ORIGINAL ARTICLE

Assessment of 3-dimensional computer-generated cephalometric measurements

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The purpose of this study was to assess the reliability of 3-dimensional computer-generated linear and angular measurements produced by different computer algorithms and various combinations of cephalogram projections compared with direct and CT measurements. A computer program was written to provide 4 computer algorithms and 4 combinations of cephalogram projections generating 22 linear and 10 angular 3-dimensional measurements from 20 landmarks. A new technique to produce biplanar cephalograms from a single x-ray source using a special facebow was developed, and its reliability was assessed. Sets of lateral, frontal, and basilar cephalograms of a human dried skull were taken both with 20 radiopaque landmark markers and without markers. Paired *t* tests based on marker position demonstrated reliability of the facebow; there were no statistically significant differences in repositioning the skull over time using the facebow at $P < .05$. In the ideal situation, with minimal head rotation and landmark identification error (with the facebow and radiopaque markers), the average error of linear measurements was 1.5 mm and 3.5º for the angular measurements. Subsequent trials evaluated the errors in head position (within 5º of head rotation) and in landmark identification (by removing all markers); two-way ANOVA with Scheffé groupings concluded that the vector intercept with manual adjustment algorithm using the lateral-frontal biplanar projection provides not only greater accuracy but also clinical practicality for both linear (mean of 2.2 mm error) and angular (mean of 4.0º error) measurements compared with direct or CT measurements ($P < .05$). The effect of landmark identification error was found to be slightly greater than the head rotation error in the accuracy of 3-dimensional linear and angular measurements (mean, 2.85 mm error for linear and 4.4º error for angular measurements). Lastly, this study concluded that linear measurements in the transverse direction were found to have a slightly larger error than vertical measurements. Anteroposterior measurements have the least error. (Am J Orthod Dentofacial Orthop 1999;116:390-9)

The method of generating 3-dimensional (3D) cephalometric measurements from 2-dimensional (2D) cephalometric projections was described by Broadbent,[1] who used 2 orthogonal x-ray sources to generate the biplane projections. The requirement for 2 x-ray sources as proposed by Broadbent et al[1,2] has made it difficult to implement the method. Another difficulty occurs because the same cephalometric landmarks may not be visible on radiographs from different projections.

Grayson et al[3-5] published a technique used to generate 3D measurements using the "vector intercept with averaging algorithm," in which the midpoint of the shortest distance between two nonintersecting vectors is designated as the location in space of a landmark. Brown and Abbott[6] described the "vector intercept with manual adjustment algorithm" to calculate 3D cephalometric measurements. They also advised the use of a leveling device to check for head positioning as the subject's head rotated from 1 projection to another.

The 2 objectives of this project were the following:

1. To assess the accuracy of different computer algorithms and combinations of projections in 3D linear and angular measurements under ideal conditions (using a facebow specially developed by Kusnoto[7] to minimize the head positioning error and radiopaque markers to minimize the landmark identification error); and
2. To investigate the effect of head rotation and landmark identification error on the accuracy of 3D linear and angular measurements in comparison with direct and computerized tomography (CT) scan measurements.

MATERIAL AND METHODS

Four computer algorithms (no 1, 3D slice algorithm used by CT software; no 2, stereophotogrammetry; no

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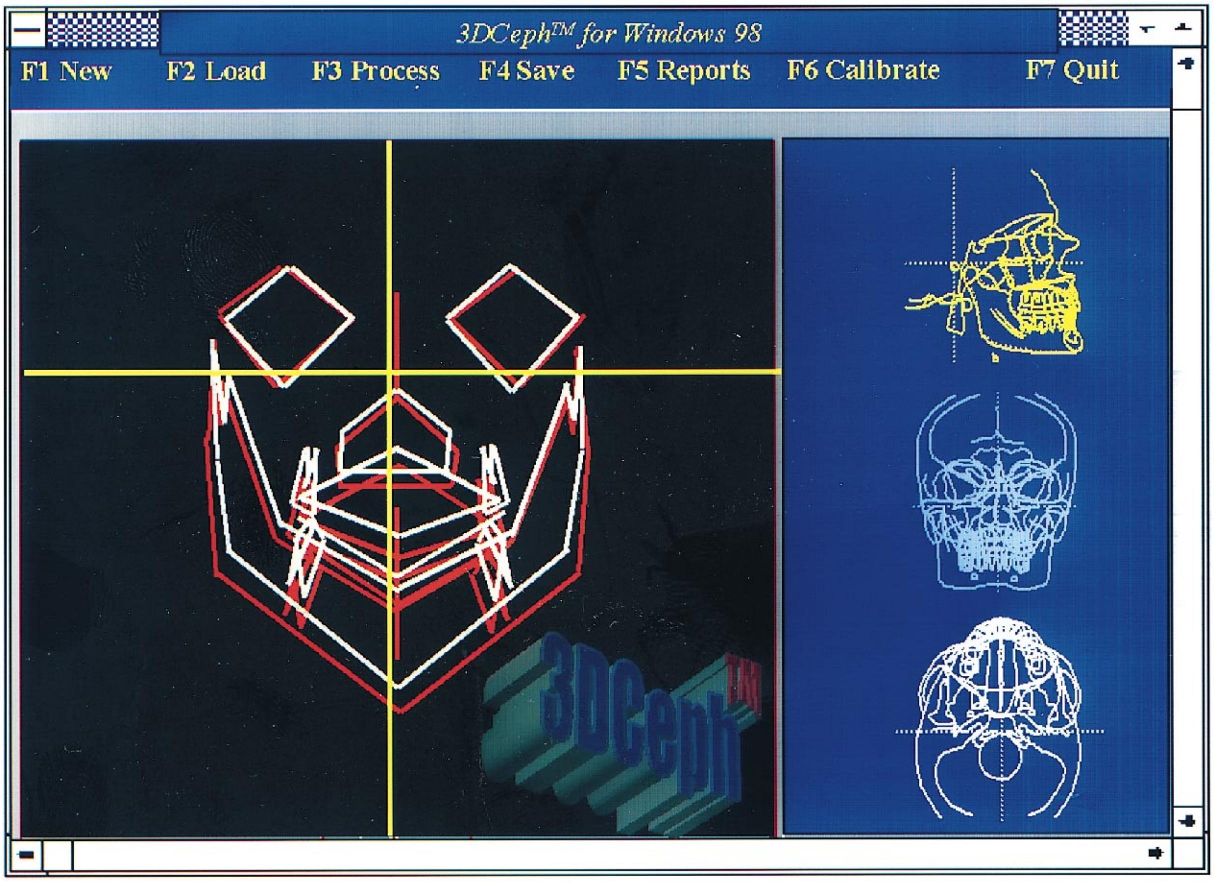

Fig 1. 3DCeph computer program screen.

3, vector intercept with averaging; and no 4 vector intercept with manual adjustment) were used along with 4 combinations of orthogonal projections (LF, lateral-frontal; LB, lateral-basilar; FB, frontal-basilar, and LFB, lateral-frontal-basilar). The customized computer program, 3DCeph (Department of Orthodontics, University of Illinois at Chicago), which integrated the algorithms and combinations of projections, was written in Borland Turbo Pascal (Borland International, Inc, Scotts Valley Calif) (Fig 1). A human dried skull with symmetric skeletal and dental structures was used. Twenty radiopaque markers representing right, left, and midline cephalometric landmarks were placed.

In the first part of the study, the special facebow (Fig 2) was used to help position the skull in order to produce orthogonal lateral, frontal, and basilar projections. Lateral projections were established with FHP parallel to the floor and the midsagittal plane parallel to the film. For frontal projections, the midsagittal plane was set to be perpendicular to the film. Basilar projections were established with FHP and midsagittal planes perpendicular to the floor and film (Fig 3). The 20 landmarks (radiopaque markers) in lateral, frontal, and basilar projections were digitized by a single operator with a SummaSketch II (Summagraphics Corp, Austin, Tex) digitizer with 0.05 mm accuracy. Twenty-two linear and 10 angular measurements were derived (see Table I).

The CT study was done with 64 standard 3 mm slices (120 mA, 120 kV, 2 secs) in a GE9800 CT unit (General Electric Medical System, Milwaukee, Wis). After that, GE-Advantage Windows 3D Dentascan CT software (General Electric Medical System) was used to calculate linear and angular measurements. Paired *t* tests with the Bonferroni correction were used to assess absolute error differences between the 3DCeph measurements, direct measurements, and CT measurements for various algorithms and combinations of projections. Two-way ANOVA with Scheffé classification was used to assess the statistical differences.

Next, the effect of head rotation was investigated. Skull positions at ($x = 0^o$, $y = 0^o$, $z = 0^o$) rotation for lateral, frontal, and basilar projections were established; the facebow was used in the control group. In

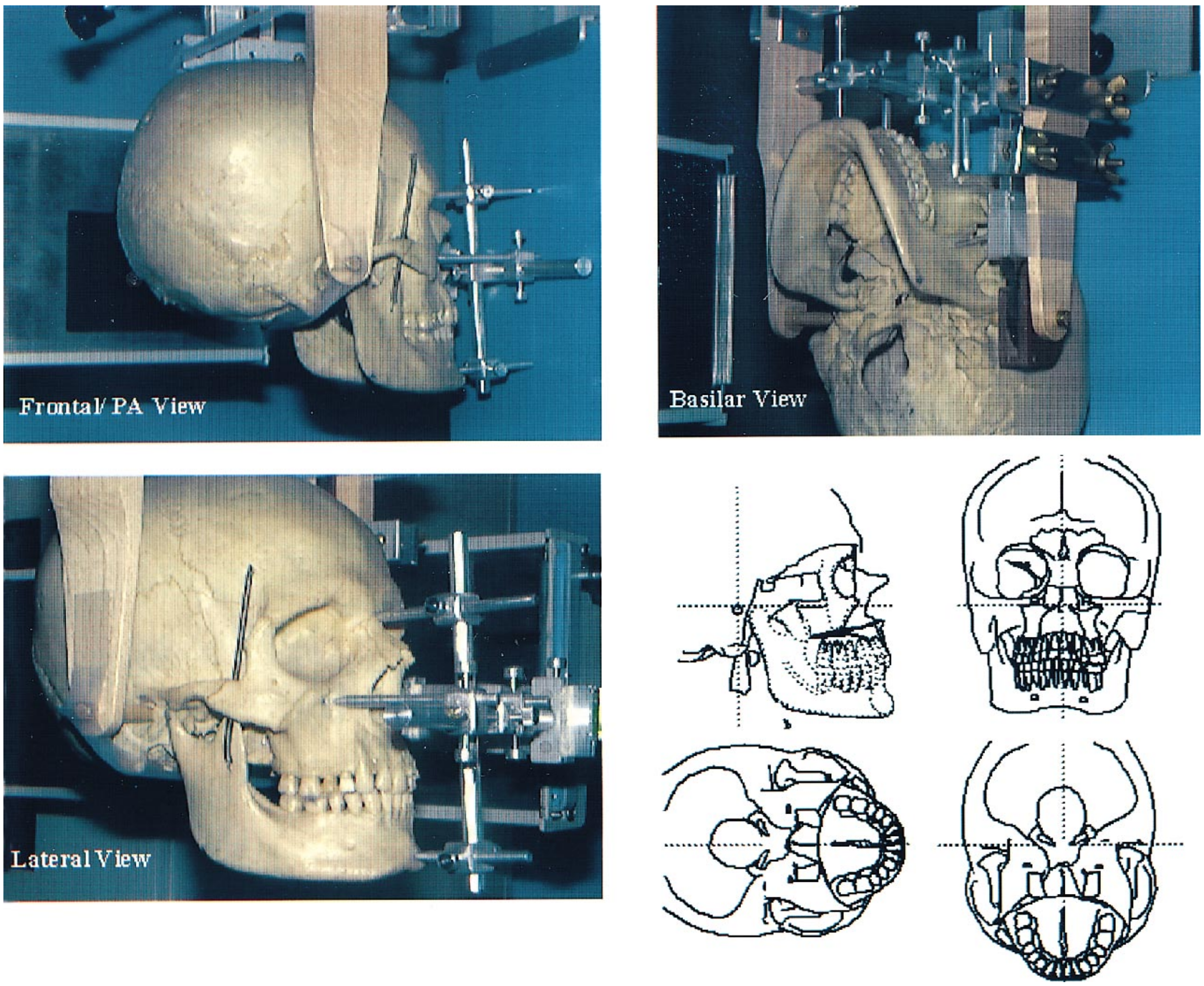

Fig 2. Lateral, frontal, and basilar projections with special face bow.

each projection, 4 (2^2) sets of radiographs with changes along 1 axis were used as the experiment groups. Altogether, 15 radiographs were obtained and digitized (12 experimental and 3 control from 3 projections). In addition, the computer program was used to simulate the dual-axial error (combination of error along 2 axes) producing another 4 (2^2) rotation errors. The number of samples in each projection was nine ($2^2 + 2^2 + 1$) producing 81 (9×9) orthogonal biplane projections (LF, LB, FB) or 729 ($9 \times 9 \times 9$) of triplane projections (LFB). When four combinations of projections were used, a total of 972 (81 + 81 + 81 + 729) head-positioning errors are mathematically possible. All rotation errors were controlled not to exceed 5º in each axis (x, y, and z). The 3D linear and angular measurements were compared with direct and CT measurements as described in the first part of the study. Statistical differences were analyzed with the 2-way ANOVA with Scheffé method to isolate pairwise mean differences. The 2 factors in the study design were different algorithms and different combinations of projections. Landmarks (radiopaque markers) from 15 cephalograms were identified and digitized by a single operator.

Lastly, after removing all radiopaque markers, the effect of landmark identification error was assessed. Five sets of lateral, frontal, and basilar x-ray projections were made with each set taken 1 week apart (t_1 to t_5). All landmarks from each projection were identified and digitized by a single operator. The 3D linear and angular measurements were compared with direct and CT measurements, as described in the first part of the study. Statistical differences were analyzed, using the 2-way ANOVA with Scheffé classification (different algorithms and different combinations of projections).

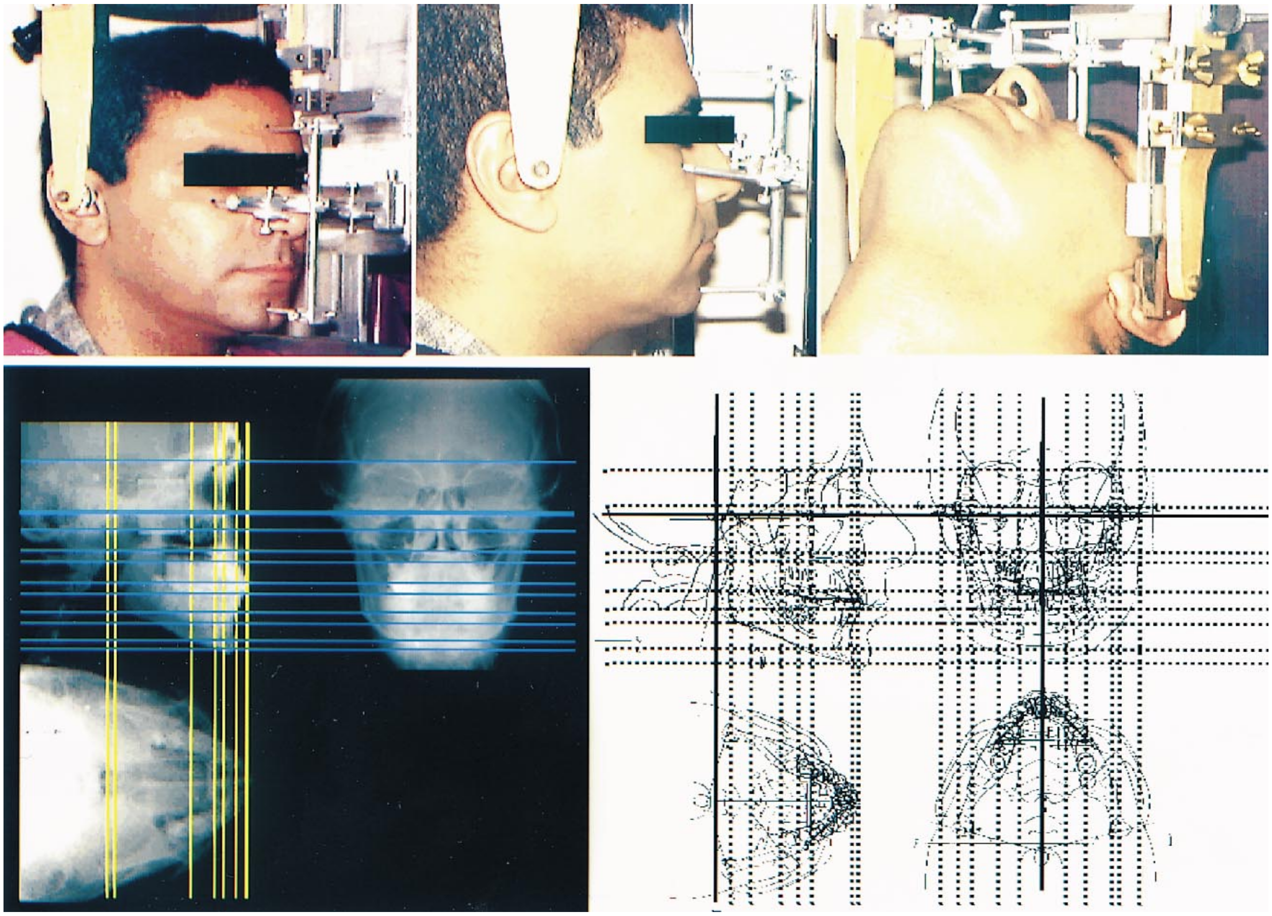

Fig 2. Cont'd..

RESULTS

For the 20 landmarks observed, indicated by the paired *t* tests, most of the landmarks' locations can be reproduced (t_1, t_2, t_3, t_4, and t_5) without statistically significant differences in the lateral and frontal projections at $\alpha = .05$. However, statistically significant differences (nonreproducibility) were noted for the basilar projection in 7 landmarks along the horizontal direction and 2 landmarks in the vertical direction (see Table I).

Table II summarizes the accuracy of linear and angular measurements under ideal conditions. This study found that, on the average, algorithm 3 (1.1 ± 0.7 mm) produced the minimum absolute error followed by algorithm 4 (1.3 ± 0.9 mm). Statistically significant differences were found only when frontal-basilar combinations of projections were used to produce 3D linear measurements. This is true for comparison with both direct measurements and CT measurements. Combinations of lateral-frontal-basilar projections also produced statistically significant differences with a mean of 1.6 ± 1.5 mm compared to CT measurements. For angular measurements, a minimum average error of 2.8° ± 1.9° (direct comparison) and 3.2° ± 2.4° (CT comparison) was achieved when using combinations of lateral-frontal projections.

Two-way ANOVA tests with Scheffé classification summarizing the effect of different algorithms and combinations of projections under the influence of head rotation and landmark identification errors can be found in Table III and IV. The minimum average absolute error was found to be 2.2 ± 1.0 mm for linear measurements and approximately 4.0° ± 2.0° for angular measurements. Under landmark identification error, the minimum average absolute error was found to be 2.9 mm ± 1.7 mm for linear measurements and approximately 4.4° ± 2.6° for angular measurements. The effects of head rotation and landmark identification errors, regardless of the algorithm and combinations of projections used, are summarized in Figs 4 and 5.

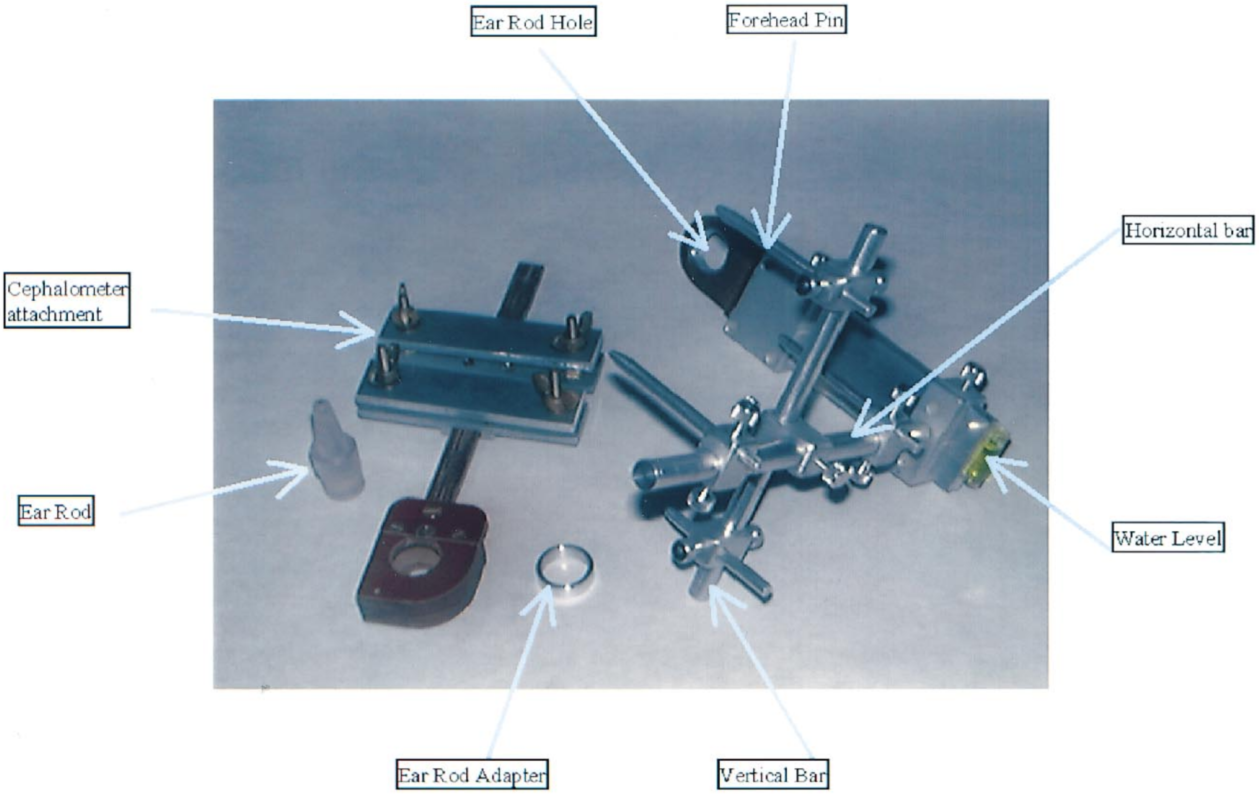

Fig 3. Special facebow.

DISCUSSION

The use of the special facebow described in this study will facilitate the use of 3D modeling for most orthodontists. The user does not need a special research cephalometric radiography unit with 2 perpendicular x-ray sources. The facebow enables the user to use an ordinary single x-ray source unit with good precision in repositioning the patient's head. This study found that the facebow technique can adequately reorient the subject's head between exposures to create biplane orthogonal projections. However, when available, an x-ray unit of the Bolton-Broadbent setup with 2 x-ray sources is preferable for ease of use and to further lower the risk of head-positioning error. Even though it was not assessed in this study, it is possible to apply the facebow technique to produce a biplane projection without having the subject's midsagittal, transverse, and horizontal planes parallel to the x-ray machine's planes. Such an arrangement will theoretically improve landmark identification by reducing superimposed anatomic structures and enhancing the accuracy of the 3D system. Though it was not included in this study, application of the special facebow was tried in live human beings with similar result in its reliability as in the dry skull experiment (Fig 6). The final version of computer program (3DCeph for Windows), which works under Windows 95/98/NT operating system, was developed to give future users more accurate and more flexible user friendly software. Several studies have incorporated the use of this protocol (special facebow and 3DCeph for Windows) with satisfactory accuracy.[8]

It was found that under ideal conditions, when head rotation and landmark identification errors were minimal, algorithm 3 (vector intercept with automatic averaging) and algorithm 4 (vector intercept with manual adjustment) appeared to have the same degree of accuracy for both linear and angular measurements. Under such circumstances, the frequency of performing adjustments of landmark identification can be greatly reduced by using algorithm 3, thus providing a more efficient approach.

The landmark identification error produced less accurate measurements when compared to the effect of head rotation error, regardless of the algorithms or combinations of projections used. On the average, algorithm 4 was found to produce the smallest error, followed by algorithm 3 (the second smallest error).

Table I. Paired *t* tests for accuracy of the facebow in lateral, frontal, and basilar projections

		Lateral		*Frontal*		*Basilar*			
Number	*Landmark*	*x*	*y*	*x*	*y*	*x*	*y*	*Linear*	*Angular*
1	RGo	*	*	*	*		*	RGo-LGo	SNA
2	RCo	*	*	*	*	*	*	RCo-LCo	SNB
3	RSOrb	*	*	*	*			RCo-RGo	U1/L1
4	ROOR	*	*	*	*	*		RGo-Me	RCo-RGo-Me
5	UR6	*	*	*	*	*	*	RCo-Me	LCo-LGo-Me
6	LR6	*	*	*	*	*	*	LCo-LGo	UR6-U1/L1-UL6
7	S	*		*	*		*	LCo-Me	LR6-U1/L1-LL6
8	N	*	*	*	*	*	*	LGo-Me	ROOR-S-LOOR
9	A	*	*	*	*	*	*	RSOrb-LSOrb	RGo-Me-LGo
10	U1Apx	*	*	*	*	*	*	ROOR-LOOR	RSOrb-S-LSOrb
11	U1/L1	*	*	*	*	*	*	UR6-UL6	
12	L1Apx	*	*	*	*	*	*	LR6-LL6	
13	B	*	*	*	*		*	UR6-U1/L1	
14	Me	*	*	*	*		*	UL6-U1/L1	
15	LGo		*	*	*	*	*	LR6-U1/L1	
16	LCo	*	*	*	*		*	LL6-U1/L1	
17	LSOrb		*	*		*	*	S-N	
18	LOOR		*	*		*	*	N-A	
19	UL6	*	*	*	*	*	*	N-B	
20	LL6	*	*	*	*		*	N-Me	
								U1Apx-U1/L1	
								L1Apx-U1/L1	

*$P > .005$ with the Bonferroni Correction.
RGo = right gonion angle; RCo = right condylion; RSOrb = right supra orbitale; ROOR = right outer orbital rim; UR6 = upper right first molar; LR6 = lower right first molar; S = sella; N = nasion; A = point A; U1Apx = upper incisor apex; U1/L1 = interincisal angle; L1Apx = lower incisor apex; B = point B; Me = menton; LGo = left gonion angle; LCo = left condylion; LSOrb = left supra orbitale; LOOR = left outer orbital rim; UL6 = upper left first molar; LL6 = lower left first molar.

Table II. Two-way ANOVA of different algorithms and combinations of projections under ideal condition. Comparison with direct and CT measurements

	A1	*A2*	*A3*	*A4*	*LF*	*LB*	*FB*	*LFB*
Comparison with direct measurements								
Linear								
Mean	1.50	2.10	1.10	1.30	1.40	1.30	1.80*	1.50
SD	1.20	2.00	0.70	0.90	1.20	1.10	1.50	1.10
Angular								
Mean	2.80	3.90	3.10	2.70	2.80	2.90	4.00	2.70
SD	2.40	3.80	2.80	1.50	1.90	2.00	4.70	2.00
Comparison with CT measurements								
Linear								
Mean	1.80	2.20	1.00	1.10	1.40	1.30	1.80*	1.60*
SD	1.40	2.10	0.90	1.00	1.20	1.00	1.80	1.50
Angular								
Mean	4.10	4.90	3.60	3.20	3.20	3.40	5.20	3.80
SD	3.00	4.20	3.80	2.20	2.40	2.50	5.60	2.80

*$P < .05$.
A1, A2, A3, A4 = Algorithm 1, 2, 3 and 4.
LF, lateral-frontal; LB, lateral-basilar; FB, frontal-basilar; LFB, lateral-frontal-basilar.

This was true for both linear and angular measurements when compared with the CT measurements, and also to most of the linear measurements when compared with direct measurements. But only algorithm 3 appeared consistent for both linear and angular measurements when compared with either direct or CT measurements. Algorithm 4 allows the user to interactively adjust any misidentified landmarks within a certain

Table III. Two-way ANOVA of different algorithms and combinations of projections under the influence of head rotation error

	A1	*A2*	*A3*	*A4*	*LF*	*LB*	*FB*	*LFB*
Comparison with direct measurements								
Linear								
Mean	2.55	2.75	2.14	1.23*	2.02	1.74	2.75*	2.15
SD	1.66	2.07	1.19	0.84	1.48	1.08	2.02	1.60
Angular								
Mean	4.09	4.91	3.88	2.69*	3.01	3.45	5.56*	3.55
SD	3.15	4.16	2.94	1.46	1.80	2.02	5.02	2.03
Comparison with CT measurements								
Linear								
Mean	2.60	2.84	2.12	1.05*	2.04	1.63	2.77*	2.18
SD	1.93	2.16	1.25	0.84	1.38	0.97	2.36	1.86
Angular								
Mean	4.49	5.16	4.32	3.23*	3.30	3.77	5.94*	4.19
SD	3.64	4.66	3.38	2.21	2.38	2.72	5.29	2.84

*$P < .05$.
A1, A2, A3, A4 = Algorithm 1, 2, 3 and 4.
LF, lateral-frontal; LB, lateral-basilar; FB, frontal-basilar; LFB, lateral-frontal-basilar.

Table IV. Two-way ANOVA of different algorithms and combinations of projections under the influence of landmark identification error

	A1	*A2*	*A3*	*A4*	*LF*	*LB*	*FB*	*LFB*
Comparison with direct measurements								
Linear								
Mean	3.20	3.25	3.03	2.19*	2.57	2.26	3.88*	2.97
SD	2.92	3.09	2.64	2.02	2.25	2.07	3.53	2.56
Angular								
Mean	3.93	5.21	4.12*	4.34	3.91	3.62	6.35*	3.73
SD	3.16	4.48	3.24	3.32	2.58	2.47	5.36	2.42
Comparison with CT measurements								
Linear								
Mean	3.19	3.05	2.84	2.03*	2.36	2.02*	3.91*	2.82
SD	2.98	3.14	2.56	1.65	1.88	1.83	3.58	2.66
Angular								
Mean	3.68*	4.83	4.01	4.38	3.52	3.18	6.24*	3.96
SD	3.67	5.11	3.42	4.01	2.74	2.50	6.38	2.80

*$P < .05$.
A1, A2, A3, A4 = Algorithm 1, 2, 3 and 4.
LF, lateral-frontal; LB, lateral-basilar; FB, frontal-basilar; LFB, lateral-frontal-basilar..

degree of confidence (in this study it was set to 95%) by means of intersecting vectors (locked vector and unlocked vector). Certain protocol and hierarchy factors were included in the computer program, such as lateral, frontal, and basilar. Hierarchy was established under criteria of most identifiable landmarks, chances for being distorted projection, and crucial axis of the projection. For example, when using combinations of lateral-frontal projections, the lateral projection, the first in the hierarchy (by having the most identifiable landmarks), was used to establish the x and y coordinates (locked), whereas the z component was derived from the frontal projection (unlocked/second in the hierarchy). Any adjustment requested by the computer program will adjust the second hierarchy, in this case, the vertical (y) component of the frontal projection. Nevertheless, the user's judgment will determine the final result, after reexamining the suggested misidentified landmark by the computer program. Under certain circumstances, the error could lie in the lateral projec-

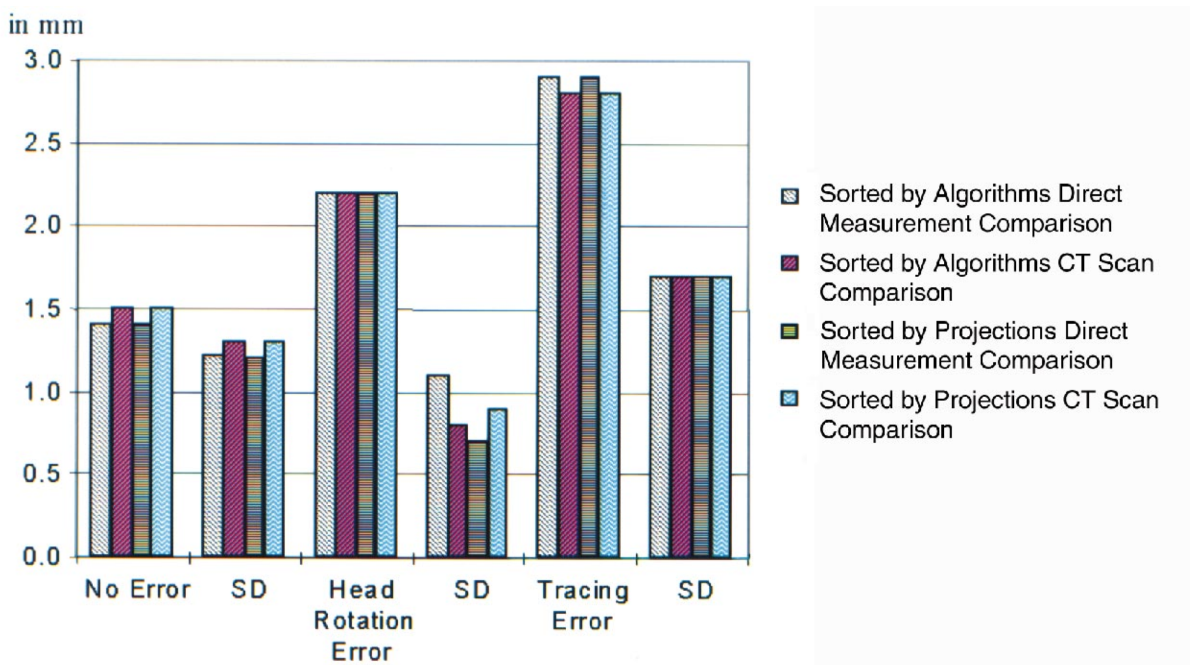

Fig 4. Summary of the accuracy of 3D linear measurements in comparison with direct and CT measurements categorized by different algorithms and different combinations of projections under the influence of head rotation and landmark identification.

tion even though it has the highest hierarchy of all. Finally, when the user is well trained, the accuracy of this algorithm will improve significantly. Algorithm 4 will help the operators to make adjustments when the landmarks traced in 1 projection do not coincide with the landmarks on the other projection, but the final decision still relies on the operator's judgment and experience. To minimize the error caused by landmark identification, especially for dental landmarks in a lateral projection, the panoramic film and dental cast were found to be useful in assisting the operator in determining the correct left and right dental landmarks.

Needless to say, both algorithms 3 and 4 share a similar basic algorithm, which is the vector intercept. Both algorithms work by using the vector principle to approximately locate landmarks in space. The only difference between the 2 algorithms is the involvement of the operator during the process of identifying landmarks. In algorithm 3 (vector intercept with averaging), the operator does not need to manually adjust 1 of the vectors to get the intersection point between 2 vectors (lateral and PA). The use of midpoint coordinates from the closest distance between the 2 "supposedly" intersecting vectors was assumed to average the error in landmark identification. Even though this method is very efficient in time and accurate enough most of the time, it limits the flexibility of the operator when indeed he or she realizes that the error definitely lies in one of the projections and correction needs to be done in that projection. The computer program using this algorithm will automatically take the midpoint without giving the operator a chance to correct manually. On the other hand, the use of algorithm 4 (vector intercept with manual adjustment) allows the operator to manually adjust nonintersecting vectors with only 1 disadvantage, which is the time consumed. When the analysis involves only a small number of landmarks, this method works with great accuracy (in some landmarks less then 1 mm error). In the event that the number of landmarks involved in the analysis increases, the time involved to manually adjust every landmark is also increased, thus increasing operator working time. This is when the human judgment comes to play; the dichotomy between accuracy and operator time can only be solved by the operator.

The need for computerized 3D reconstruction as a diagnostic tool led to the development of sophisticated technology such as the CT unit. Despite the well-demonstrated usefulness of the CT and its versatility, it has disadvantages. The high cost of performing a 3D CT reconstruction is far greater than the cost of several ordinary cephalograms. The radiation exposure from the CT unit is also much higher than the total radiation

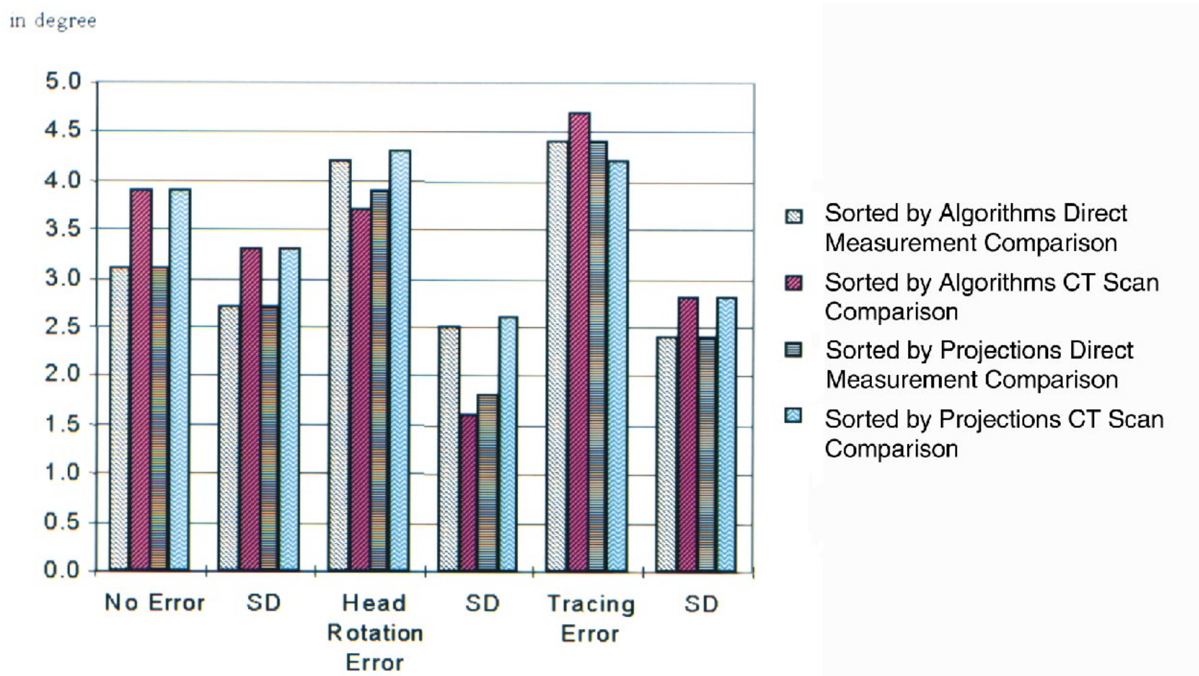

Fig 5. Summary of the accuracy of 3D angular measurements in comparison with direct and CT measurements categorized by different algorithms and different combination projections under the influence of head rotation and landmark identification.

of several ordinary cephalograms. Moreover, with new developments in digital x-ray film, the amount of radiation exposure for cephalograms can be reduced even further by up to 90%.

CONCLUSIONS

It can be concluded that the special facebow is satisfactory for acquisition of lateral, frontal, and basilar projections in order to create orthogonal projections. Each landmark in each projection appears to have its own envelope of error. When the facebow was used, under conditions of reduced landmark identification and head rotation error, the accuracy of the system was affected to the greatest extent by identifying the correct landmarks, followed by the choice of algorithms, and lastly by the influences of different combinations of projections.

Landmark identification errors produced more measurement inaccuracies when compared with head rotational error for comparison with both direct and CT measurements. Errors in linear measurements are fewer than those of the angular measurements. Comparison with either direct or CT measurements found that algorithm 4 (vector intercept with manual adjustment) was superior for both linear and angular measurements. The accuracy of algorithm 3 is slightly lower than algorithm 4 but its overall performance considering time efficiency is comparable to algorithm 4. Even though, in this study, combinations of lateral-basilar projections showed the lowest mean of error for linear measurements, differences from lateral-frontal projections were not statistically important; thus the more practical lateral-frontal projection combination becomes preferred. Increasing the number of projections (LFB/ triplane) does not increase the accuracy of both linear and angular measurements in comparison with either direct or CT measurements. It was found that LFB combinations of projections will be useful when landmarks are not clearly identified in either one of the projections because the use of the third projection will help reduce the landmark identification error.

Identifying correct landmarks in each projection is essential in producing accurate 3D linear and angular measurements. The use of the special facebow as a head-repositioning device was found to minimize the effect of head-rotation error, especially for the basilar projection.

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