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Volumetric determination of normal and scoliotic vertebral bodies

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Abstract A new method is presented for stereological evaluation of the volume of the vertebral body in vivo. The height of the vertebral body is measured at three standardised points on an anteroposterior radiograph and at two other points on a lateral one. The area of the body is also measured using a special grid superimposed on a CT scan from the middle part of the vertebra. The volume of the vertebral body is then calculated using Cavalieri's principle for irregular objects: $V = \Delta a \times H$, where V is the volume of the vertebral body, Δa is the mean cross-section surface area on the CT scan and H is the mean of the heights at the five points on the radiographs, computed as mean weighted circumferential height. The volume of one normal and one scoliotic vertebra was evaluated in vitro using this formula. The obtained values were compared with the values derived from serial CT scans of the two vertebrae. The results showed that the volume of the normal vertebra measured with our new method was 15.9 cm^3 and measured with serial CT scans using the same grid it was 15.07 cm^3 .

For the scoliotic vertebra the values were 17.6 and 17.3 cm^3 , respectively. The degree of accuracy of the measurements with the presented method as compared with the serial CT method was 95% for the normal and 98.5% for the scoliotic vertebra. To prove the clinical applicability of the method, the heights of the apical and of the upper and the lower end vertebrae of the curve and the volume of the apical vertebrae were evaluated in eight scoliotic girls (nine curves) before and 3 years after spinal instrumentation and posterior fusion. The results showed that the mean circumferential height of the three vertebrae had increased significantly at the last follow-up. The volume of the apical vertebra had also increased, but the difference was not significant. It is concluded that the described method is easy to apply and has satisfactory accuracy for in vivo longitudinal studies of the volume of the vertebral body on radiographs and CT scans.

Key words Vertebral body volume · Method · Apex vertebra · Scoliotic vertebra · Longitudinal studies

Introduction

Vertebral growth is a determining factor for the configuration of the spine in health and disease. There are several reports on vertebral growth per se [4, 18] and in relation

to clinical aspects of idiopathic scoliosis (IS) [19, 22], in Scheuermann's disease [6, 20] and in relation to the pathomechanism in experimental scoliosis [15]. There are also reports on vertebral growth asymmetry during development of scoliosis [3, 18] and still others vertebral growth after posterior spinal fusion [11, 14, 17] or after spinal in-

strumentation and fusion [2, 7, 12, 13, 16]. The conclusion drawn from these studies are based exclusively on measurements of the vertebral height and width on radiographs, or on evaluation of certain CT scan variables [23, 25, 26]. However, vertebral growth is a three-dimensional process and, except for serial CT scans which carry a high radiation risk for the patient, there is at present not method for evaluation of the volume of a vertebral body in vivo.

The aim of this study was to present a model stereological method for in vivo evaluation of the volume of the vertebral body by measurements of its weighted circumferential height from plain anteroposterior and lateral radiographs and of its surface area on a CT scan. In order to prove the clinical applicability of the method, the volume of the apical vertebra was evaluated in eight patients with adolescent IS (nine curves) before and on average 3 years after spinal instrumentation and posterior fusion.

Materials and methods

Model study

One isolated normal thoracic vertebra and the apical vertebra from a scoliotic spine were used in this part of the study.

Method

The height of the normal and scoliotic vertebral body was measured at five easily determined points: 1, 2, and 3 on anteroposte-

rior (AP) and 4 and 5 on lateral radiographs of the vertebrae. Points 1 and 2 were determined at the corners of the upper endplate of the vertebra on the AP radiograph and point 3 was at the midpoint between the two. Point 4 was determined at the anterior corner of the upper endplate of the vertebra on the lateral radiograph, and point 5 was halfway between this point and point 2. Lines were then drawn from these points perpendicularly to the lower endplate of the vertebra, representing the height of the vertebra at each of these points (Fig. 1).

The power of the height at each of the points 1, 2, 3, 4 and 5 in relation to the mean height of the vertebra was calculated as follows: the distance between neighbouring points was measured with a flexible wire and divided at the middle. Then the sum of the two distances of the points to the mid distance on each side was calculated and expressed as a percentage of the whole circumference of the vertebral body. The weighted height, i.e. the power, of points 1, 2, 3, 4 and 5 were found for the normal and the scoliotic vertebra to be 25, 15, 12, 29 and 19%, respectively (Fig. 2). The mean of the heights derived in this way, i.e. the weighted circumferential height of the vertebral body, was used.

The magnification constant was taken into consideration with the aid of the radio-opaque ruler placed parallel to the examined vertebra during exposure.

On the CT scan, taken approximately at the middle of the vertebral body, the surface area of the body was determined as follows. A grid (Fig. 3) with equidistant points in two dimensions was superimposed on the CT scan image of the vertebral body (Fig. 4). The number of points of the grid included in the area of the CT image of the vertebral body was then counted repeatedly by replacing the grid ten times, and the mean of the ten measurements was used. By counting the number of points of this grid in 1 cm² of the calibrated CT scale a factor equal to 0.065 was derived, which is dependent on the CT magnification scale and the size of the grid itself.

For evaluation of the volume of the vertebral body a stereological method was used based on the following principle for estimation of the volume of irregular objects, established by Cavalier (an

Fig. 1 Definition of points 1, 2 and 3 on the anteroposterior radiographs and points 4 and 5 on the lateral ones for estimation of the height of vertebral body **a** normal vertebra, **b** scoliotic vertebra

Fig. 2 Determination of the power of the five points as percentages of the vertebral circumference

Fig. 3 The grid used for measurement of the area of the vertebral body in the horizontal plane

Italian mathematician, 1598–1647, and disciple of Galileo Galilei): $V = \Delta a \times H$, where V is the volume of the vertebral body, Δa is the mean cross-section surface area on the CT scan, and H is the mean weighted circumferential height of the vertebra, derived from AP and lateral radiographs as described above. For maximal precision, according to Cavalieri's principle, 150–200 points should be counted each time over the CT scan image, the precision being degraded if the numbers of points counted outside this interval [10].

In order to evaluate the intraobserver variation of the measurements, the whole procedure was repeated ten times for each vertebra, and the mean value was used. To establish interobserver variation, a second examiner independently evaluated three measurements for the normal and the scoliotic vertebra, respectively.

To evaluate the accuracy of the values obtained according to Cavalieri's principle, the volume of the two vertebral bodies was also calculated by measurements of the cross-section surface area of the vertebral body on serial CT scans taken at fixed 3-mm-intervals, using the same procedure. Six to seven scans were taken for the normal and the scoliotic vertebra respectively and the most central one, including the whole surface area of the vertebral body, was used for the measurements.

The real volumes of the normal and the scoliotic vertebral bodies were also determined using Archimedes' method. The posterior element of the specimen was sawed off. The vertebral bodies were sealed by soft bone wax to make them impermeable to water. Each vertebral body was then immersed in distilled water at room temperature, and the displaced water was estimated volumetrically. This procedure was repeated six times for each vertebra, and the mean value was used.

To further prove the accuracy of Cavalieri's formula, the volume of a 3-cm-high regular cube, and its width and length were calculated following the same procedure, by measuring the surface area of a cross-section of the cube using the grid and the known height of 3 cm as the mean height.

Finally, to determine the effect of rotation or tilting, each vertebra was mounted in a special device allowing gradual rotation at the frontal and horizontal plane (accuracy of the goniometer 1°). Rotation at the sagittal plane was obtained by tilting the gantry of the computer tomograph [1, 25]. AP and lateral radiographs and CT scans were taken with the vertebra in 0° forward-backward tilt and right-left rotation and then in rotation of 5°, 10°, 15°, 20°, 30° and 90° and in tilting position of 5°, 10°, 15°, 20° and 30°.

Clinical study

The applicability of the method was assessed using the AP and lateral radiographs and one CT scan, taken at the level of the apical vertebrae, of nine scoliotic curves in eight patients with adolescent idiopathic scoliosis before and at the last follow-up after CD spinal instrumentation and posterior fusion. The mean weighted circumferential height of the upper end vertebra (UEV), the lower end vertebra (LEV) and the apical vertebra (AV), and the volume of the apical vertebral body were estimated.

The mean age of the patients at operation was 14.35 years (range 11–18 years); the mean Cobb angle was 40.9° (range 30°–50°); the curve was right convex thoracic in seven cases and in one double primary; the mean follow up time was 3 years (range 2.25–4.5 years); the apical vertebra was the T9 in four cases, the T10 in two cases, and there was one case each of T7, T8 and L3.

In order to determine the advantages or disadvantages of the mean weighted circumferential height in the measurements of the height of the upper and lower end vertebrae, and the height and the volume of the apical vertebra in this study, these variables were also computed using the means of absolute heights at the five points of the radiographs (Fig. 1).

The magnification on the radiographs was evaluated by measuring the length of one CD rod immediately after the operation on the AP radiograph, with the same rod being measured again on the radiograph taken at the last follow-up.

Statistical analysis

Paired Student *t*-test was used to test the significance of the registered differences between the values obtained by the intra- and the interobserver measurements for the model study, and to estimate the pre- and postoperative differences in the heights of the UEV, LEV and AV and also the volume of the AV in the clinical study computed by use of the weighted circumferential and the absolute height values.

Fig. 4 The grid superimposed on the CT image of **a** the normal and **b** the scoliotic vertebra

Results

Model study

For the normal vertebra, the mean of ten measurements of the cross-section surface area was 7.67 cm^2 , and the mean weighted circumferential height was 2.08 cm . Application of the formula yielded a mean volume of $15.9 \pm 0.12 \text{ cm}^3$. The volume derived from the serial CT scans was 15.07 cm^3 . The volume of the vertebral body derived from the formula therefore corresponds to 95% of the volume obtained by the measurements on serial CT scans. The mean volume derived from the Archimedes principle was 12.7 cm^3 (Table 1).

For the scoliotic vertebra, the mean of ten measurements of the surface area was 9.11 cm^2 , the mean weighted circumferential height was 1.93 cm , and the mean volume derived from the formula was $17.6 \pm 0.25 \text{ cm}^3$. The volume obtained from the serial CT scans was 17.3 cm^3 . Thus the volume of the body of the scoliotic vertebra derived from the formula represents 98.5% of the volume obtained from serial CT scans. The mean volume derived from the Archimedes principle was 15.5 cm^3 (Table 1).

The mean variations of three measurements by a second examiner were, for the cross-section surface area of the normal vertebra, 7.94 cm^2 , and for the mean weighted circumferential height, 1.97 cm . Application of the formula yielded a mean volume of $15.64 \pm 0.09 \text{ cm}^3$. The mean values for the scoliotic vertebra were, for the cross-section surface area, 9.42 cm^2 , for the mean weighted circumferential height, 1.82 cm , and for the volume, $17.14 \pm 0.44 \text{ cm}^3$.

There were no significant differences between the values obtained by the two observers, either for the normal or for the scoliotic vertebra. There were no significant differences between the values of the cross-section surface area on the CT scans taken at different degrees of frontal or horizontal rotation of the vertebrae up to 90° or for tilting of the vertebrae up to 15° ($P > 0.1$); for tilt of more than 15° the differences were significant ($P < 0.01$).

Table 1 Comparison of the values obtained by three methods used for estimation of the volume of the normal and the scoliotic vertebral body (mean difference, cm^3)

	Cavalieri's vs serial CT	Cavalieri's vs Archimedes'	Serial CT vs Archimedes'
Normal	0.83	3.2***	2.37***
Scoliotic	0.30	2.1***	1.80***

*** Significant at 99.9%

Table 2 Pre- and postoperative values of the mean weighted circumferential height of the upper end vertebra (UEV), the lower end vertebra (LEV) and the apical vertebra (AV) of the nine curves (mean height, cm)

Vertebra	Preop	3 years postop	Difference	%
UEV	1.74	1.89	0.15	8.62*
LEV	2.04	2.29	0.25	12.25**
AV	1.85	2.05	0.2	10.81***

*Significant at 95%; **Significant at 99%; ***Significant at 99.9%

Fig. 5 Changes in the circumferential height of the upper end vertebra, the apical vertebra and the lower end vertebra for nine curves before and after spinal instrumentation

Table 3 Comparison of the pre- and postoperative values of the height of the UEV, the AV and the LEV, as computed with the mean weighted circumferential height and the mean absolute height

	UEV			AV			LEV		
	Preop	Postop	P	Preop	Postop	P	Preop	Postop	P
Circumf h	1.74	1.89	0.04	1.85	2.05	0.0001	2.04	2.29	0.007
Absolute h	1.73	1.87	0.054	1.82	2.02	0.0001	2.03	2.28	0.008
P	0.5	0.08		0.0002	0.01		0.2	0.3	

Table 4 Pre- and 3-years postoperative values of the volume of the apical vertebrae of nine curves (volume, cm³)

Vertebra	Pre-operative	3 years postop	Difference	%
T9	17.07	17.63	0.56	3.28
T9	8.29	7.6	-0.7	-8.38
T10	16.13	16.01	-0.12	-0.75
L3	19.62	23.36	3.74	19.07
T9	12.77	14.41	1.63	12.78
T8	10.41	9.7	-0.71	-6.85
T9	19.59	16.08	-3.51	-17.93
T7	6.6	10.73	4.13	62.66
T10	15.8	17.69	1.88	11.9
Mean	14.03	14.8	0.77 n.s.	8.4

The known volume, 27 cm³, of the model cube was 27.09 cm³ by application of the formula, i.e. 99.7% of the real volume.

The coefficient of variation of the measurements by the same observer was 0.7 for the normal and 1.4 for the scoliotic vertebra. The corresponding values for the inter-observer variations were 1.4 and 2.5 respectively.

Clinical study

The mean preoperative Cobb angle decreased from 40.9° to 13.5° at the last follow-up ($P < 0.001$). The mean weighted circumferential height of the AV, UEV and LEV of the nine curves was significantly increased for each vertebra on the last follow-up radiographs ($P < 0.0001$, $P < 0.03$, $P < 0.006$ respectively; Table 2, Fig. 5). The increase in the mean weighted circumferential height of the AV was significantly greater than that of the UEV and LEV ($P < 0.0001$; Table 3).

The volume of the nine apical vertebrae was increased in five cases and somewhat decreased in four cases. The mean value was increased by 8.4%, but the difference was not significant ($P = 0.3$; Table 4).

The comparison between the values obtained by use of the mean weighted circumferential heights and those obtained by using the mean absolute heights showed that:

1. The height of the UEV at follow-up, when derived from the mean weighted circumferential height, was significantly higher than the preoperative height ($P < 0.05$), but not if it was derived from the mean absolute height.

2. The height of the AV at follow-up was significantly higher than the preoperative value ($P < 0.0001$) with both methods.

3. The height of the LEV was significantly increased at follow-up ($P < 0.01$) when derived with either method.

With regard to the volume of the apical vertebra, the values derived using the mean weighted circumferential height were significantly higher than those obtained from the mean absolute height ($P < 0.01$).

The values obtained from measuring the length of the CD rod on the radiographs taken immediately after the operation and at the last follow-up showed a mean, not significant, percentage magnification of 0.9%, implying that the magnification factor was negligible.

Discussion

The results of the in vitro model study indicate that the values of the volume of the vertebral body derived from the presented method were in close concordance with the values obtained from serial CT scans, i.e. 95% for the normal vertebra and 98.5% for the scoliotic. There was also almost complete concordance between the volume of the model cube with known dimensions and its volume derived by application of the formula, i.e. 27 cm³ and 27.09 cm³ respectively. Moreover, the new method has high repeatability, with a coefficient of variation of 0.7 for the normal and 1.4 for the scoliotic vertebra.

The lower values yielded by using Archimedes' principle as compared with the values obtained by use of the Cavalieri formula or serial CT scans are mainly attributable to the differences between the methods in determining the volume of the body. Archimedes' method takes into consideration the biconcavity of the vertebral body, while the other two methods are based on standardised points of the vertebral body on radiographs. Uneven sawing of the posterior elements of the vertebra and defective wax sealing of the vertebral body may be other contributing factors for the difference. However, considering the high degree of repeatability of the presented method, this difference is of less importance, especially in longitudinal studies of the vertebral body volume in vivo.

The purpose of the clinical study was to validate the applicability of the derived method in vivo rather than to evaluate the long-term effect of instrumentation on the volume of the apical vertebra. The varying age of the pa-

tients at operation and the known decline of the growth velocity after about 13 years, the relatively short and varying time of follow-up, and the limited number of cases allow no such conclusion from this material.

However, despite these limitations, the results of this study showed that the derived method provides the possibility for accurate evaluation of changes of the volume of the vertebral body in longitudinal studies, by defining adopted landmarks of a vertebra on existing radiographic material. The results of a comprehensive study on the accuracy of measurements of the lumbar vertebrae on lateral radiographs indicate the complexity in defining radiological and anatomical landmarks of a vertebra [9].

The main advantage of the presented method is the introduction of a stereological approach for estimation of the vertebral body volume *in vivo*. Lack of appropriate methods for this purpose has until now hampered investigations into normal vertebral growth as well as into the development of pathological vertebral changes, for instance in scoliosis. This is also true of studies of the effect of treatment.

Another advantage of the method is the use of weighted circumferential height instead of absolute mean height of the vertebral body. The differences in the value for vertebral height and volume of the apical vertebra obtained by the two ways of measuring the height indicate that use of weighted values yields significantly higher differences in longitudinal studies than when absolute values are used. This implies that the former method, giving a better representation of the vertebral height, is more sensitive for similar comparisons than the latter. The fact that the vertebral height difference was more pronounced in the AV than the UEV and LEV may be due to the fact that the AV is more deformed than the two end vertebrae.

Moreover, vertebral body volume is measured on the available AP and lateral radiographs of the spine and one CT scan of the apical vertebra. The latter is increasingly used by several authors [5, 8, 21, 24] for evaluation of

change of the degree of the vertebral rotation and the rib hump, for instance after instrumentation. It is true that the volume of the apical vertebra can also be evaluated by serial CT scans, but then the patient is exposed to repeated irradiation, in each follow up, which is especially undesirable for young persons.

Finally, the results of the clinical study also showed that under the prevailing circumstances the mean weighted circumferential height of the apical vertebra increased significantly more than that of the end vertebrae of the curve and that even the volume of the apical vertebra at the end of the mean follow-up period had increased by 8.4% though this difference was not significant.

Methods used for evaluation of vertebral growth [18] or vertebral remodelling after spine surgery are based on measurements of distances between selected points on radiographs of the concerned vertebrae [11, 12, 14, 17] or the disc [15, 16] for indirect estimation of the vertebral growth.

However, all these methods give measurements of vertebral changes in only two dimensions and not in a spatial (stereometric) dimension, i.e. the volume of the vertebra. Measurements of vertebral rotation and other vertebral variables do not add information on the growth in volume of the vertebra

In the absence of a method for accurate evaluation of the volume of a vertebral body, the described stereological method, based on measurements of the mean weighted circumferential height on available radiographs and of the cross-section surface area on one CT scan, provides a useful tool with broad applications for *in vivo* longitudinal evaluation of vertebral growth in general, and of the remodelling of the apical vertebra after spinal instrumentation in particular.

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