the atlas included anterior and posterior spina bifida, absence of sectors of the posterior arch, and anomalous ossification centers and synchondroses. Anomalies of the axis were much less common. What appeared possibly to be chronic, incompletely healed fractures of the atlas were discovered on review for this analysis in 6 cases. No fractures of the axis were discovered.

Conclusions. There is substantial variation in the time course and pattern of development of the atlas, and anomalies are common. Some fractures of the atlas may escape recognition without manifest sequelae. Variation in the time course of the development of the axis is notable as well, but anomalies seem much less common.

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Key Words • atlas • axis • computed tomography • synchondrosis • ossification center • spine

STUDY has been devoted to the normal development of the atlas and the axis in childhood as imaged by skeletal radiography and CT scanning.5,7,9,13–16,20,22 Early investigations were purely descriptive.4,9 Some papers have focused on the evolution of single anatomical features over time.7 More recent work has attempted to be quantitative, but the datasets have been small in relation to the frequencies of common variations.5,14–16,22 Motivated by an interest in more confident distinction among synchondroses, developmental anomalies, and acute and healing fractures, we have undertaken a more extensive investigation of the normal postnatal development of ossification centers and synchondroses in the atlas and axis by CT scanning.

Methods

Digital records in the Department of Radiology were queried to identify patients who had undergone CT scanning of the neck. The files of 932 patients whose stud-
ies were available for review on the institution’s picture archiving and communication system (known as PACS) were accessed. Studies in patients with skeletal dysplasia—as determined by radiology reports or review of the electronic medical records—were noted and not analyzed further, as were studies with developmental lesions of the spine at other levels, postoperative studies, and studies that did not include the atlantoaxial region. Among patients who had had more than 1 CT scan of the neck, only 1 study was analyzed, generally the most recent. The majority of studies were indicated for soft-tissue lesions of the neck; these studies were viewed in bone windows with edge enhancement. A minority of studies was formatted specifically for osseous imaging. Images were acquired in 5-mm or thinner slices in all cases.

We analyzed 841 studies of the atlas. The status of the neurocentral, anterior midline, and posterior midline synchondroses and other anomalous synchondroses was recorded as follows: 1) totally radiolucent; 2) not totally radiolucent but still visible as a partial radiolucency or sclerosis; and 3) no longer visible (Fig. 1A). Inequality of the widths of the neurocentral synchondroses was noted. The tubercles for the transverse ligament were said to be present if distinct osseous prominences were visible on both sides. Qualitative notes were recorded describing other anomalies and observations of interest.

We analyzed 835 studies of the axis. The status of the neurocentral, posterior midline, dentocentral, and apical synchondroses and other anomalous synchondroses was recorded as for the atlas. Except as noted, no distinction was made between the portions of the neurocentral synchondrosis separating the neural arch ossification center from the dentate center or from the basal central ossification center (Fig. 1B). The “dentocentral” synchondrosis was defined as the synchondrosis between the dentate ossification center and the basal center. The dentocentral synchondrosis was visible reliably only on 2D sagittal or coronal reconstructions, which were available in 166 (20%) of axis studies.

The primary analysis yielded data that were readily presentable as bar charts describing the prevalence of specified anatomical features in each year of childhood. Because the study design was cross-sectional rather than longitudinal, there were no actual observations of the appearance or disappearance of any anatomical feature, so direct calculation of statistics such as median, mean, standard deviation, or confidence intervals for the times of such developmental events was not possible. For selected developmental events, however, median values and IQRs were estimated as follows: bar charts were reformatted as line graphs that approximated cumulative probability distributions for the selected developmental events. These graphs were smoothed visually, or, when variance was too great to permit confident visual smoothing, data points weighted by the numbers of observations at each age were fit to cubic curves. The median values and IQRs were taken manually from these curves.

The data collection instrument was constructed in Excel, and data were analyzed in Excel, Adobe Photoshop version 5.0, and SPSS version 17.0.

This project was conducted under the supervision of the Nemours Delaware Institutional Review Board.

Results

The number of studies of the atlas and the axis available for analysis at each age is presented in Table 1.

Studies of the Atlas

The neural arches begin to ossify in the fetal period, but in most individuals ossification of the anterior arch begins postnatally (Fig. 2). The earliest observation of ossification of the anterior arch was at 1 month of age. The oldest infant who had no ossification of the anterior arch was 22 months of age.

Ossification at the neurocentral synchondrosis is depicted in Fig. 3A. The estimated median age at initial ossification was 3.6 months (IQR = 1.7 to 5.5 months). The estimated median age at complete ossification was 12 months (IQR = 9.0 to 15.0 months). The estimated median age at initial ossification of the posterior midline synchondrosis was 3 months (IQR = 1.5 to 4.5 months). The estimated median age at complete ossification was 12 months (IQR = 9.0 to 15.0 months).

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TABLE 1: Numbers of studies available for analysis by patient age

<table>
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Fig. 1. Axial CT scans demonstrating synchondroses of the atlas (A) and the axis (B). 1 = anterior midline synchondrosis; 2 = accessory synchondrosis of the anterior arch; 3 = neurocentral synchondrosis; 4 = posterior midline synchondrosis; 5 = apical ossification center; 6 = neurocentral synchondroses; 7 = dentocentral synchondrosis.
Development of atlas and axis based on CT studies in children

Classification of both synchondroses was 5.2 years (IQR 4–6.3 years). The estimated median age at complete ossification was 8.5 years (IQR 5.5–13 years). The oldest patient in whom a totally lucent neurocentral synchondrosis was observed was 7 years 3 months of age. Asymmetry of the degree of ossification of the neurocentral synchondrosis was seen in 7 (7.2%) of 787 of all patients who had some degree of ossification of that anterior arch. Asymmetry about the midline plane in the location or patterns of the neurocentral synchondroses was common as well; it was seen in 7.4% of patients. Accessory neurocentral synchondroses were seen in 4% of patients, and in most cases they were either unilateral or asymmetrically situated.

Ossification of the posterior midline synchondrosis of the atlas is depicted in Fig. 3B. The estimated median age at initial ossification was 2.8 years (IQR 2–3.8 years). Unlike other synchondroses of the atlas, small but not negligible fractions of patients at all ages persistently exhibited radiolucency of the posterior midline synchondrosis. The overall prevalence of radiolucency of the posterior midline synchondrosis among patients older than 5 years was 5%; these individuals might be said to have posterior spina bifida. In 10 patients (1.2%), development of the posterior arch of the atlas included a posterior midline ossification center and paired paramedian synchondroses.

Unlike the neurocentral synchondroses and the posterior midline synchondrosis, which seem to be nearly universal features of the development of the atlas, the presence of an anterior midline synchondrosis is variable. The prevalence of radiolucency at this site is depicted in Fig. 3C. An anterior midline synchondrosis seems to be a feature of the development of the atlas in no more than 20% of patients. In most cases an anterior midline synchondrosis was found in association with neurocentral synchondroses, the former generally in a more advanced state of ossification than the latter. In 6 instances the anterior arch of the atlas seemed to be developing by extension of the neural ossification centers without any central ossification center whatsoever (Fig. 4).

Another assortment of radiolucencies in the ring of the atlas had less certain provenance. Figure 5 presents examples of radiolucencies that, because of their asymmetries or the irregular contours of the adjacent bone, suggest old, unhealed fractures. None of these cases had relevant histories in the medical record, so the traumatic nature of the findings is purely speculative. Figure 6 depicts radiolucencies of the posterior arch that are presumed to be of developmental origin.

The transverse ligament of the atlas arises from the medial aspects of the lateral masses, and in some individuals an osseous tubercle develops at its insertion sites (Fig. 7). Traumatic disruption of the transverse ligament can be associated with avulsion of this tubercle from the lateral mass, and displacement of the ossified tubercle can thus be a critical diagnostic finding on axial CT scans. A scan was judged to exhibit tubercles if osseous prominences were seen arising from the medial aspect of both lateral masses at appropriate locations behind the dentate process of the axis. The tubercles were better developed in older patients and less distinct in younger. Figure 8 depicts the prevalence of tubercles for the transverse ligament. The estimated median age at the appearance of tubercles for the transverse ligament was 9.5 years (IQR 6.4–13.5 years).
Studies of the Axis

In postnatal life the axis develops from 5 ossification centers: paired neural arch ossification centers; a basal central ossification center; a dentate center; and an apical center. For the purposes of this study, a note was made of the radiolucency of the posterior midline synchondrosis and the neurocentral synchondroses, which were easily seen on axial images. In fetal life the dentate center arises from paired ossification centers that are symmetrical around the sagittal midline plane. By the time of birth, most often these centers have fused, and all that remains of their earlier separation is a sagittally oriented cleft at the superior end of the ossifying odontoid. When it appears later in childhood, the apical center seems to rest in this cleft. The 2D coronal reconstructions of CT scans generally depict the apical center sitting atop the cleft of the odontoid, giving the appearance of the stamen in the bloom of a flower. As the dentate develops, the bloom closes on the stamen (Fig. 9). Because of the complex geometry of this relationship, the apical center was noted simply to be absent, present as a protrusion from the dentate center or as a distinct nodule, or completely incorporated into the dentate process. In scans that included sagittal and coronal reconstructions, the status of the dentocentral synchondrosis was noted as well.

Few scans of patients in the first 2 years of life demonstrated ossification in the apical center, but by the 6th year of life almost all scans showed some degree of ossification (Fig. 10). The estimated median age at initial ossification of the apical center was 2.7 years (IQR 1.9–3.6 years). The oldest child with no ossification in an apical center was 12 years 10 months of age; the dentate process in this case exhibited a deep but totally radiolucent sagittal notch (Fig. 11). Figure 12 depicts the time course of incorporation of the apical center into the substance of the odontoid. The estimated median age at incorporation of the apical center was 8.2 years (IQR 7.1–9.9 years).

Radiolucency in the neurocentral synchondrosis of the axis is easily visible on axial images in infancy, but it disappears in early childhood (Fig. 13A). The estimated median age at initial ossification of the neurocentral synchondrosis was 3.8 years (IQR 2.9–4.6 years). The superior portion of the neurocentral synchondrosis, between the neural arches and the dentate process, closes later than the inferior portion, between the arches and the basal central ossification center. The oldest child exhibiting radiolucency in the neurocentral synchondrosis was 5 years 8 months of age.

Similarly, radiolucency in the posterior midline synchondrosis between the neural arches is present in 96% of infants, and it is gone by the end of the 3rd year of life (data...
Development of atlas and axis based on CT studies in children

Fig. 5. Examples on CT scans of radiolucencies of the ring of the atlas of uncertain provenance. The asymmetrical locations and irregular but mostly corticated contours are suggestive of past trauma, but there were no histories of trauma in the medical record. In panel C the posterior arch of the atlas lies out of the plane of the image; it was bifid. The patient whose atlas is depicted in panel D was a 12-year-old boy with acute neck pain after a spearing tackle in football. He was judged possibly to have reinjured an old, forgotten, unhealed fracture site. His pain resolved with a brief period of immobilization in a rigid cervical orthosis, and he did not return for follow-up imaging.

not shown). Aside from 1 anomalous 14-year-old patient, the oldest individual exhibiting radiolucency in the posterior midline synchondrosis was 2 years 5 months of age.

The dentocentral synchondrosis was visible only on coronal and sagittal 2D reconstructions and was better demonstrated on the latter. One hundred sixty-six patients had such reconstructed images. Radiolucency of the dentocentral synchondrosis began to disappear very early in childhood (Fig. 13B). The oldest patient with complete radiolucency of the dentocentral synchondrosis on sagittal reconstructions was an anomalous 8 years 6 months of age, but the next oldest was 3 years 4 months. On the other hand, sclerotic traces of this synchondrosis remained visible in virtually all the oldest patients in this study; this is what Ogden and colleagues call the “dentocentral ghost” (data not shown).

In contrast to the atlas, where these anomalies are seen with moderate frequency, only 3 patients (0.4%) exhibited anomalous ossification centers. In each instance the anomalous centers were bilateral and symmetrical, intercalated into the neurocentral synchondroses (Fig. 14). The patients in these cases were 7, 16, and 25 months of age.

Estimated median ages and IQRs for selected developmental events are presented in Table 2.

Discussion

Qualitative features of the development of the atlas and the axis are presented in major textbooks and are familiar to experienced pediatric radiologists and neurosurgeons; however, documentation of variation in the timing of developmental changes is very limited. Also, varying sets of anatomical parameters have held interest for different authors.

In 1952, Bailey presented observations based on cervical spine radiographs of 100 normal children younger than 14 years. He noted that the anterior arch of the atlas is not visible at birth, but generally begins to ossify in the 1st year of life. He noted that the posterior midline synchondrosis “fuses” by the 7th year. He described the occasional development of the anterior arch from 2 ossification centers or by extensions from the neural arch ossifications centers, and he commented on the possible persistence of an anterior midline cleft. With regard to the axis he noted that the neurocentral synchondroses and the dentocentral synchondrosis are generally no longer visible after the 6th year. The posterior midline synchondrosis remains unfused until approximately the age of 3 years. He stated that the apical center appears between 3
and 6 years of age and fuses with the dentate process by 12 years.

In a classic series of publications, Ogden studied skeletal development by radiography of fresh cadaver specimens. On the basis of examination of 36 specimens of the atlas, the authors noted complete ossification of the anterior arch, with well-formed neurocentral synchondroses by 18–21 months of age. Posterior midline synchondroses were closed by 5 years, and by 6 years the neurocentral synchondroses were closed as well. In a companion study of the axis, the authors noted that the paired ossification centers of the dentate—present in fetal life—were fused by 3 months of age. The posterior midline synchondrosis was closed by 3 years, and by 9 to 10 years the neurocentral synchondroses were solid. The dentocentral synchondrosis was noted to begin to close at approximately 3 years, but a sclerotic “ghost” persisted through adolescence. An apical center appeared as early as 5 years, and was completely incorporated into the dentate process at “skeletal maturity.” This anatomical material included an example of an accessory ossification center lying within the neurocentral synchondrosis of a neonate (the author’s Fig. 1).

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Fig. 6. Axial CT scans demonstrating radiolucencies of the posterior arch that are presumed to be developmental. Panels A and B are cuts from the study of a single patient demonstrating symmetrical radiolucencies just posterior to the lateral masses (arrowheads). Panels C, D, and E depict absences of half, three-quarters, and the entire posterior arch, respectively. The spinous processes of the axis are visible in panels D and E (arrows). Panels F–H demonstrate medial and lateral sectoral radiolucencies (asterisks).

Fig. 7. Axial CT scans demonstrating tubercles for the transverse ligament (arrowheads) in an 8-year-old child (A) and a 20-year-old patient (B).

Fig. 8. Bar graph showing the prevalences of the tubercle for the transverse ligament of the atlas. Numbers of observations at each age are presented in Table 1.
Development of atlas and axis based on CT studies in children

Elliott reviewed lateral radiographs obtained in 508 children to document the relationship of the dentate process to the anterior arch of the atlas. He observed that in children younger than 9 years the superior tip of the dentate often fails to cross the superior border of the anterior arch, creating an appearance of hypoplasia. The development of synchondroses was not within the scope of this study.

In what appears to be the only longitudinal study of the cervical spine in childhood, Wang and colleagues reviewed archived radiographs of 96 children enrolled in the Cleveland Study of Normal Growth and Development between 1927 and 1942. Radiographs were obtained at regular intervals in all patients between 3 months and 17 years of age. The focus of the study was linear growth, but the authors comment that ossification of the anterior arch had begun in 33% of children at 3 months, and in 80% of children at 1 year—fractions very comparable to the observations in the current study. Ossification of the arch was complete in all patients by 3 years.

Suss and colleagues studied the offset of the lateral mass of the atlas with respect to the superior articular facet of the axis as seen in “open mouth” radiographs. Among adults, an offset of more than 2 mm is regarded as a sign of disruption of the ring of the atlas, but it is a common, normal finding among young children. These authors tabulated the prevalence of “pseudospread” at intervals through early childhood, and developed a normative metrical index for identification of pathological degrees of offset.

In the only previous developmental study based on CT scans, Calvy and colleagues reviewed scans obtained in 129 normal patients from birth to 18 years of age. These authors did not define the terms that they used to describe the status of the synchondroses. With respect to the atlas, the oldest patients in whom the neurocentral synchondroses and the posterior midline synchondroses were “apparent” were 7 years 1 month and 4 years 2 months of age, respectively. In contrast, in the current study we have documented a small but persistent rate of radiolucency in the posterior midline through adolescence. With respect to the axis, Calvy et al. comment that the sagittal cleft in the dentate process persists much later posteriorly than anteriorly. In seemingly good agreement with the current study, a density corresponding to the apical center was “visible” as late as 9 years of age. The neurocentral synchondroses of the axis were “visible” at late as 15 years of age, whereas the current study documented disappearance of radiolucency by 7 years of age.

The current study complements the report of Senoglu and colleagues, who sought anomalies of the adult atlas in 1106 CT scans, 166 dried anatomical specimens, and 84 fresh cadaveric specimens. They found 37 examples of congenital defects of the posterior arch (3.35% of CT scans) and 1 case (0.09%) with a defect of the anterior arch together with a sectoral defect in the posterior arch. The prevalence of posterior arch defects observed by Senoglu et al. is consistent with the persistence of radiolucency in the posterior midline in approximately 5% of older teenagers in the current study (Fig. 3B). The virtual absence of anterior arch defects among adults suggests that the great majority of the anterior defects observed in the current study were destined eventually to ossify completely.

Fractures of the immature atlas seem generally to follow a benign course requiring minimal intervention, and a number of authors have expressed curiosity or concern

Fig. 9. Coronal CT scan reconstructions obtained through the dentate process at various stages of development. See text for more details.

Fig. 10. Bar graph showing absence of ossification in the apical center of the dentate process. The numbers above the bars represent observations in each age group. The total number of observations was 627.

Fig. 11. A CT scan demonstrating a deep, sagittally oriented radiolucent notch in an otherwise well-formed dentate process in a 12-year-old child. This dentate seems to have developed without an apical ossification center.
about the possibility of missed diagnosis. Contemporary clinical experience with fractures of the immature atlas has indicated that they present—often in a delayed fashion—with neck pain and torticollis after injuries of sometimes trivial severity. Symptoms respond to rather brief periods of immobilization, and the fractures seem to heal without long-term sequelae. That some children with atlas fractures might never come to medical attention is entirely plausible, and if a never-treated fracture were to heal imperfectly, it might be interpreted as an "anomaly" on a subsequent CT scan obtained for an unrelated reason. Figure 5A, C, and D from the current study bring such a possibility to mind (see also Fig. 1B in the report of Senoglu et al., Ogden, and Fig. 6B of Currarino et al.). Each case exhibits an irregular anterior cleft in association with a posterior arch defect. This association may reflect simply the occurrence of developmental errors, but another possibility is that a congenital defect in the posterior arch weakens the ring of the atlas and lowers the resistance of an anterior midline synchondrosis to fracture from unrecorded trauma, with the synchondrosis fracture eventually healing with irregular osseous margins. The true incidence and the natural history of fractures of the immature atlas must be regarded as unknown.

In contrast to the atlas and despite its inherently greater developmental complexity, variations in the basic pattern of ossification centers and synchondroses were distinctly uncommon in the axis. In the current study we captured only 3 examples of accessory ossification centers intercalated into the neurocentral synchondroses. The current study sheds no light on the continuing mystery of the provenance of os odontoideum, except to affirm the well-known lack of correspondence between the pathological anatomy of this lesion and the developmental anatomy of the normal dentate process.

The current investigation suffers from a number of obvious limitations. As a retrospectively examined convenience sample, the scans exhibited widely varying technical quality, and only a limited number were reconstructed in coronal or sagittal planes. Grading of the degree of maturation of synchondroses was subjective, and no assessment of intrarater or interrater consistency was undertaken. There was no analysis of variation by sex or race. Finally, the ideal format for study of developmental anatomy is longitudinal, but our study was cross-sectional. We limited our analysis to 1 imaging study per patient. Consequently, a synthetic and subjective process was used to estimate medians and IQRs for selected developmental events, which were never observed directly. A longitudinal study in which ionizing radiation is used will never be performed for ethical reasons.

**Conclusions**

Greater familiarity with the normal developmental patterns of the atlas and the axis, as displayed on CT scans, will enhance the recognition of fractures in younger children, clarify the natural history of such injuries, and support more assured clinical management.
Development of atlas and axis based on CT studies in children

![Image](7 months, 16 months, 25 months)

Fig. 14. Examples on CT scans of anomalous ossification centers in the axis from 3 different cases. Symmetrical accessory ossification centers have arisen within the anterior portions of the neurocentral synchondroses.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation. Conception and design: both authors. Acquisition of data: both authors. Analysis and interpretation of data: Piatt. Drafting the article: Piatt. Critically revising the article: both authors. Reviewed submitted version of manuscript: both authors. Approved the final version of the manuscript on behalf of all authors: Piatt. Administrative/technical/material support: Grissom. Study supervision: both authors.

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