Original articles

Geometry of coplanar stereoscopic radiographic pairs for analysis of the lateral cervical radiograph: a study using mathematical models

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Abstract

Objective: This study evaluated 3-dimensional (3D) assessments of points of interest on a phantom replica of the human skull and cervical vertebrae to better understand how structures are represented in space using mathematical methods.

Methods: Three basic geometric equations derived from the “Law of Similar Triangles” are introduced, and measurements are taken after 4 trials to demonstrate how 3D data extracted from 2-dimensional (2D) digitized radiographic pairs can be used to produce coordinate points associated with 3 areas on the atlas.

Results: An analysis of variance test for multiple group comparison shows no significant statistical difference between 4 trials ($P = 0.995$). In addition, 6 strong positive correlations are evident using Pearson product-moment coefficient test ($r = 0.9008$ through 0.9977 , $P = 0.002$).

Conclusion: This study suggests that it is possible to use coplanar stereoscopic radiographic pairs to define an object’s location in 3D space by taking retrospective measurements directly from 2D digitized radiographs.

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Introduction

Before the era of computed tomography and magnetic resonance imaging (MRI), radiography was the only imaging technique available to provide critical measurements, such as those for spinal canal

encroachment or other upper cervical conditions that required careful radiographic evaluation.¹ It is this author’s view that, even after the emergence of improved technology, standard radiographic analysis remained the procedure of choice for investigation for most chiropractic upper cervical evaluations. However, in recent years, the scientific community has questioned the usefulness and accuracy of measurements from plain radiographs.^{1–4} For example, a spirited debate pro and con in the chiropractic community between Ennes² and Barge⁵ with respect to line drawing was presented

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in a non-peer-reviewed forum in the mid-90s. Harrison⁶ (1986) published an opinion article stating that more practicing chiropractors were in favor of and used radiographic line analysis than those who did not. In contrast, a reliability study published by Sigler and Howe concluded that changes in atlas position from line drawings were just as likely to be from marking error as from actual atlas position change. The concerns of the scientific community relative to plain film radiographic measurements are related to possible errors in measurement attributed to magnification, distortions, asymmetries, and malformations.^{1,3,7-11} Any one of these factors can affect radiographic measurement in all of the upper cervical listing techniques used in clinical practice today.⁹ Listings are shorthand notations derived from radiographic line drawing that describe the direction of spinal misalignment on a radiograph.⁹ Wong et al¹ as well as others have investigated the affect that magnification and distortion have on cervical measurement of the spinal canal in patient suspected of having spondylosis with spinal cord encroachment¹⁰⁻¹²; these studies were designed to statistically compare MRI and plain radiographs. The stated conclusion is as follows: in contrast to MRI measurements, the routine cervical radiograph could not predict the level or degree of cervical spinal cord compression.¹ Limitations of plain radiographs are attributed to magnification and distortion errors. Magnification ratios can be altered by both the focus-to-film and/or object-to-film distances.¹ Boijesen¹⁰ found that the difference between 1 m and 1.5 m focus-to-film distance on sagittal canal measurements was 0.5 mm and that a 5-cm change in object-to-film distance changes this measurement by 1.2 mm at a focus-to-film distance of 1 m. A difference of 5 cm may be substantial because it equals the mean difference between men and women regarding shoulder breadth; also, accounting for patient movement and cervical and/or thoracic deformities (humps) can affect the magnification of various structures on the radiograph.^{1,10} Senol et al¹¹ and Blackley et al¹² also concluded that plain film radiographs failed to reflect the true size of the spinal canal when compared with anatomical computed topographic measurements.

Although much of the literature on upper cervical chiropractic techniques is not published in peer-reviewed sources, these sources may provide characteristic and pertinent information about the techniques. In chiropractic, most upper cervical radiographic procedures are modifications of BJ Palmer's upper cervical method known as "hole-in-one" (HIO).¹³ Ralph Gregory and John Grostic modified BJ's HIO,

which led to the development of an orthogonal approach where misalignments are measured in small acute angular differences (ie, the side that contains the acute angle relative to a sagittal skull line is the side of atlas laterality). This approach was adopted and further modified by others.

Although an atlantooccipital (AO) misalignment syndrome has been described for a number of years in the chiropractic profession, no single radiometric method has emerged as a standard by which the accuracy of other radiographic methods may be evaluated and/or tested. Obtaining such a standard has been elusive because existing analytical methods (1) exploit bony landmarks that are remote from the misalignment, (2) have measurement errors related to the radiograph angles, and 3) have measurement errors due to inaccurate focal spot and/or object-to-film distances.¹⁴ This author proposes the use of a 3-dimensional (3D) coplanar method in which the actual position of objects in the radiographic field can be calculated retrospectively by mathematical location of inherent system parameters (ie, the central ray, the principal point location, and calculation of focal spot-to-film distance). The goal of this method, as is the case in medicine, dentistry, and other disciplines, is to display the true anatomical structures and their positions relative to the actual positions of other structures observed in the radiograph.¹⁵⁻¹⁸

From a historical perspective, in 1838, the theory of stereoscopic vision was first introduced by an English physicist, Sir Charles Wheatstone,¹⁹ paving the way for many other stereoscopic advances down through the years. The use of stereoscopic radiographic analysis in chiropractic is hallmarked by the work of Remier²⁰ (1938) at Palmer College of Chiropractic and in the 1960s by Dr WG Blair.^{7,8} *Cephalometry* is a term defined by Moyers et al²¹ as a radiographic technique for abstracting the human head into a measurable geometric scheme. Cephalometric radiography is used in medicine and dentistry (1) to describe the morphology and/or growth of the craniofacial skeleton, (2) to plan clinical treatments, and (3) to evaluate treatment results.²¹⁻²⁴ Most of these tasks require identification and location of specific landmarks derived through calculation of various angular and/or linear variables.²¹⁻²⁴ *Stereoscopy* is defined as any technique capable of producing images in which 3D visual information can be abstracted. Clinically, the analysis of depth and position of objects in 3D will provide the practitioner with the ability to take stereoscopic measurements and assess alignment of the cervical spine with an enhanced degree of precision and accuracy.^{7,8}

Conventional radiographs of the head and neck generated at the focal spot of an x-ray tube will radiate from that tube source and cover a larger area the further it is projected from that source.^{23,24} This phenomenon is associated with a body of mathematics known as *projection geometry*.²³⁻²⁵ Imagine an infinite number of points on a lateral radiograph, parallel to the film plane but at different distances from it (Fig 1). Points on various planes between the film and the radiograph source fall within the area referred to as *3D space*. When pairs of 2-dimensional (2D) radiographic images are combined and objects of interest are viewed from 2 different perspectives, a perception of depth is evoked, as 2 slightly different images are captured on the film. From a binocular viewer's perspective, the 2 images arriving simultaneously at the visual cortex are united into 1 picture. The mind combines the 2 images by matching up the similarities of the images and adding in the small differences.^{26,27} Small differences between the images are what produce a final 3D image that may be viewed by using various binocular stereoscopic visual techniques.^{7,8}

However, according to Baumrind et al,²⁸⁻³¹ information taken from coplanar radiographs may be measured directly from the radiographs provided the following conditions are met: (1) the distances between the 2 radiograph source positions are known (L1 to L2 "base"), (2) the distance from the radiograph source to

Fig 1. Parallel planes. The path of emission of an x-ray beam from a single source. As the beam passes through the subject, which is aligned for exposure of a lateral radiograph, an infinite number of points are exposed in various planes, parallel to the film plane but at different distances from it. The dark line (F) represents the film plane, and other parallel planes between the film and the radiograph source represents 3D space.

Fig 2. Radiograph phantom. A human-like phantom that contains internally correct bony structures. This phantom is used as the subject in this study to avoid human exposure to ionizing radiation.

the film plane is known ("H" altitude), and (3) the 2 views contain the same point of interest ("P") (Fig 2). The mathematics of making 3D measurements from paired coplanar radiographic images is not mysterious and only requires basic mathematical ability. The purpose of this study is to describe an upper cervical stereoscopic model that mathematically corrects for magnification and distortion associated with measurement errors on plain 2D radiographs.

Methods

The data in this study are normally distributed but contain multiple trials (groups) to be compared to assume or reject the null hypothesis. Analysis of the groups is completed with an online analysis of variance program provided by the physics department at St Benedict and St Johns Universities.³² In addition, correlations are completed using Pearson product-moment coefficient test (Excel; Microsoft, Redmond, WA) to assess linear association between the 4 trials.

Radiography

There are no live human subjects in this study (Fig 2). Centered and offset stereoscopic radiographic pairs are exposed with a radiograph system that contains an American X-ray Corporation (Louisville, TN) tube, model AXTS, and a high-frequency radiograph

Fig 3. System parameters. The path of x-rays from 2 source positions are shown as they pass through a point of interest “P” and form the base (S) of a triangle located in the film plane. Points p_1 and p_2 also located in the film plane are located where crossing rays from L1 and L2 strike the datum. The z-axis extends out from the center of “S” to point “P.” A second triangle is formed by connecting points P, L1, and L2. The base of this second triangle “B” is the actual distance between the 2 x-ray tubes focal spots. The altitude (“H”) represents the distance from the source to the film plane. The system parameters above are used to calculate the x, y, and z coordinates for that specific point in 3D space. xP_1 , xP_2 , yP_1 and yP_2 are the actual distances measured in the horizontal and vertical film direction.

generator, model V-425 (manufactured by GTR Laboratories, Gassaway, WV). The generator has a peak output capacity of 125 000 VDC at 30 kW. In addition, a digital film processor, OREX PcCR 1417 (Carestream Health Company, Rochester, NY), and the Lenovo computer “think center” (IBM, Morrisville, NC) are used.

Radiographs are exposed from a distance of 40 cm, and the film size is 14×17 cm. The system is calibrated to obtain system parameter measurements, and measurements are also taken from 3 points of interest on the atlas for analysis. The atlas interest points are the (1) distal anterior tubercle, (2) anterior lateral transverse process, and (3) distal posterior arch. A total of 9 coordinate calculations per trial ($n = 36$) are completed from measurements taken from the 3 atlas locations. The desire is to determine the true spatial location in 3D space of each landmark of interest.

Coordinates

Coordinate values are obtained by first assigning zero for the x, y, and z components at the origin, which is located in the centered radiograph where the central ray exposes the datum. The 2D coordinates have origin locations at x and y of (0, 0) respectively; and 3D coordinates have origin locations at (0, 0, 0) for x, y, and z components. Three orthogonal axes pass through the 3D origin at right angles to each other.³³ The x-axis is located in the horizontal position in the film plane and is parallel to the floor. System parameters composed of “B,” “S,” “H,” and the origin O are analyzed (Fig 3). The base “B” (distance between L1 and L2) is also horizontal and parallel to the floor. The tube is shifted 5.1 cm. Base distance in the film plane is obtained by measuring the distance from the central ray to the film edge in both the centered and offset radiographs. The y-axis is located in the vertical direction in the film plane and is perpendicular to the x-axis. The z-axis represents the central ray and extends away from the midway point at “S” (base of triangle in film plane) toward the radiograph source. “H,” the focal film distance or altitude, is defined as the distance along the central ray between the focal spot and the film plane²⁸⁻³¹ (Fig 3). To calculate the coordinate of a point, designated as any point “P,” 4 geometric formulas are derived through the use of the law of similar triangles (triangles are similar if their corresponding angles are congruent [equal] and/or the ratio of their corresponding sides is proportional).^{30,31} In addition, the ratio of the base to altitude between similar triangles is also equal. Calculation of coordinate values requires that equation 1 (below) be solved first

Fig 4. Calculation of focal spot-to-film distance. Figure demonstrates how an image from a 22.86-cm rod (rod top to rod bottom is the known value) is projected onto the surface of the radiograph datum. The top of the rod is projected laterally and form the images RTI. Triangle sides O_1 to RTI and RB to RTI are proportional. The similarity ratios formed by these 2 sides are used to calculate the distance L_1 to O_1 that is equal to ‘H,’ the focal spot-to-film distance.

for the value of Z at point P . Z_p is then used to solve for X_p and Y_p in equations 2 and 3, respectively. Data are obtained from measurements taken from points p_1 or p_2 to the origin in the horizontal direction or y_1 or y_2 in the vertical directions. Because a 2-generator stationary radiograph system is not used in this study and the spatial relationship between the radiograph tube positions and the film surface is not known before the images are generated, it is necessary to do a calibration at the time the radiographic images are exposed.^{30,31} Equation 4, which is also derived from the “Law of Similar Triangles,” is solved by taking the data obtained from measurements from radiographic images created by the 4 calibration rods. That data are used to calculate the focal spot to film distance “ H ” (Fig 4).

Equations

1. $Z_p = SH/B + S$
2. $X_p = xP_1/H(H - Z_p)$
3. $Y_p = yP_1/H(H - Z_p)$
4. $L_1 - O_1/RT - RB = O_1 - RTI/RB - RTI$

Calibration

A calibration is completed by imaging upon each overlapping coplanar stereo radiographic pair an opaque array that consists of four 22.86-cm metal rods (Fig 5). The precise relationship of the rods to each other is known (15.29×20.32 cm) in advance of image generation.³¹ The rod tops are physically located on a plane, parallel to the film plane, between the subject and

Fig 5. Four parallel calibration control rods. The illustration above shows the tops of 4 and bottoms of 2 of four 22.86-cm rods. This array is projected onto the datum of both the centered and offset radiographs. The tops are located between the radiograph source and the subject, and the bottoms are located on a plane parallel to the first between the film plane and the subject.

Fig 6. Central ray location. The radiograph above shows how the tops and bottoms of the 4 calibration rods appear on a centered view that contains the origin. In object space, the tops (larger lateral end projections) are actually positioned between the subject and the radiograph source. The bottoms (smaller medial end projections) are located closer to the film plane between the subject and the film. The central ray is located by extending a line from each rod bottom image to the opposite bottom image. The points where the perpendicular lines cross represent the point of exposure of the central or principal ray. Measurements are taken from the bottom and top edges of each rod. Limits of the software have cut off the measured values of the top left and bottom left rods. Those values are 53.30 mm and 40.24 mm, respectively. Points of interest are indicated on the radiograph by 3 black arrows (distal anterior tubercle, anterior transverse process, and posterior tubercle). C , Central or principal ray; T , rod top; B , rod bottom.

the radiograph source. As the rods extend toward the film plane, the rod bottoms, located on a second plane parallel to the first but physically located between the subject and the film plane, project a smaller, more medial set of points onto the radiographic datum. The back and front surfaces of the array unit are composed of a ridged Plexiglas material that holds the rods in a fixed position. The array is placed in the radiograph field of each exposure. As a result, 8 images of the rod tops and rod bottoms are arranged in 4 pairs near each corner of each radiograph³¹ (Fig 6). A total of 192 system parameter measurements associated with the 4 superimposed rods were measured directly from the radiographs.

Results

Base distance measurements for trials 1 through 4 are 34.96, 35.17, 32.71, and 33.49 cm, respectively.

Table 1 System parameter measurements collected from calibration control arrays

Trial no.	Array no.	B	H	R	RB-RT	O-RTI	RB-RTI
C1	1	34.96	92.35	4.04	22.86	17.4	4.23
	2			3.36		18.59	5.53
	3			4.57		16.73	3.66
	4			4.13		17.34	4.2
O1	1	34.96	105.92	2.87	22.86	20.03	6.97
	2			3.82		18.12	4.74
	3			3.18		18.99	5.97
	4			8.66		14.9	1.72
C2	1	35.17	89.71	4.02	22.86	17.45	4.15
	2			3.57		18.31	5.13
	3			3.76		16.86	4.48
	4			4.16		17.12	4.12
O2	1	35.17	102.92	2.99	22.86	19.35	6.48
	2			4.59		16.8	3.66
	3			3.07		19.1	6.22
	4			7.36		15.22	1.95
C3	1	32.71	88.17	4.57	22.86	16.97	3.67
	2			3.63		17.93	4.94
	3			3.63		17.47	4.81
	4			3.6		17.34	4.82
O3	1	32.71	109.04	3.8	22.86	17.47	4.6
	2			5.86		16.08	2.74
	3			5.64		16.35	2.9
	4			3.78		17.56	4.64
C4	1	33.49	86.41	2.93	22.86	19.58	6.66
	2			2.69		21.23	7.87
	3			4.37		17.66	4.04
	4			5.13		15.91	3.1
O4	1	33.49	93.04	2.62	22.86	21.61	8.24
	2			2.88		18.98	6.6
	3			7.32		14.43	1.97
	4			3.46		19.32	5.58

Centered radiograph exposures have the letter *C* preceding the trial number, and offsets are identified by the letter *O* in front of the trial number. Measurements above are all in centimeters except the similarity ratios *R*.

The altitudes (H) results for trials 1 through 4 are 92.35, 89.71, 88.17, and 86.41 cm, respectively (Table 1). The calculated x, y, and z coordinates results for the 3 atlas locations are shown in Table 2. An analysis of variance test revealed no statistical difference between the 4 trials ($P = 0.995$). Correlations between trials 1 through 4 using Pearson product-moment coefficient are very strongly positive for all 6 comparisons (Table 3).

Discussion

For some chiropractors, an upper cervical correction is an important procedure that they perform. There are 2 basic schools of thought concerning radiographic line drawings for upper cervical analysis: (1) those derived from BJ Palmer that are orthogonal in nature (eg,

NUCCA, Atlas-Orthogonal) and (2) those derived from Palmer that are nonorthogonal (eg, HIO and Blair). In mathematics, 2 vectors are orthogonal if they are perpendicular; that is, they form right angles. The word comes from the Greeks meaning *straight*. An orthogonal-based upper cervical technique compares a line drawn through the middle of the skull with the atlas that theoretically should be perpendicular to C1.⁷ However, this approach requires addressing the issue of possible skull malformations.

Empirical observation of upper cervical cadaver specimens was completed in the 1950s by Dr WG Blair.^{7,8} He concluded that (1) architectural asymmetry and malformations of the condyle exist in 77% of cases when comparing the length of the condyles with the orbital floor and 66% when comparing the condyle with the skull base line^{7,8} and (2) many individuals respond to asymmetry by adaptive changes, such as

Table 2 The calculated x, y, and z coordinates from 3 locations on the atlas

	Calculated coordinate values (trials 1-4)			
	Trial 1	Trial 2	Trial 3	Trial 4
Ant T				
x	1.32	1.28	1.75	1.84
y	1.67	1.71	1.83	1.42
z	4.62	4.34	4.83	2.50
Post T				
x	2.97	2.92	2.66	2.96
y	2.90	1.53	3.48	1.28
z	18.01	16.72	19.92	19.08
TPs				
x	1.23	1.29	1.51	1.11
y	1.85	1.95	2.52	1.86
z	4.23	3.26	4.06	6.80
Mean	9.45	8.63	10.3	9.96
Standard deviation	7.82	7.30	8.76	8.33

The system parameters used to calculate the values are measured directly from the radiograph film. *Ant T*, Anterior tubercle of C1; *Post T*, posterior tubercle of C1; *TPs*, anterior transverse processes of C1.

increased lateral mass thickness on the side of the short condyle, elevation of the superior articulating surface on the malformed condyle side, increased head tilt away from the malformation, and scoliosis convexing toward the side of the short condyle.^{7,8} In contrast, the nonorthogonal techniques rely on measurements taken from overlap and/or underlap joint surfaces, that is, superior and inferior articular facets of the AO joint. In 2008, the author found asymmetric AO articular surfaces within a selected small cadaveric sample with a minimum of 1 mm of overlap between AO surfaces in all joints analyzed.⁹ The problem that limits methods that use overlap/underlap is the small results obtained, which are as small as 1 to 1.5 mm and which make it difficult to determine if a true misalignment is present. This is evident in the Bolijsen¹⁰ studies and the studies conducted by Senol et al¹¹ and Blackley et al¹² who concluded that magnification ratios can be altered by both the focus-to-film and object-to-film distances. These factors are not as important with the coplanar stereoscopic method because calibrations are performed at the time of exposure and calculations of system parameters are retrospective. This is the major advantage that the coplanar stereoscopic method has when compared with orthogonal and nonorthogonal analytical approaches. In addition, structural location using a position coordinate system will produce more accurate measurements and decrease measurement

errors due to magnification and/or distortion. Compared with computed tomography, the present coplanar radiographic method has the advantage of lower levels of radioactivity to the patient if used clinically.

To date, the profession continues to have difficulty in figuring out how to limit a number of assumptions adopted by various radiographic analytical methods.^{7,8} The present study contains tools that have the capability of providing direct measurements from coplanar radiographic pairs and may provide an avenue through which precise 3D coordinate points may be established. In an effort to become more precise and because the presented technique is time consuming, we are initiating the development of software to perform all mathematical computations used in the study. The proposed advantage that this method may have over other upper cervical methods will be the ability to compute specific spatial location of structures observed on the radiograph. Other radiographic methods make an assumption about the position of various structures that are observed. The assumption is that the observed seated position of structures on the 2D radiograph is the true position or very close to it. This assumption needs to be reinvestigated. The facts may reveal that points of interest may actually be located some significant distance from the assumed positions. Potentially, this may have an effect on how some listings are determined and how and where misalignment corrections are implemented. Although there are some upper cervical techniques that do use stereoscopic techniques, the major difference between those procedures and the present study is they are all visually orientated and seek to measure stereoscope alignment of structures via prism and/or mirrors. The problem is that the combined 3D images are subject to the same problems of magnification and distortion as the 2D radiographs unless a calibration is performed or the radiographs are taken with a fixed stationary system. The Blair procedure has taken this into account; but again, it looks at visual alignment of structures instead of determining the true mathematical position.

In the present study, the calibration system is in place at the time of image exposure; so if there is

Table 3 Correlation coefficients between trials

	Trials 1 and 2	Trials 1 and 3	Trials 1 and 4	Trials 2 and 3	Trials 2 and 4	Trials 3 and 4
Pearson <i>r</i>	0.9008	0.9977	0.9734	0.9934	0.9690	0.9671

Pearson product moment correlation coefficient results are shown above. All correlations are strongly positive.

patient movement, a new source-to-object distance and/or a new object-to-image distance is calculated based on the new position after movement. An accurate standard method can clarify assumptions through support and/or confirmation of the correctness of listing in both orthogonal and nonorthogonal methods. A comparison standard that demonstrates acceptable scientific merit is warranted to ensure that a high degree of clinical excellence is established and adhered to by the many currently used radiographic methods.

Limitations and future research

This study was performed to better understand how anatomical structures are represented in space using mathematical methods and was not a study of validity, reliability, or clinical effectiveness. Therefore, the interpretation of the current study findings should be limited to mathematical models.

Additional limiting factors in the present study are associated with the lack of computer support, so practical applications are not feasible at this time because of the amount of time required to perform the necessary mathematical operation. Software capable of detecting landmarks automatically in both radiographs and matching this information with data from the other radiograph is being developed to overcome this limitation. In addition, lack of computer support introduces the factor of human error, which is likely when solving mathematical operations without computer help. Another limiting factor is that slightly larger structures relatively speaking were chosen for analysis to ensure image correspondence of the coplanar pairs. Again, the problems can be solved mathematically through calculation of determinants of a 3×3 matrix or a matrix of arbitrary size. Software must be capable of performing the following task: (1) landmark detection, (2) object recognition, (3) image registration, (4) self calibration, (5) determination of correspondence of structure, and (6) mathematical computation of coordinates. The description of each of the categories above requires mathematical explanations that go beyond the necessary topics in the present study; therefore, they will not be described in this communication. Finally, if this procedure is used clinically, there is a higher health risk to the patient due to the additional exposure to ionizing radiation.

The next step for future research is to assess the system's ability to evaluate the alignment of structures above and below various calculated points (coordinate). Point location and alignment assessment potentially will lead to the development of a listing system

that is based on the actual location of the observed structures (vertebrae).

Conclusion

This study showed that it is possible to obtain stereoscopic information from 2D coplanar radiograph pairs and retrospectively measure system parameters and use those data to calculate 3D coordinates of structures of interest.

Funding sources and potential conflicts of interest

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