www.revistageintec.net
ISSN: 2237-0722
revista GEINTEC Gestão, Inovação e Tecnologias

3D X-ray based Method for Diagnostics of Spinal Deformities

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Abstract

Research Funding: *The "OrthoLine" research and production company has provided funding for the research study.*

Conflict of interest: *The authors have no conflicts of interest to declare.*

Research Objective: *to revise the "arc angle" parameter for estimating the value of spinal curvature and, if necessary, to search for another parameter or to develop another method for mathematically correct estimation of spinal deformity value.*

Materials and methods. *The critical analysis has been performed both theoretically and experimentally. It has been demonstrated that the angle parameter is incorrect, and another estimation parameter and procedure should be developed. A method of 3D X-ray diagnostics and construction of 3D structure using two orthogonal projections of two-dimensional spine image involve several procedures. Software-based scaling and horizontal-wise image synchronization, synchronised selection of spinal arc on images and construction of a geometric image of the studied arc are performed stepwise. Software-based measurements of a number of geometric parameters on 2D images, utilised for mathematical analysis and construction of a 3D picture of geometric spine images, are made, and geometric parameters of some arcs, among which the arc plane curvature and azimuth angle are assumed to be the major ones, are found. 2D X-ray diagnostics was performed using a light-dose device AGFA DX – D 300, which allows having the images of the entire spinal column in a single shot.*

Results. *A method for the 3D X-ray diagnostics of the pathologically deformed spine has been proposed. The relationship between the deformity value and severity and the true arc curvature and azimuth angle of the arc plane position between frontal and lateral planes of the trunk has been established. There have been developed the procedures for software-based examination of 2D orthogonal images of the trunk projections and computation of parameters of the 3D spine state along with constructing its true image. There has been created a two-parameter function, with correction factors, of spinal deformity degree based on comparative estimations of radiographic*

Received: 24.02.2021 – Accepted: 02.04.2021

images, measured parameters, and posture of the pathologically deformed trunk, made by independent experts.
Conclusion. *The developed method of 3D X-ray diagnostics and analysis of radiographs eliminates critical errors of conventional method. What principally distinguishes this method is a research object, namely, a three-dimensional state of the spine rather than two-dimensional on the frontal projection, and the use of the arc curvature parameter and azimuth angle of the arc plane position instead of mathematically erroneous angle parameter – the Cobb angle. The method of (3D) X-ray diagnostics provides new beneficial properties of the 2D spondylography based on state-of the-art digital technologies.*

Key-words: X-ray Diagnostics, Spinal Deformity, Cobb Angle, Scoliosis Degrees.

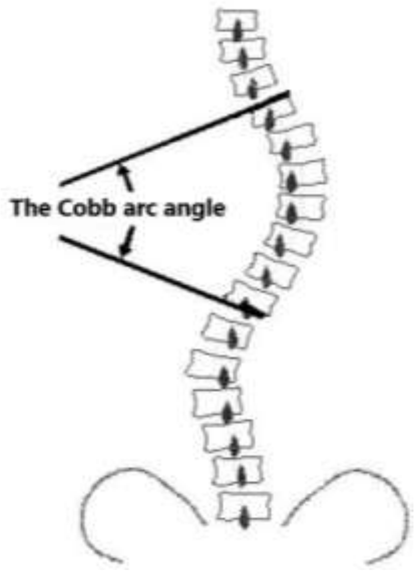
1. Introduction

A central problem in orthopaedics of the pathologically deformed spine is to evaluate the patient condition severity or its derivative – to estimate the value of spinal curvature (deformity), based upon which any other technologies and methodologies are developed.

Today it is well accepted that the problem of choosing the deformity estimation parameter is successfully solved. As from the middle of the last century, the **"arc spanning angle"** has gained an absolute popularity throughout the world. The Cobb angle represents a prominent example of an angle parameter. The European Scoliosis Research Society [1], established in 1966, has officially accepted it as a standard characteristic of scoliosis intensity. The International Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT) [2], North American Spine Society [3], and some other global communities involved in scoliosis problems, i.e. European Spine Society [4] follow the same method. The Cobb method not only gained the worldwide popularity but came to be mandatorily used [5] in some countries. Any article in the leading worldwide journals devoted to scoliosis problems can be taken, and there will be definitely found an estimation of spinal deformity applying the Cobb angle [6-9], even when the development of new modern methods for estimating deformity, for example, measurement of curvature in the plane of maximum intensity using ultrasound imaging [10], is underway.

The essence of the angle parameter is that an arc is singled out on the radiograph of the frontal spine view based on the principle of the most one-side tilted vertebrae, and generating lines (sides) of the arc spanning angle are constructed at a tangent to the outer edges of end vertebrae in the arc, Fig.1 [1,11].

Fig. 1- The Cobb Arc Angle



The arc angle measured therewith is assumed to be the deformity characteristic: the pathologic curvature value. Medical literature contains multiple comments on the quality of such estimations. An error of the method is mentioned that can reach 5˚- 8˚and more degrees. The errors, associated with the technique of constructing generating lines of the arc angle and correctness of integrating critical vertebrae into the arc, have generally been considered [12-14]. Some scientists are engaged in developing the methods for computerising measurements of the arc angle in expectation of increasing the accuracy of measurements [15].

At the same time, in practice the marked discrepancy between the value of the arc angle and the state of the patient posture is encountered on a regular basis by orthopaedic doctors. And what is between the "apparent correspondence" and "obvious failure to correspond" categories, remains unnoticed at all, since there is not any parameter to divide this interval for specifying the estimation of the deformity condition. In rough terms, the "deformity degree" category has traditionally been used, which is directly related to some range of the arc angle. Hence, wrong arc angle leads to erroneous estimation of the state severity as an argument.

2. Research Objective

To revise the "arc angle" parameter for estimating the degree of spinal curvature and, if necessary, to search for another parameter or to develop another method for mathematically correct estimation of the spinal deformity value.

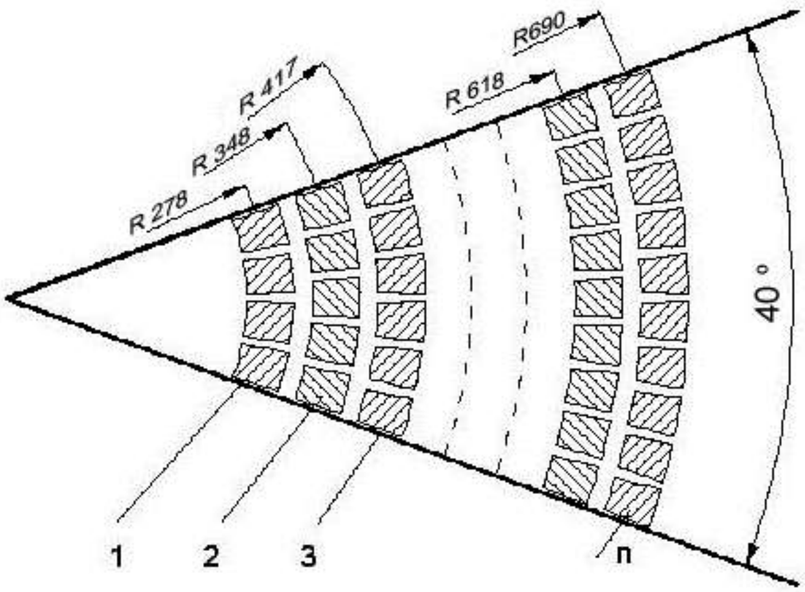
3. Materials and Methods

The first part of the formulated problem has been solved analytically. It has been noted that the angle parameter is mathematically incorrect, including two major errors and several implications therefrom.

It has been known that the pathologically deformed spine can have one, two and more arcs. A specific arc can incorporate 4, 5, more and even 9, 10 vertebrae with C-shaped deformity. The number of vertebrae in the arc and their sizes define the arc length. The arc spanning angle can be the most various for a number of arcs or, on the contrary, identical for a group of various length arcs. In the last case, longer arcs will have lesser curvature, i.e. smaller deformity, Fig.2. Quite apparently, a group of various-curvature arcs belongs to any angle, and the measured value of an angle has no way of indicating the unique deformity of an individual arc. And the angle parameter, as a yardstick for measuring the arc curvature value, has not any information-related significance.

It is more convenient to examine the problem in detail on the model, in which the spine arcs are represented as a part of circumference, Fig.2. Looking ahead, it should be noted that the two-year experience of working with the 3D X-ray diagnostics software programme has shown that an overwhelming majority of the spine arcs are approximated by a circular arc with an accuracy of more than 90%. In addition, measurement as such of the Cobb arc angle has sense, if it implies the form of an arc as a circumference, concentric to the measuring scale of an angle protractor.

Fig. 2- Group of Various Curvature Arcs with Equal Arc Angle



ISSN: 2237-0722
Vol. 11 No. 2 (2021)
Received: 24.02.2021 – Accepted: 02.04.2021

Fig. 3- The Spine in the System of Three Orthogonal Planes
A – the spine “under normal conditions”; B – the spine with scoliotic deformities;
λ – azimuth angle of the arc plane position

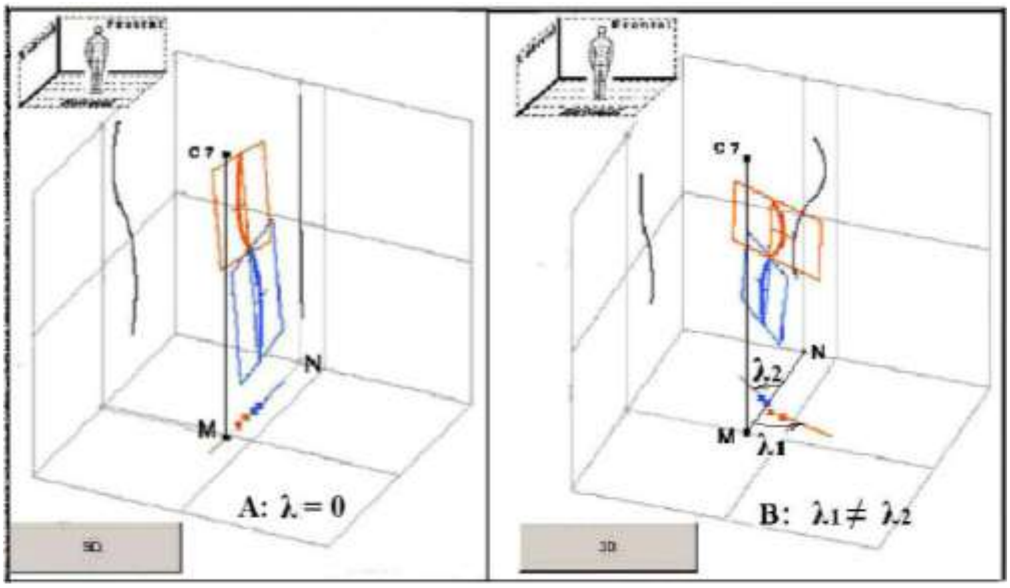


Fig.2 presents the angle of 40°, in the field of which several arcs of various patients have been conceptually shown, that differ in length and radius. The more vertebrae an arc has, the greater its length and radius are, hence, the smaller its curvature is, since the latter is the reciprocal of the arc radius: $K = 1/R$ [16]. Thus, the arc angle of 40° belongs to the group of various curvature arcs, hence it does not measure the sought parameter of a specific arc.

2. The arc angle classically measured on the radiograph of the spine frontal view, characterises only the projection of the true spine on this plane. No allowance is made in this angle for the value of the true arc curvature, namely, scoliosis, which, being the “spine lateral deviation” essentially indicates that the plane of the true arc, for example, thoracic, is positioned at some angle «λ» in the area between the sagittal and frontal plane of the trunk, Fig.3B. Here, the spine arcs are presented as a curve – a geometric image, constructed by averaging of outer and inner contours of the arc vertebrae on the radiograph. It has been suggested that angle «λ» be called an ***arc azimuth angle*** **(AAA*).*** It should not be confused with the ***arc spanning angle,*** similar to the arc Cobb angle (ACA).

The measured value of the Cobb angle on the spine frontal view radiograph, is representative of two above-mentioned parameters: the value of the true arc spanning angle and the value of the true arc plane azimuth angle. Both a small curvature arc with a wide azimuth angle, and a greater curvature arc with a narrow azimuth angle can have one and the same spanning angle. Hence, measuring solely the arc angle causes errors in estimating the deformity degree.

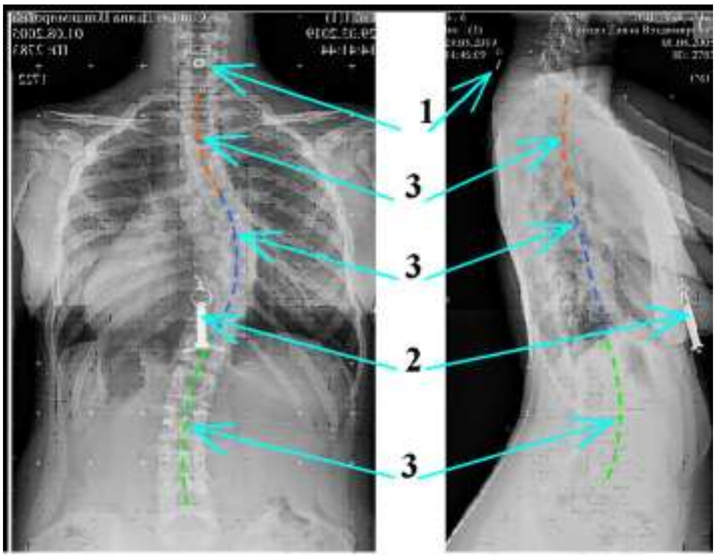
Because of key mistakes, an error, for example, can be pointed out in measuring the arc angle during the dynamic observation of the growing spine. Since measurements of the arc angle are made for a growing arc chord, the arc angle must also increase. Here, this component of the arc angle increase is traditionally attributed to the deformity progression, what is erroneous, if no growth in the arc curvature is registered.

Thus, the angle parameter of estimating the severity of the patient pathologic deformity and condition is incorrect, inaccurate, and impractical. Its use causes serious mistakes. The question of seeking alternative estimations and methods becomes not only pertinent, but essential.

The "OrthoLine" research and production company has developed a method of three-dimensional (3D) X-ray diagnostics and analysis of radiographic images [17]. The method is patented [15] and has been experimentally tried out for several years. The 3D analysis works have previously been carried out and are currently underway. Computer-based topographic technologies have enjoyed the greatest popularity [19,20,21]. The first two methods employed original techniques with original estimations made, however, the Cobb angle is applied in both as an output measurement parameter. The last one [21] uses solely curvatures of certain areas of the spine surface as an estimation parameter. Here, at least, there are no errors stemming from the Cobb method.

Technically speaking, the concept of the 3D curvature method implies that the value of deformity and disorder severity level is estimated for the 3D spine state. It is reproduced analytically based on the data of the 2D X-ray diagnostics, Fig.4.

Fig. 4- Geometric Image of the Spine Arc on a Radiograph: 1. RCM* in the form of a Ring 2. RCM* in the form of a Short Bar 3. Geometric Image of an Arc
* Resistant Composite Material



Prior to a diagnostic session, two radio-opaque markers are fixed on the patient trunk; one in the form of a short metal bar of calibrated length is placed in the area of xiphoid, and the second in the form of a flat ringlet, is fixed on the spinous process of the C7 vertebra, Fig.4.

A digitalised image of two projections is uploaded to the software programme to analyse the radiograph. The programme first scales two radiographic images, through comparing software-based and physical markers, and then horizontally synchronising the position of images.

In what follows, the synchronised segments of arcs are singled out on two orthogonal radiographs using, for example, the Cobb method, and the programme constructs a geometric image of an arc. The programme calculates a number of parameters for this arc. Then all these steps are repeated for the next arc. A protocol, resulting from the analysis, contains the tables for each arc of the spine with several 2D geometric estimations for frontal and lateral projection and estimations for the 3D spine state, including the level of deformity severity. The programme estimates misalignment of the trunk pelvic and shoulder girdle, gives a prescription of compensating heel pad, and others. At the programme operator's will, it can construct a 3D image of the spine arcs in the system of three orthogonal planes, synchronised with the 2D spine arc images on frontal and lateral projections of radiographs, Fig.4. A rectangle around each 3D arc is constructed for convenience of presenting the position of the plane of these arcs, and the horizontal projection depicts the heights of each 3D arc, clearly demonstrating the azimuth angle «λ».

The main characteristics of the 3D spine arc state involve its curvature, value of the arc azimuth angle, length of arc and its chord, angles of chord inclination, and several others.

The software programme envisages measurement of the arc azimuth angle to quantitatively characterise the spine state, Table 1 and Fig.5. The method involves classification of deformity types by the value of azimuth angle (3d-type) with the following two intents:

- To avoid traditional mistakes of estimating the type of deformity of one and the same arc, e.g. thoracic, independently by two orthogonal projections, especially along the spine segments of different length.
- To facilitate the creation of a unified system of concepts that define the specific features of deformity with the known curvature and value of azimuth angle, including a degree of flattening (lordosis of thoracic and kyphosis of lumbar deformity) and potential for correction when treated both conservatively, and surgically.

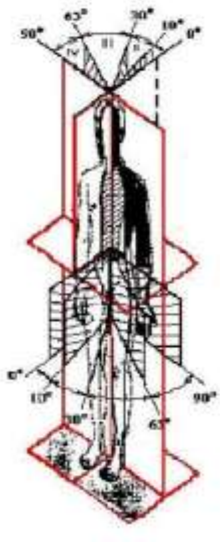
In addition, introduction of three sub-degrees into the II, III and IV intervals of degrees proved to be helpful and possible.

Two parameters serve as a basis for prescribing the severity level of the patient condition: the value of the true arc curvature and the value of the spine arc azimuth angle. The effect of each factor is determined experimentally based on the results of observing several hundreds of measurements. Three independent experts examined radiographs and photos of the trunk as viewed from the back. The pathology was evaluated using a 9-grading system against the background (series of images) of the typical posture of various severity level simultaneously with measuring the Cobb angle and 3D parameters.

Table 1- Classifier of the 3D deformity type

	Value of the azimuth arc angle, degrees	**3D deformity type**
Thoracic segment of the spine	± 0 …10	kyphosis
	± 11… 30	kyphoscoliosis
	± 31… 65	scoliosis
	± 66… 90	lordoscoliosis
Lumbar segment of the spine	± 0 …10	VC* lordosis
	± 11… 30	VC* lordoscoliosis
	± 31… 65	VC* kyphosis
	± 66… 90	VC* kyphoscoliosis * vertebral column

Fig. 5 - 3D Deformity Type



ISSN: 2237-0722
Vol. 11 No. 2 (2021)
Received: 24.02.2021 – Accepted: 02.04.2021

All images and estimations were recorded in the software database and analysed using unified criteria. Based on these data, the relationship has been determined between the degree of the spine deformity (severity of a state) and the arc curvature and the value of the arc plane azimuth angle.

The X-ray spine diagnostics was performed using the state-of-the-art digital light dose device AGFA DX – D 300, which allows having the images of the entire spinal column in a single shot. To date, there have been analysed radiographs for more than 250 patients, some of which have already had 2-3 and more semi-annual repetitions. Man-hours for programme analysis and the protocol preparation, including computations of torsion of particular spine segments and construction of scoliotic and kyphotic profile of a compound arc, as may be required, amount to about 30 min. And a week suffices to train the staff to use the software.

4. Results and Discussions

A technology has been created that can eliminate the mistakes of conventional methods for X-ray estimation of the pathologically deformed spine curvature value. A fundamental feature is the parameter of estimation, namely, curvature and azimuth angle of the 3D arc plane position instead of the arc spanning angle according to the Cobb method.

The established deformity degree function has been compared with the conventional estimation – a classifier with fixed values of the arc spanning angle [1] and the sub-degrees additionally introduced by the authors. The deformity degree has been verified when estimated traditionally and using the 3D curvature method through the example of 327 patients. The main conclusion from this part of the entire work is that conventional estimations of the degree differed in most cases in 0-1.7 units of the four possible, with their topographic random positioning both above, and beneath the 3D deformity degree graph. Inherent here is that the conventional estimation of the scoliosis degree is registered as too high where there are wide angles of the spine arcs with more than 5 constituent vertebrae. The longer the curvature arc is, the more overstated the degree is. Conversely, where there were narrow arc angles the degree estimation was often understated. The reason for such results is clear: the classical function of the degree is erroneous, since the parameter is incorrect, and it depends solely on the value of the absolute arc angle on the frontal projection radiograph. 3D calculation estimations of the deformity degree by the example of more than 300 patients, have shown a high correlation with the clinical picture and the specifics of the trunk posture.

The following beneficial practical properties of the method for 3D X-ray diagnostics and analysis of radiographs can be mentioned:

- 3D method provides mathematically correct parameters of the spine deformity to evaluate the state severity;
- The method eliminates such routine mistakes of conventional estimation of the deformity value, as e.g. estimation of the arc curvature on one projection, or double estimation on each projection, not synchronised according to the arc length and composition;
- For the first time the spine torsion is estimated in terms of quantity. Estimation of torsion in units [degrees/cm] is easy to perceive and simplifies understanding about the state of an individual arc.
- For the first time an opportunity has been provided for quantification of the value of lordosis of the spine kyphosis, and the value of kyphosis of the spine lordosis;
- For the first time an opportunity has been provided for quantification of the value of flattening of thoracic and lumbar spine segments, potential examination of changes in this parameter as one of the main parameters in the development of scoliosis;
- In surgical treatment of scoliosis, the method helps to substantially enhance the level of pre-surgical planning due to increased accuracy of selecting the sizes and area for placing implants. It may help a lot to implement the "vbt" (vertebral body tethering) technology [22], precisely indicating the arc plane location;
- 3D diagnostics enables prediction of the potential effectiveness of correcting deformity according to the arc azimuth angle. The greater its value is, the lower the potential for correction is since an increase in the lordosis degree is accompanied by an increase in the "bending section modulus" [23] in the frontal plane.

5. Conclusion

In the area of X-ray diagnostics and orthopaedics of the pathologically deformed spine, an error has long remained unnoticed in the parameter of estimating the value of the spine curvature, or the arc angle, e.g. the Cobb angle. This error is automatically extended to a whole spectrum of findings, solutions, and conclusions. Particularly, it relates to the quality of findings by the results of carried out routine and scientific studies, the results of allocating social assistance to persons with disabilities, certificates of fitness for military service and studying in educational institutions, and even wrong recommendations concerning surgical treatment.

The present-day quality of images on radiographs and the level of digital technologies make it possible not only to correct mistakes, but to obtain new estimation parameters to study the processes of forming pathological deformities. The proposed method for 3D X-ray diagnostics and analysis of radiographs creates mathematically correct estimations of the deformity value and particular features of positioning of the spine arcs. The deformity degree is specified solely for the three-dimensional spine state. The deformity degree function has been determined according to the survey of more than 250 patients, and it has proved that there is a high correlation between the deformity degree and posture.

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