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Computer-Generated Index for Evaluation of Idiopathic Scoliosis in Digital Chest Images: A Comparison with Digital Measurement

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An intelligence system was used to generate index for scoliosis. Tests were designed to evaluate the consistency of the automatic computer-generated index and to quantify the correlation between Cobb angle and computer generated scoliosis classification index (SCI). A fully automatic computer-generated index can be used to assess the extent of spinal curvature rather than manual measurement on radiographs. This study aims to evaluate the relation of an automatic computer-generated index in assessing the spinal curvature of scoliosis quantitatively on digital chest images. Sixty chest radiographs were obtained in this study. Cobb angle measurement and the index generated were compared by parametric statistical tests. The SCI method was demonstrated to be reproducible. There was also statically significant positive correlation between Cobb angle and SCI (Pearson's correlation: $r = 0.9229$). The Computer-generated index method is valid and reliable in quantifying measurement of spinal curvature of scoliosis as the correlation between Cobb's angle and SCI in nearly perfect positive for Cobb angle more than 10 degree. It is noted that with widely use of this computer method, this quantitative method proposed is a promising method in improving the reliability of scoliosis assessment and reducing the workload of clinical staff.

KEY WORDS: Computer-aided diagnosis (CAD), fuzzy logic, chest radiographs, classification

INTRODUCTION

R adiographic evaluation of Cobb angle* is one of the most widely used methods for assessing scoliosis.[1] However, using such a measurement method may lead to errors such as intraobserver and interobserver variations by different examiners.[2–7] The quality of the images will also affect the reliability of the measurement method. These limit the validity and consistency of the measurement results and thus affect the treatment patients receive.

Greenspan[8] proposed the scoliotic index (SI) to obtain a more accurate determination of the spinal curvature. By this method, the deviation of each involved vertebral segment from the vertical spinal lines is measured with multiple points taken along the scoliotic curve and provides a more comprehensive and accurate representation of the scoliotic curve. However, this method involves many tedious measurements that limit the extensive use of the SI. On the other hand, with the use of a computer, an automatic measurement of indexes can facilitate a more objective and consistent result and minimize the errors created by the subjectivity of human examiners.

It has been noted that with the help of computer-assisted measurement, the reliability and consistency of Cobb angle measurement is improved.[3,7,9] Nevertheless, the computer-assisted method is still not automatic in tracking the affected vertebrae, and there are various levels of user intervention

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*Cobb angle: angle between lines drawn on endplates of the end vertebrae (superior endplate of upper end vertebra; inferior endplate of lower end vertebra) see: Scoliosis Research Society (SRS) http://www.srs.org/professionals/glossary/glossary.asp.

such as location of anatomical landmarks by observers.[9] Despite the improvements in reducing interobserver variation, time-consumption is still an influential factor for evaluation of scoliosis. In addition, the estimation of endplates for scoliosis measurement still strongly relies on visual estimation from examiners.

It seems logical that the establishment of a more objective and automatic method would help reduce errors in distinguishing patients with scoliosis. A fully automatic computerized method is suggested as a preferable tool compared with other existing measurement methods, which rely on subjective visual estimation. The purpose of this study was to evaluate the performance of an automatic computerized method with reference to Cobb angle measurement and to substantiate the feasibility of using a computer-generated index in evaluating scoliosis.

BACKGROUND

Since 2000, the Hong Kong Polytechnic University has established a homegrown picture archiving and communication system (PACS).[10,11] Since 2001, the PACS has been used clinically in the Radiography Clinic on the University Campus. A number of cases of idiopathic scoliosis have been detected in chest x-ray examinations among students. The detection of idiopathic spinal deformity will be of interest to orthopedic clinicians and community health doctors. Hence, an intelligent system was developed to automatically classify chest images with scoliosis in the image database.[12]

MATERIALS AND METHODS

Theory

The method used meant that the location of a normal vertebral column could be represented as a single straight line, fitting the estimated central points of the each vertebral body in a chest radiograph. As the spine is usually overshadowed by the heart shadow in a conventional posteroanterior (PA) chest image, a fuzzy estimator was used to locate the central point of the each vertebral body. A cost function was defined to quantify the deviations of estimated spine locations from the fitted straight
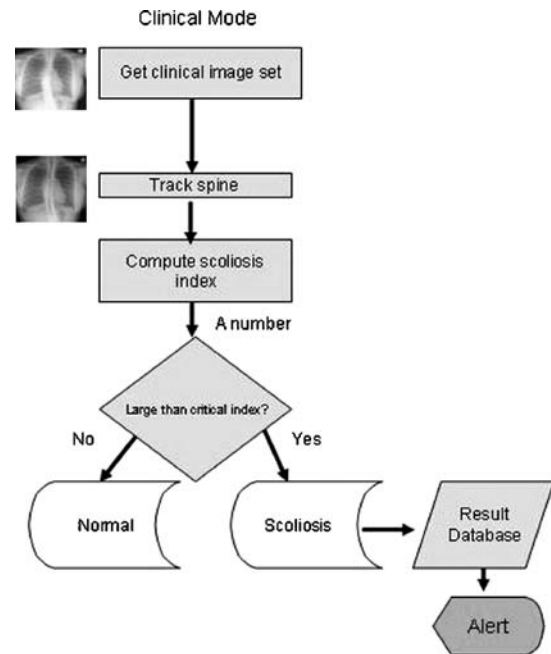

Fig. 1. The workflow diagram of the intelligence system.

line. When the spine is normal, the cost function converges to zero. In reality, there are some deviations of the cost function from zero because of noise in the images and normal variance of human body configurations. A tolerance level was obtained with the input of experts (orthopedic clinicians and radiologists) during the training mode of the system. During the operation mode, the cases were classified as normal if the cost function was less than the tolerance level, and the cases were classified as abnormal by contradiction if the cost function was greater than the tolerance level.

The implementation of the system included two computing processes: (a) the vectorization of the spine's central points and (b) the computation of the cost function. The overall flow of the intelligence method is outlined in Figure 1.

(a) Vectorization of spine's central points

The approach taken meant it was not necessary to outline every vertebra to evaluate the severity of scoliosis. The location of the central points of the spine of the digital chest radiograph is adequate to fulfill the requirement. To locate the central point, an intelligent hybrid approach, which facilitates the switching from the correlation method to the fuzzy estimator based on prespecified criteria, was
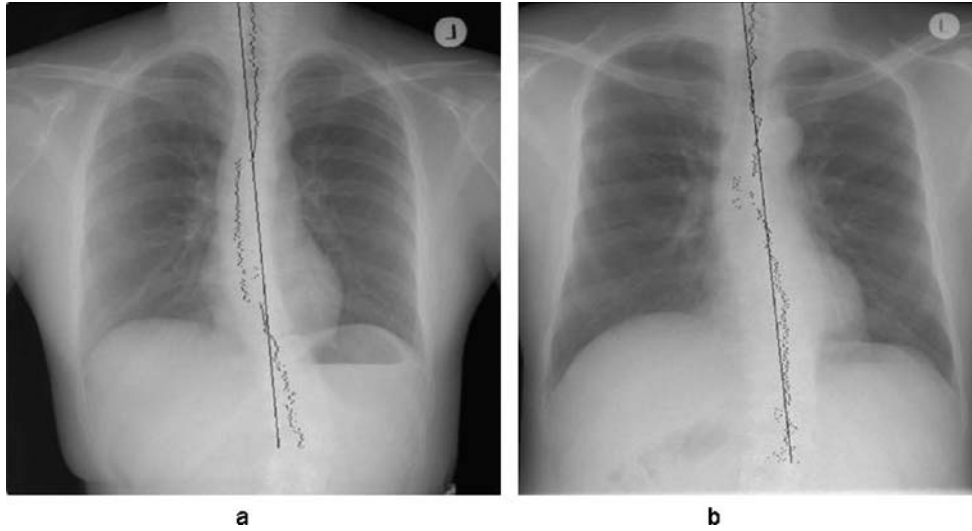
Fig. 2. Sample output of automated image analysis. *Scattered dots* are points located automatically by intelligence method. The *straight line* is best fit line of these points. a Typical image with scoliosis. b Image with the spine poorly obscured by mediastinum. It is an image without scoliosis.

used to vectorize the shape of spines from chest images. A sample output of the location of the central point by the automatic location method is given in Figure 2. More detail about this approach is given in an earlier paper (Tang and Chan 2006: An intelligent-enhanced system for early detection of idiopathic scoliosis in chest radiography, paper submitted under review).

(b) Computation of the cost function

If the vector $(u(j), v(j))$ represents the central point of spine at the jth line of the image matrix, the incidence of scoliosis can be determined after the vectors $(u(j), v(j))$ at every line of the chest image are obtained. The determination is by contradiction, in which it is assumed that the spine is normal, and the trace of spine is almost a straight line. Under this assumption, the vectors $(u(j), v(j))$ are able to fit a straight line given by,

$$u = m \cdot v + c \qquad (1)$$

with zero modeling error given by,

$$e(j) = u(j) - m \cdot v(j) - c \approx 0 \qquad (2)$$

However, the data inevitably contains a certain amount of noise, and thus, the least square method[13] was considered here to obtain the best-fitting straight line. Consider the N lines of the chest image. From Eq. 2, the modeling error is given by,

$$\varepsilon = \begin{bmatrix} e(1) \\ e(2) \\ \vdots \\ e(N) \end{bmatrix} = \begin{bmatrix} u(1) \\ u(2) \\ \vdots \\ u(N) \end{bmatrix} - \begin{bmatrix} \nu(1) & 1 \\ \nu(2) & 1 \\ \vdots & \vdots \\ \nu(N) & 1 \end{bmatrix} \begin{bmatrix} m \\ c \end{bmatrix}$$

$$= U - Vw \qquad (3)$$

where $\varepsilon = [e(1), e(2), ..., e(N)]^T$, $U = [u(1), u(2), ..., u(N)]^T$, $V = [v(1), v(2), ..., v(N)]^T$, and $w = [m, c]^T$. According to the least square method, the best estimate of w is given by,

$$\widehat{w} = \left(V^T V\right)^{-1} V^T U \qquad (4)$$

From Eqs. 3 and 4, the corresponding modeling error is given by,

$$\widehat{\varepsilon} = U - V\widehat{w} \qquad (5)$$

To evaluate how good the data fits the straight line, the mean square error (MSE) is considered,

$$MSE = \frac{1}{N} \sum_{j=1}^{N} \widehat{e}(j)^2 = \frac{1}{N} \widehat{\varepsilon}^T \widehat{\varepsilon} \qquad (6)$$

Without loss of generality, it is always true that the spine's central points are lying on a nonlinear curve given by,

$$U = \Phi(V) + n \qquad (7)$$

where $\Phi(\cdot)$ is a nonlinear function, and $n \sim N(0, \sigma^2)$ is white noise corrupted during image formation and vectorization; σ is the standard deviation of the noise. The extent of scoliosis, Δ, at every line of the image matrix is characterized by,

$$\Delta = \Phi(V) - V\hat{w} \qquad (8)$$

Note that the expression 8 is statistically independent of white noise n. Adding Eqs. 5, 6, and 7 and substituting Eq. 8 into the resulting expression, we get

$$\hat{\varepsilon} = \Delta + n \qquad (9)$$

Thus, the MSE in Eq. 6 can be rewritten by,

$$MSE = \frac{1}{N}\hat{\varepsilon}^T\hat{\varepsilon} = \frac{1}{N}\Delta^T\Delta + \frac{2}{N}\Delta^T n + \frac{1}{N}n^T n \qquad (10)$$

Taking the expected value yields,

$$E[MSE] = \frac{1}{N}E[\Delta^T\Delta] + \sigma^2 \qquad (11)$$

From Eq. 11, it can be seen that the expected value of MSE comprises of two components, the extent of scoliosis and the variance of noise. By this implication, the value of MSE can be split into two amounts S and R, i.e., MSE=S+R, in which,

$$S = \frac{1}{N}\left(\Delta^T\Delta + \delta_1\right) \qquad (12)$$

$$R = \frac{1}{N}\left(n^2 + \delta_2\right) \qquad (13)$$

where δ_1 and δ_2 are small residual values given by,

$$\delta_1 + \delta_2 = 2\Delta^T n \qquad (14)$$

The amount R accounts for the acceptable extent of scoliosis and noise, whereas the amount S accounts for the notable extent of scoliosis. It is suggested that the value of R is obtained after training of the system by an expert's input if an image is scoliosis or not. In the training mode of the system, the expert will read a reasonable numbers (say, 30–50) of normal spine images and decide the index for those normal spines. The value of the index will converge to R, which is the threshold value for normal spine. If the MSE for a particular image i, for example, MSE (i)<R, the assumption is valid, and the spine is normal. If the MSE(i)>R, the trace of the spine is no longer close to a straight line, and there exists an abnormality of the spine by contradiction. We later assigned the MSE as scoliosis classification index (SCI) for a particular value when the system determined if the images obtained demonstrated a case of scoliosis or not. In earlier evaluations using SCI to classify images as demonstrating scoliosis or not, a result with sensitivity of 1 and specificity of 0.93 was obtained (see Tang and Chan 2006, paper submitted under review in "Theory"). In this study, we attempted to evaluate the performance of this computer-generated index in comparison with the Cobb angle.

Subjects

Sixty digital chest images demonstrating the presence of scoliosis (45 cases with a Cobb angle of between 10 and 30°, 15 cases with a Cobb angle of between 5 and 10°) were selected from the PACS of the Radiography Clinic. Two experts (an orthopedic clinician specializing in scoliosis and one anatomist) were invited to validate the images with scoliosis. All subjects were over 18 years old, and all images were anonymized to ensure patient confidentiality. The study was approved by the institutional ethics committee.

Equipments

A PACS workstation was connected to the PACS server for obtaining digital chest radiographs. The measurements of the Cobb angle were obtained by the image workstation's software measurement (Cedara I-Report, Canada Software Corp, Mississauga, Canada). Another workstation with a specified computer-aided intelligence program was used to generate the computer-generated index of scoliosis.

Methods

The PACS workstation was used to select chest images with scoliosis from the PACS image server. The images were further postprocessed for better visualization of the spine (if necessary) for Cobb angle measurement using the built-in Cobb angle function of the software. Assessors were guided by the orthopedic

Table 1. Validation Test for the Computer-Generated Index Program

	First Trial	Second Trial	Unpaired t test[a]: $p > 0.9999$[b]
Computer-generated index (mean)	58.79	58.79	
Computer-generated index (standard deviation)	58.54	58.54	
Computer-generated index (range)	12.04–219.68	12.04–219.68	

[a]Unpaired t test was used to test the difference between data in the first and second trial
[b]Difference was significant when $p < 0.05$

expert to follow the same protocol for measurement of scoliosis. The same image set was transferred to the workstation where the SCI was generated. The images were subjected to the tests as described below.

Evaluation Test of Validated Human Expert Marked Data

Ten scoliosis images were randomly selected for evaluating the human expert marked Cobb angles. Three trained assessors were invited to separately measure the Cobb's angle.

The measurement was performed manually with the aid of image software (Cedara-I report, the viewing software has been calibrated for angle measurement). Three assessors viewed the digitized images via computer and independently determined the upper and lower endplates. The measured angles were evaluated and compared among three assessors.

Consistency Test

The test aimed to evaluate the reproducibility and consistency of the computer-generated SCI. Ten digital chest images were randomly selected from the image database and analyzed using the SCI program. The generated indexes corresponding to the images were recorded, respectively, by following their file names. Two independent trials were undertaken. All indexes generated by the computer program in both trials were assessed by unpaired t test to test for consistency.

Correlation Between Cobb Angle and Computer-Generated Index

The images were measured independently for Cobb angle with the image workstation's measurement tools. The computer-generated SCI was obtained for the corresponding images. The data were divided into two groups: Group A was the image set with Cobb angles ranging 5–10° and Group B with Cobb angle ranging 10–30°, respectively. The correlation between Cobb angle and Computer-generated Index was analyzed using Pearson's correlation test by statistical package Instat 3 (GraphPad Software, Inc., San Diego, USA).
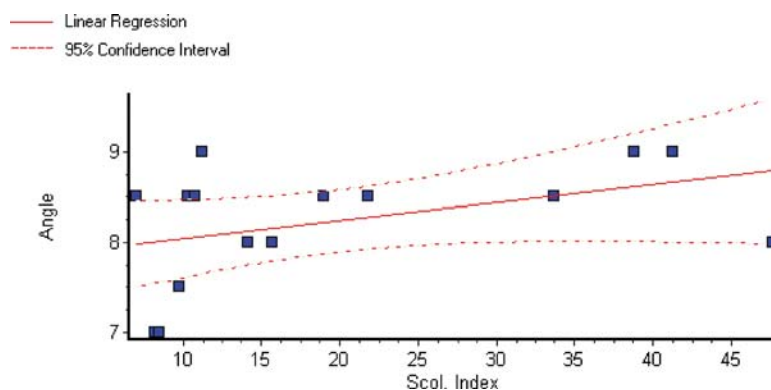
Fig. 3. Cobb angle against computer-generated index in a range smaller than 10°.

Table 2. Relationship Between Computer-Generated Index and Cobb Angle in 15 Sets of Digital Chest Images in Range Smaller than 10°

	Computer-generated Index	Cobb Angle
Mean	19.86	8.23
Standard deviation	13.67	0.65
Pearson' correlation test $(r) = 0.4141$	$r^2 = 0.1715$	Unpaired t test $p = 0.0027$

RESULTS

Evaluation Test of Validated Human Expert Marked Angle

Results from the evaluation test of Cobb angle measurements of randomly selected cases of scoliosis among three experts showed a mean variation of 3.85° (range of 0.5°–11°). There was no significant difference in performance of Cobb angle measurement among the three experts ($p > 0.05$, one-way analysis of variance).

Validation of the Consistency of the Computer-Generated Index Program

Two test trials were applied for the randomly selected sample, an identical value of mean, standard deviation and the range of index were obtained in both the first and second trial. Unpaired t test showed there was no significant difference between these two trials. (p>0.9999, unpaired t test, Table 1).

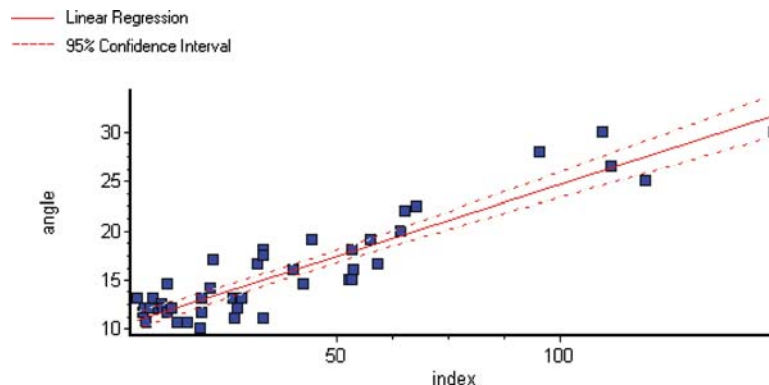### Correlation Between Cobb Angle and Computer-Generated Index

For correlation between the Cobb angle and computer-generated index, the data was divided into two groups. For image samples with Cobb angles less than 10°, there was significant difference between the Cobb angle measurement and the SCI ($p<0.005$, unpaired t test), and there is no evidence that the two groups of measurements were correlated ($r=0.4141$, Pearson's Correlation test, Fig. 3 and Table 2). However, for those chest images with a Cobb angle of more than 10° (up to 30°), results indicate that the computer-generated SCI strongly correlated with the Cobb angle ($r=0.92$, Pearson's Correlation test, see Fig. 4 and Table 3). In addition, it is noted that there is an intercept value of about 12° Cobb in Fig. 4, this suggests that SCI includes a systematic error.

DISCUSSION

Interobserver Variation

The results indicated that, for the interobserver test of manual measurement of the Cobb angle, the mean variation was 3.85°, comparable to similar findings by Shea[2] (mean variation of 3.3°) and Cheung et al.[9] (mean variation of 3.1°). It should be noted that, when a clinician measures the Cobb angle, it is accepted that this is only an estimate. This takes into account all the errors of manual measurements and intra/interobserver

Fig. 4. Cobb angle against computer-generated index in a range greater than 10°.

Table 3. Relationship Between Computer-Generated Index and Cobb Angle in 45 Sets of Digital Chest Images in Range Greater than 10°

	Computer-Generated Index	Cobb Angle
Mean	39.05	15.8
Standard deviation	33.6	5.35
Pearson' correlation test (r) = 0.9229	r^2 = 0.8518	Unpaired t test $p<0.001$

variations, and that the curve angle itself is not precise.

Therefore, the main focus of this study is on the improvement in reliability and consistency of evaluation methods as discussed below.

Digital Chest Images Versus Whole Spine Images

Digital chest images were chosen instead of whole spine images. However, there was an analogy between these sets of images from the positioning point of view: both were taken in the erect PA position as a standard positioning procedure.[14,15] With manipulation of the digital images by adjusting contrast and brightness, it was possible to include the lower lumbar region when considering the end-vertebra to as low as L-3. However, the study could not include those scoliotic spines where the end vertebra was lower than L-4 when we tried to validate the relation of computer-generated index and Cobb angles. It follows that a future study of scoliosis images of whole spine and comparison to chest images results should be conducted to evaluate the clinical relevance.

Consistency of the Computer-Aided Method

The computer-generated index was calculated from the program. Consistency test was performed to see if there was any inconsistency for the indexes generated by the same set of digital images. The results indicated that the corresponding indexes were almost identical. This suggests that the computer-generated method can produce more consistent and reproducible results and can reduce human subjectivity and observation errors.

Correlation Between the Cobb Angle and Computer-Generated Index

A Cobb angle greater than 10° is considered clinically as scoliosis.[16,17] The Scoliosis Research Society has defined scoliosis as: "lateral deviation

of the normal vertical line of the spine, which, when measured by x-ray, is greater than 10°."[18] Therefore, an angle of 10° was set as the cut-off point in our study. The group with a Cobb angle of less than 10° showed no correlation between the Cobb angle and SCI (Fig. 3 and Table 2). As the angle value is small, the percentage error in measurement becomes significant. This can be further explained by the fact that, from the graphs, there is an intercept in the regression relationship, that is, the index method would suggest a Cobb angle of 8° or less when there is no scoliosis is present. Furthermore, inconsistency in locating the end-vertebra attributes to the error in small Cobb angle measurements. Conversely, a very positive correlation was indicated in the larger angle group ($r=0.9229$, Pearson' Correlation Test). The results were relatively reliable without the impact of significant percentage error. It is observed that the computer-generated index can also present the severity of scoliosis with a similar trend of Cobb angle distribution.

Comparison of Preceding Research

Greenspan[8] had proposed using the SI to obtain more accurate determination of the spinal curvature. The principle of this method was to measure the deviation of each involved vertebral segment from the vertical spinal lines with multiple points taken along the scoliotic curve. It seems that our proposed method has taken the advantage of the method suggested by Greenspan by considering every vertebra instead of the affected end-vertebra. Furthermore, this computerized method is fully automatic and thus avoids many tedious human measurements.

CONCLUSION

We have proposed a fully automatic computer-generated SCI to evaluate the extent of scoliosis based on digital images of the chest. We have also demonstrated the consistency and correlation of

the computer method in relation to Cobb angle measurement and indicated that the SCI is a reliable and efficient alternative for monitoring changes in scoliosis treatment. Because no human measurement is needed, the proposed method can significantly reduce the work load for clinical staff.

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