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Comparison of cephalometric analysis using a non-radiographic sonic digitizer (DigiGraph™ Workstation) with conventional radiography

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SUMMARY Cephalometric analysis conventionally requires radiographic exposure which may not be compatible with the growing concern over radiation hazards. Recently, the Dolphin Workstation Imaging System introduced to the dental profession a non-radiographic system, called the DigiGraph™ Workstation which may be an alternative to cephalometric radiography. The aims of this study were to compare the validity and reproducibility of cephalometric measurements obtained from the DigiGraph™ Workstation with conventional cephalometric radiographs.

The sample consisted of 30 human dry skulls. Two replicated sets of lateral cephalograms were obtained with steel ball markers placed at the majority of the cephalometric landmarks. Duplicate tracings prepared from each radiograph were digitized to obtain cephalometric measurements using the computer software, Dentofacial Planner. For the DigiGraph™ Workstation, double sonic digitizations were repeated twice for each skull, on two occasions. Fifteen angular and one linear measurements were obtained from both methods and these findings compared using ANOVA, paired *t*-tests and *F*-tests.

All, except one, cephalometric measurement showed significant differences between the two methods ($P < 0.0001$). The DigiGraph™ Workstation consistently produced higher values in 11 measurements (mean differences +0.5 to +15.7 degrees or mm) and lower values in four measurements (mean differences –0.2 to –3.5 degrees). The standard deviations of the differences between readings of both methods were large (0.4–5.8 degrees or mm). The reproducibility of the DigiGraph™ Workstation measurements was lower than that of the radiographic measurements. The method error of the DigiGraph™ Workstation ranged from 7 to 70 per cent, while that of radiographic tracings was less than 2 per cent. It was concluded that measurements obtained with the DigiGraph™ Workstation should be interpreted with caution.

Introduction

Since its introduction, cephalometric radiography has been widely used in research and clinical orthodontics (Broadbent, 1931; Hofrath, 1931). With skull radiographs taken under standardized conditions, the spatial orientation of different anatomical structures inside the skull can be studied more thoroughly by means of linear and angular measurements. From the derived information, the morphology of the dental, skeletal, and soft tissues of the cranium can be described and orthodontic treatment plans formulated. With serial cephalometric radiographs, one can study, and predict the growth and development of the craniofacial skeleton (Brodie, 1941; Downs, 1948; Ricketts, 1981), and orthodontic treatment effects can be evaluated from changes between the pre- and post-treatment measurement values (Baumrind and Frantz, 1971a,b; Baumrind *et al.*, 1976).

Despite the extensive application of radiographic cephalometry over the past 50 years, there have been relatively few changes in how the cephalometric radiograph and the embodied information are obtained. Limitations and problems inherent in radiographic cephalometry, mentioned by early workers, are still present nowadays (Adams, 1940; Thurow, 1951; Franklin, 1952; Hallet, 1959). These include: (i) the fuzzy image as a result of patient movement; (ii) loss of image sharpness and definition due to the use of intensifying screens, secondary radiation, and the penumbra effect of small anode focal spot; (iii) various errors in relation to geometric enlargement and distortion, patient's head positioning, landmark identification and measuring instrument; and more significantly (iv) radiation exposure.

In addition to cephalograms, other radiographs, for example, panoramic and upper anterior occlusal views, are often required in order to provide further diagnostic information (Atchison, 1986; Tyndall and Turner, 1990; Atchison *et al*., 1991). Very often, serial cephalometric radiographs also have to be taken. These will inevitably add to the patient's total absorbed radiation dose (Bankvall and Hakansson, 1982; McNicol and Stirrups, 1985). Although radiation doses normally received in the dental environment are low and may best be compared with daily background radiation exposure, the dentist should never assume there is absolutely no risk involved (Jones, 1987; White 1992). In an epidemiological study, diagnostic radiography was identified as the most important risk factor for parotid gland cancers and about 85 per cent of the cumulative parotid dose came from dental examinations (Preston-Martin and White, 1990). As orthodontic patients are mostly adolescents and young adults, they are significantly more susceptible to radiation-induced carcinogenesis (Valachovic and Lurie, 1980). Because there appears to be no threshold dose below which biological damage does not occur (Valachovic and Lurie, 1980; Taylor *et al*., 1988) and every increment of exposure increases the risk of an adverse effect by a proportional amount, the clinician has to seek methods of achieving exposures that are as low as reasonably achievable.

Various methods have been suggested and investigated for the purpose of reducing radiation exposure in cephalometric radiography. These include the use of fast screen/film combinations (Halse and Hedin, 1978), rare-earth filtration (Tyndall and Washburn, 1986; Tyndall *et al.*, 1988), collimation of the X-ray beam to areas of diagnostic interest (L'Abée and Tan, 1982; British Society for the Study of Orthodontics and the British Society of Dental and Maxillofacial Radiology, 1985) and patient shielding (Whitcher *et al*., 1979, 1980; Eliasson *et al*., 1984; Sikorski and Taylor 1984; Wootton, 1993).

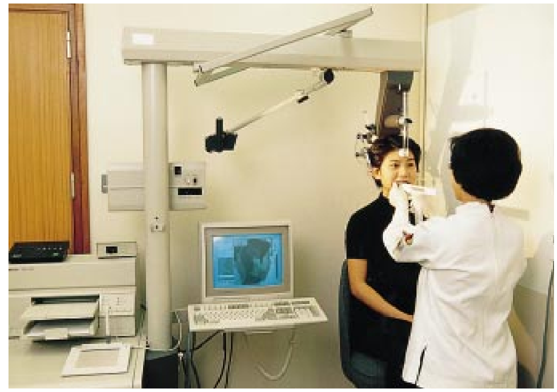

Figure 1 A patient seated in the DigiGraph™ Workstation in preparation for sonic digitization.

Recently, a new system, called the DigiGraph™ Workstation (Dolphin Imaging Systems, Valencia, California, USA; Figure 1), was introduced which may be a possible alternative to conventional cephalometric radiography (Chaconas *et al.*, 1990a). Generally speaking, the DigiGraph™ Workstation utilizes direct sonic digitization of patients to obtain various cephalometric measurements. After the patient has been properly positioned in the system with the Frankfort plane parallel to the floor, a sonic digitizing probe is placed on each facial or intra-oral cephalometric landmark. While the landmark is being digitized, sonic signals are emitted from the digitizing probe and picked up by the system's overhead microphones. The DigiGraph™ Workstation computer measures the length of time taken for the sound to reach each one of these microphones and locates the spatial location of each cephalometric landmark in three dimensions. From this information, the system can then generate various cephalometric measurements of different analyses (Figure 2). It is obvious that the non-radiographic nature of the new

Figure 2 Superimposition of tracing over patient's image by the DigiGraph™ Workstation.

technique allows repeated longitudinal cephalometric monitoring without concern over radiation exposure.

Due to the design of the equipment, some of the landmarks are not directly and physically digitized on the patient. For example, the points, sella, and upper and lower incisor apices, are determined geometrically and mathematically from other digitized landmarks. If there is misdigitization of other landmarks, cephalometric measurements involving the indirectly determined landmarks will be incorrectly derived.

The aim of the present study was therefore to compare the validity and reproducibility of cephalometric measurements obtained from the DigiGraph™ Workstation with those from conventional cephalometric radiographs.

Materials and methods

The study material consisted of 30 human dry skulls and two replicated sets of 30 lateral cephalometric radiographs. The radiographs of all skull subjects were taken with steel ball markers placed at the majority of the cephalometric landmarks. The technical details of obtaining the radiographs have been described previously (Tng *et al*., 1994). Briefly, 11 skeletal and dental landmarks on each dry skull were made identifiable on radiographs with steel ball markers. A set of 30 lateral cephalometric radiographs was then taken of these dry skulls in a cephalostat using a special skull holder. The steel ball markers and the skulls were then repositioned and a further set of 30 radiographs was taken. In addition to the landmarks marked with steel balls, a further six landmarks without the steel ball markers (porion, orbitale, ramus point, articulare, gnathion, and pterygoid point) were also included in the study (Figure 3). From a total of 11 marked, and six unmarked, cephalometric landmarks, 15 angular, and one linear cephalometric measurements were derived for comparison between the two methods.

Skeletal angular measurements

1. Nasion–sella–articulare (Saddle)
2. Sella–nasion–point A (SNA)
3. Sella–nasion–point B (SNB)

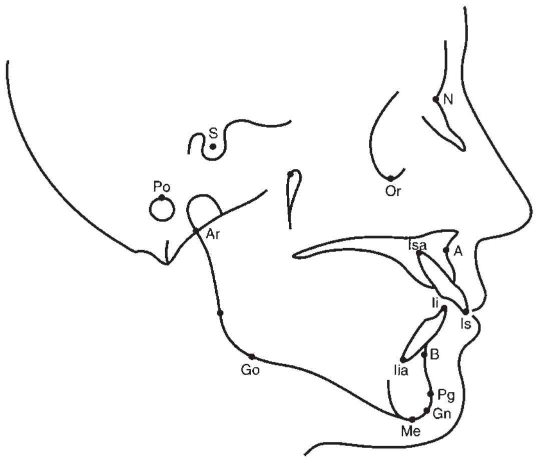

Figure 3 The dental and skeletal landmarks used in this study. Sella (S), pterygoid point (Pt), upper and lower incisor apices (Isa, Iia) are the indirectly determined landmarks with the DigiGraph™ Workstation. Porion (Po), orbitale (Or), articulare (Ar), ramus point (Ra), gnathion (Gn), and pterygoid point (Pt) are the landmarks without the placement of steel ball markers on radiographs.

4. Point A–nasion–point B (ANB)
5. Sella–nasion to mandibular plane (SN/MnP)
6. Mandibular plane to Frankfort horizontal (MnP/FH)
7. Nasion–sella–gnathion (*Y*-axis)
8. Pterygoid point–gnathion to Frankfurt horizontal (*F*-axis)
9. Articulare–ramus point to mandibular plane (gonial)

Dento-skeletal angular measurements

10. Maxillary incisor to Frankfort horizontal (U1/FH)
11. Maxillary incisor to sella–nasion (U1/SN)
12. Mandibular incisor to sella–nasion (L1/SN)
13. Mandibular incisor to mandibular plane (IMPA)
14. Mandibular incisor to Frankfort horizontal (FMIA)
15. Mandibular incisor to APg line (mm) (L1/APg)

Dental angular measurement

16. Interincisal (Interincisal)

Radiographic measurements

Duplicate tracings were first prepared from each of the 60 radiographs under standardized conditions. For landmarks with steel ball markers, a cross was drawn at the junction between the steel ball marker and the bone/tooth surface. The cross, however, was drawn at the centre of the steel ball for the point sella. For landmarks without steel ball markers, the contours of the relevant areas were traced and the landmarks were subsequently determined. In order to avoid memory in locating the six unmarked landmarks from the first tracing, all subsequent tracings of the same and repeat radiographs were made with an interval of 1 week. In case of double radiographic images arising from bilateral structures, the average of the two was taken. All tracings were then digitized with an electronic digitizer connected to a personal computer. The calculations of cephalometric measurements were performed with a computer software, the Dentofacial Planner (Dentofacial Software Inc., Toronto, Canada). For each skull, four sets of radiographic measurements were obtained and these were taken as the 'Gold Standard'.

DigiGraph™ Workstation measurements

Each skull was positioned in the DigiGraph™ Workstation and sonically digitized twice in the same skull positioning. During sonic digitization, the digitizing probe tip was placed at the same points where the landmarks were previously marked with steel ball markers. For landmarks without steel ball markers, the placement of the digitizing probe tip was by visual determination with reference to the Frankfort plane. After 1 week, each skull was repositioned and double sonic digitizations were made. Similarly, four sets of DigiGraph™ Workstation measurements were obtained for each skull.

Statistical analysis

ANOVA was used to assess if there was any significant difference among the eight series of measurements with the following class variables: skull, methods, skull positions, and repeated recordings. For each cephalometric measurement, an average value was calculated for each skull subject from the four recordings obtained with each method. The mean and standard deviation of the differences between the averages of the two methods was computed for all the 30 skulls.

The reproducibility of each method was evaluated by (a) the mean and (b) the standard deviation of the differences between the first recordings of the first and the second skull positioning. Paired *t*-tests were used to assess if the mean difference was significantly different from zero. *F*-tests were used to compare the variances of the differences (standard deviations squared) of the two methods to assess whether the reproducibilities of the two methods were statistically equivalent.

The method error of each technique was obtained by the square root of half the variance of the differences between the initial recordings of the first and the second skull positioning (Houston, 1983).

$$\text{Method error (me)} = \sqrt{S_d^2/2}$$

where S_d^2 is variance of the differences.

To assess the clinical significance of method error of each method, the 'error percentage' was used (Cooke and Wei, 1991) and this was given by the variance of the method error (me^2) as a percentage of the population variance measured by each method (standard deviation^2).

Results

Comparison between the DigiGraph™ Workstation and the radiographic measurements (Figure 4 and Table 1)

Significant differences between the two methods were found for all cephalometric measurements except the gonial angle ($P < 0.0001$). The DigiGraph™ Workstation on average produced higher values in 11 measurements (mean differences +0.5 to +15.6 degrees or mm) and lower values in four measurements (mean differences –0.3 to

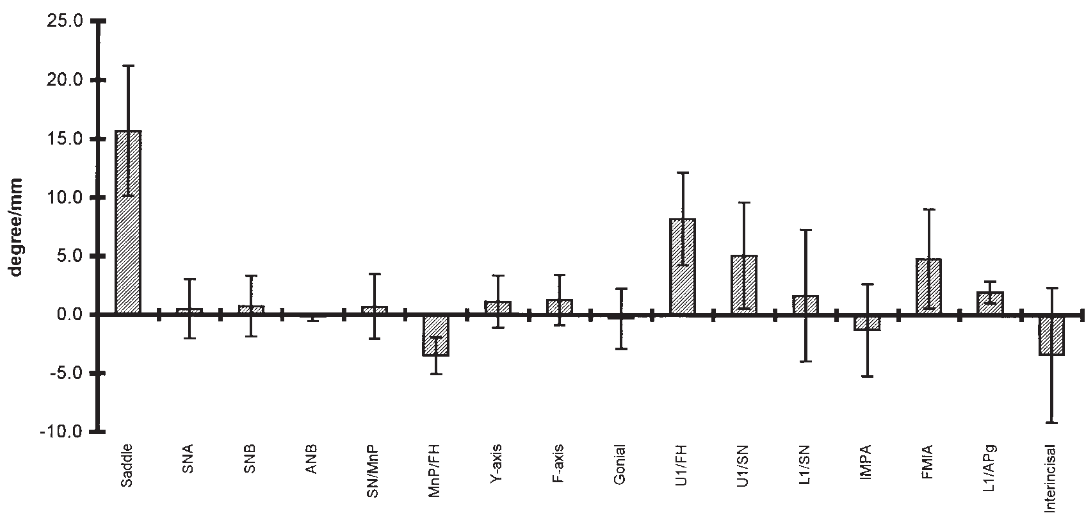

Figure 4 Mean and SD of the differences between measurement values of both methods (DigiGraph™ minus radiograph).

Table 1 Comparison between the DigiGraph™ Workstation and the radiographic measurements. The means and the standard deviations were obtained from the differences ($n = 30$) between the averaged measurements.

Cephalometric measurements	Mean (DigiGraph™ – radiograph)	SD	Mean ± 2SD (95% limits of agreement)
Angles (degree)			
Saddle	15.6	5.5	–4.6 to 26.6
SNA	0.5	2.5	–4.5 to 5.5
SNB	0.7	2.6	–4.5 to 5.9
ANB	–0.2	0.4	–1.0 to 0.6
SN/MnP	0.7	2.8	–4.9 to 6.3
MnP/FH	–3.5	1.6	–6.7 to –0.3
Y-axis	1.1	2.2	–3.3 to 5.5
F-axis	1.3	2.1	–2.9 to 5.5
Gonial	–0.3	2.6	–5.5 to 4.9
U1/FH	8.2	3.9	0.4 to 16.1
U1/SN	5.1	4.5	–3.9 to 14.1
L1/SN	1.7	5.6	–9.5 to 12.9
IMPA	–1.3	3.9	–9.1 to 6.5
FMIA	4.8	4.2	–3.6 to 13.2
Interincisal	–3.4	5.8	–15.0 to 8.2
Distance (mm)			
L1/APg	2.0	0.9	0.2 to 3.8

–3.5 degrees or mm). The standard deviations of the differences ranged from 0.4 to 5.8 (degrees or mm).

Reproducibility of cephalometric measurements (Figure 5 and Table 2)

For radiographic measurements, the mean differences ranged from –0.3 to +0.4 (degrees or mm) with SN/MnP (mean difference –0.3 degrees, $P < 0.05$) and *F*-axis (mean difference +0.4 degrees, $P < 0.01$) being statistically significant. The standard deviations of the differences ranged from 0.2 to 0.9 (degrees or mm). For DigiGraph™ Workstation measurements, the mean differences ranged from –1.1 to +0.5 (degrees or mm) with SNA (mean difference +0.5 degrees, $P < 0.05$), ANB (mean difference +0.4 degrees, $P < 0.05$)

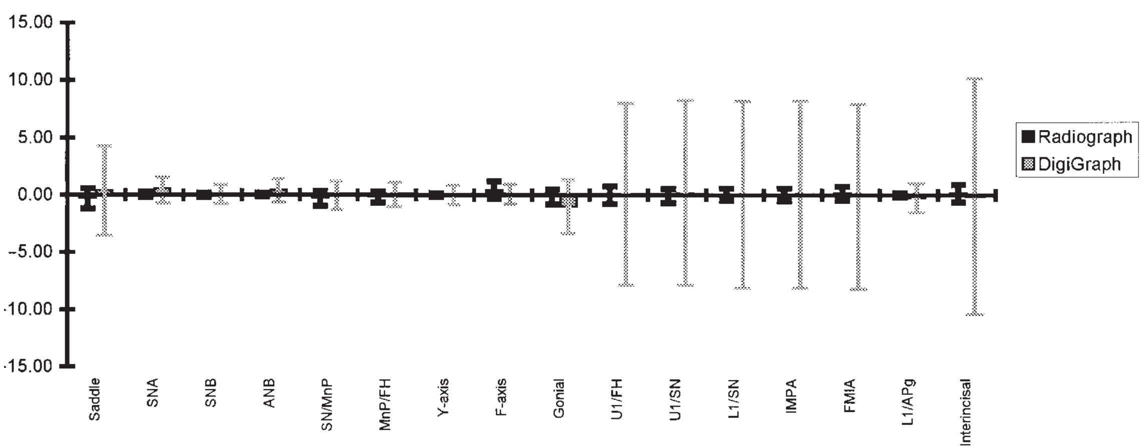

Figure 5 Mean and SD of the differences between the first recordings of the first and the second skull positionings (radiograph versus DigiGraph™).

Table 2 Reproducibility of the radiographic and the DigiGraph™ Workstation measurements. The means and the standard deviations were obtained from the differences (n = 30) between the initial recordings of the initial and the second skull positioning.

Cephalometric measurements	Mean (radiograph)	SD (radiograph)	Mean (DigiGraph™)	SD (DigiGraph™)
Angles (degree)				
Saddle	–0.3	0.9	0.4	3.8
SNA	0.0	0.2	0.5*	1.1
SNB	0.0	0.2	0.1	0.7
ANB	0.0	0.2	0.4*	0.9
SN/MnP	–0.3*	0.6	0.0	1.2
MnP/FH	–0.2	0.5	0.0	1.0
Y-axis	0.0	0.2	0.1	0.8
F-axis	0.4**	0.8	0.1	0.8
Gonial	–0.2	0.7	–1.1*	2.3
U1/FH	0.0	0.8	0.1	7.9
U1/SN	–0.1	0.6	0.2	8.0
L1/SN	0.1	0.5	0.0	8.1
IMPA	0.0	0.5	0.0	8.1
FMIA	0.1	0.6	–0.1	8.1
Interincisal	0.2	0.7	–0.2	10.3
Distance (mm)				
L1/APg	0.0	0.2	–0.3	1.2

*$P < 0.05$; **$P < 0.01$.

and Gonial angle (mean difference –1.1 degrees, $P < 0.05$) being statistically significant. The standard deviations of the differences ranged from 0.7 to 10.3 (degrees or mm). The radiographic method was more reproducible than the DigiGraph™ Workstation for all cephalometric measurement ($P < 0.002$) except the *F*-axis which was equally reproducible with both methods.

Method error of each analysis (Tables 3 and 4)

The method errors of radiographic tracing ranged from 0.1 to 0.6 (degrees or mm) while those of the DigiGraph™ Workstation ranged from 0.5 to 7.3 (degrees or mm). The error percentages of the radiographic tracings ranged from 0.1 to 1.4 per cent, while those of the DigiGraph™ Workstation ranged from 1.6 to 69.4 per cent.

Discussion

In this study, since the radiographs were taken with steel ball markers placed at the majority of the cephalometric landmarks, the error in landmark identification being the most important source of errors in radiographic cephalometry was therefore eliminated (Björk, 1947; Miller *et al.*, 1966; Savara *et al.*, 1966; Midtgård *et al.*, 1974; Cohen, 1984; Houston *et al.*, 1986; Chan *et al.*, 1994; Tng *et al.*, 1994). Accordingly, the radiographic cephalometric measurements derived from these marked landmarks could then be considered as ‘true’ and against which the DigiGraph™ Workstation measurements could be compared. Although some measurements obtained with radiographic tracings were derived from a combination of marked and unmarked landmarks, they were shown to be of sufficiently high accuracy to serve as the ‘Gold Standard’ measurements (Figure 5 and Table 2).

The availability of two different radiographs for each skull, with two positionings of the steel ball markers and skull placement in the cephalostat, allowed a more accurate comparison between the two methods. In previous studies (Chaconas *et al.*, 1990b; Prawat *et al.*, 1995), replicated DigiGraph™ Workstation readings were compared

Table 3 The method error of the radiographic tracings. The method error was equal to the square root of half the variance of the differences (n = 30) between the initial recordings of the initial and the second skull positioning. The 'error percentage' was given by the variance of the method error (method error^2) as a percentage of the population variance.

Cephalometric measurements	Mean error	Method error^2	Population variance	Error percentage
Angles (degree)				
Saddle	0.63	0.39	28.04	1.4
SNA	0.15	0.02	12.26	0.2
SNB	0.14	0.02	14.90	0.1
ANB	0.11	0.01	6.56	0.2
SN/MnP	0.45	0.20	34.05	0.6
MnP/FH	0.34	0.11	30.36	0.4
Y-axis	0.12	0.01	17.37	0.1
F-axis	0.54	0.29	22.06	1.3
Gonial	0.46	0.22	52.37	0.4
U1/FH	0.54	0.29	112.29	0.3
U1/SN	0.44	0.19	122.08	0.2
L1/SN	0.37	0.14	51.56	0.3
IMPA	0.38	0.14	69.00	0.2
FMIA	0.43	0.18	43.10	0.4
Interincisal	0.53	0.28	181.78	0.2
Distance (mm)				
L1/APg	0.14	0.02	6.46	0.3

Table 4 The method error of the DigiGraph™ Workstation. The method error was equal to the square root of half the variance of the differences (n = 30) between the initial recordings of the initial and the second skull positioning. The 'error percentage' was given by the variance of the method error (method error^2) as a percentage of the population variance.

Cephalometric measurements	Method error	Method error^2	Population variance	Error percentage
Angles (degree)				
Saddle	2.71	7.35	10.59	69.4
SNA	0.75	0.56	9.08	6.2
SNB	0.51	0.26	11.25	2.3
ANB	0.63	0.39	7.69	5.1
SN/MnP	0.83	0.69	39.71	1.7
MnP/FH	0.74	0.55	34.05	1.6
Y-axis	0.56	0.31	11.34	2.7
F-axis	0.55	0.30	13.61	2.2
Gonial	1.63	2.66	60.51	4.4
U1/FH	5.57	30.99	137.15	22.6
U1/SN	5.63	31.72	144.04	22.0
L1/SN	5.75	33.12	65.31	50.7
IMPA	5.75	33.08	65.27	50.7
FMIA	5.70	32.44	62.87	51.6
Interincisal	7.28	53.06	172.54	30.8
Distance (mm)				
L1/APg	0.84	0.70	5.93	11.9

with replicated radiographic readings of the same radiograph for each patient. These comparisons were, in reality, biased in favour of the radiographic method. When replicated measurement values were obtained from the same radiograph, the variation from one radiograph to the next as well as from one tracing to the next were not taken into account. The DigiGraph™ Workstation measurement values, however, included both types of variation since the skull was removed from and returned to the head holder between digitizations. In this study, such bias was eliminated because readings of both methods were obtained under similar controlled conditions.

Although the linear DigiGraph™ Workstation measurements had already been adjusted to allow for the magnification experienced with the cephalometric radiographs, the exact amount of magnification was not given by the manufacturer. A valid comparison of linear measurements between the two methods was thus impossible. For this reason, angular measurements were mainly selected for comparison as they were not affected by geometric enlargement.

Validity of cephalometric measurements

Prawat *et al*. (1995) showed, in a similar study, that 19 out of 22 angular measurements (86 per cent) had significant differences between the radiographic and the DigiGraph™ Workstation methods. Doll *et al*. (1996) found that the DigiGraph™ Workstation had difficulties in locating the indirectly determined landmark, sella. This study also demonstrated comparable findings with significant differences being present in 14 out of 15 angular measurements (93 per cent). In contrast, Chaconas *et al*. (1990b) found no significant differences between the radiographic and the DigiGraph™ Workstation measurements. For the linear measurement, L1/APg, the DigiGraph™ Workstation consistently overestimated this by an average of 2.0 mm, which may be due to the higher magnification factor used.

To compare the measurement values given by two methods, hypothesis testing, e.g. paired *t*-test or ANOVA, is commonly used to test for the presence, or not, of a statistically significant difference. The results of such statistical procedures, however, do not reveal the whole truth of comparison and misleading conclusion may sometimes be drawn (Altman, 1991). When the mean difference is statistically different from zero, there is, on average, an over- or underestimation of measurement value given by one method, relative to the other, for the whole studied samples. By adjusting the biased measurement values of one method with that amount of mean difference, the measurement value of the other method is easily obtained. Furthermore, if the mean difference is not clinically significant, it can be said that the two methods are, on average, in good agreement. However, to determine how a measurement value of an individual given by one method is similar to that given by the other method, knowing the mean difference is not sufficient and the standard deviation of the differences becomes important. In method comparison studies, the 95 per cent limit of agreement is important to show how any single determination of measurement value obtained with one method is different from that with the other method (Bland and Altman, 1986; Altman, 1991). This is given by the mean difference ± 2 SD to include about 95 per cent of the differences between measurement values of both methods. For clinical interpretation, the narrower the 95 per cent limits of agreement, or the range of differences, the more likely the measurement values of the two methods agree with each other.

From Table 1, it can be seen that for all cephalometric measurements, except angle ANB, the 95 per cent limits of agreement were generally too wide to be clinically acceptable. Here, the standard deviation of the differences had a more significant effect than the mean difference in determining the 95 per cent limits of agreement. In fact, measurements involving the indirectly determined landmarks, i.e. sella, pterygoid point, and upper and lower incisor apices, were found to have higher standard deviations of the differences. The angle ANB, being the only angular measurement derived exclusively from directly determined landmarks, had the lowest mean difference and standard deviations. Therefore, even though the mean difference was statistically significant, the angle ANB had the best 95 per cent limits of agreement. The clinical significance from this analysis is that difficulty will be encountered in interpreting the DigiGraph™ Workstation measurements of an individual patient. It is difficult to establish whether a patient has, for instance, a normal SNA if the DigiGraph™ Workstation measures 82 degrees, when the 'true' value may lie somewhere between 76.5 and 86.5 degrees for 95 per cent of the times. If IMPA is used to assess the change of lower incisor angulation during orthodontic treatment, the range of difference of 15.6 degrees will probably obscure the treatment effect. The performance of the DigiGraph™ Workstation in estimating the indirectly determined landmarks was therefore unsatisfactory.

Reproducibility of cephalometric measurements

In general, both methods were reproducible on repeated recordings without any systematic errors, for all except a few cephalometric measurements. For the radiographic method, SN/MnP and *F*-axis were the two measurements with statistically significant mean differences. However, since the standard deviations of the differences for these two measurements were small, the mean differences were considered not clinically significant. For the DigiGraph™ Workstation, SNA, SNB, and the gonial angle were the three measurements with statistically significant mean differences. Again, since the standard deviations of the differences for SNA and ANB were small, the mean differences were considered not clinically significant. When the reproducibility of the two methods was compared, the radiographic method was far better than the DigiGraph™ Workstation, especially for the incisor-related measurements. This finding was similar to those of Prawat *et al*. (1995) and Doll *et al*. (1996), but contrary to that of Chaconas *et al*. (1990b). On the other hand, Nanda *et al.* (1996), in a study to assess the error in digitizing various soft tissue landmarks with the DigiGraph™ Workstation, found that only two out of 36 angular and linear measurements had statistically significant errors. However, the standard deviations of the differences between repeated measurement values were generally large.

With the radiographic method, errors can be introduced at all stages, starting from positioning the skull subject in the cephalostat. On the other hand, for the DigiGraph™ Workstation, errors can only occur at the positioning of each skull subject and the sonic digitization of the facial and intra-oral landmarks. Despite the fewer stages at which errors can occur, it is rather unexpected that the reproducibility of the new method is still poorer than the conventional radiographic method. One of the reasons may be that the errors in locating and digitizing the landmarks with the DigiGraph™ Workstation are three-dimensional, whereas they are two-dimensional with the radiographic method. During sonic digitization, if the landmark to be digitized is on a broad area with gentle curvature, for example, point B, the digitizing probe tip can be placed more steadily over the same landmark with greater reproducibility. However, if the landmark is situated in a small area, with marked curvature and with a highly polished surface, for example, the incisal edges, the placement of the digitizing probe tip over the same landmark will become more difficult and less reproducible. On the other hand, since several other digitized points of the incisors are required for the estimation of incisor apices by the DigiGraph™ Workstation, the accuracy of computerized estimation is consequently greatly affected by the compounded error in digitizing these points. This might be the reason why the DigiGraph™ Workstation is less reproducible for incisor-related measurements. Also, it was found that some constructed landmarks commonly used on two-dimensional radiographic images were quite difficult to locate with the DigiGraph™ Workstation. For example, articulare is really the intersection of edges of regression and is no way part of the solid skull (Moyers, 1988). On radiographs, the images of the projected lines are often clearly visible and the determination of this point should be highly reproducible. For the DigiGraph™ Workstation, it becomes extremely difficult to determine, three-dimensionally, the point of intersection of anatomical structures at different sagittal planes. For this reason, the reproducibility of the saddle and the gonial angles was poorer with the DigiGraph™ Workstation.

Method errors

The method errors for all the radiographic cephalometric measurements were small, being less than 1 degree or mm using the steel ball markers. The 'error percentages' were thus less than 2 per cent, indicating the sufficient accuracy and warrant being the 'Gold Standard' measurements (Midtgård *et al.*, 1974; Houston, 1983).

On the contrary, the method errors for the DigiGraph™ Workstation measurements were highly variable. Only seven measurements had method errors less than 1 degree. The 'error percentages' for the saddle angle and the incisor-related measurements were all higher than 10 per cent. If 10 per cent was chosen to be the maximum limit for error variance (Midtgård *et al.*, 1974; Houston, 1983), extreme care would have to be taken in interpreting these measurements. This is particularly important when the treatment effect is evaluated by changes between the pre- and post-treatment measurements. It has been recommended that the difference observed should be at least twice the standard deviation of the estimating error (Baumrind and Frantz, 1971a,b; Gravely and Benzies, 1974). If one was to assess any change in IMPA after orthodontic tooth movement, the observed difference should exceed at least 11.6 degrees (at 95 per cent confidence interval) in order for the deviation to be representative, otherwise, any deviation may be due to the method error itself. Due to the lack of reliability for 50 per cent of the DigiGraph™ Workstation measurements, the applicability of this new method in the diagnosis, planning and monitoring of orthodontic treatment seems doubtful.

Clinical significance

Before a new diagnostic method is widely accepted by clinicians and promoted to the profession, studies have to be carried out to investigate the validity, accuracy, safety, and cost effectiveness of the new method. The obvious advantage of the new method is the elimination of radiation exposure for diagnostic information similar to that obtained from cephalometric radiographs. From the results of this study, it seems that the performance of the DigiGraph™ Workstation in obtaining cephalometric measurements was far from satisfactory, even under optimal experimental conditions. The poor agreement between the two methods limits the applicability of the DigiGraph™ Workstation. Additionally, the reproducibility of the DigiGraph™ Workstation was not as good as the radiographic method. In other words, one has to repeat the sonic digitization several times and obtain the average values in order to obtain the same amount of accuracy as the radiographic measurements. This will inevitably increase the amount of clinical time spent with each patient although ancillaries can be trained to perform these procedures. However, it may be difficult for a child patient to remain calm and motionless while repeating sonic digitizations (Prawat *et al.*, 1995). Also, the large method errors in 50 per cent of the DigiGraph™ Workstation measurements make the clinical interpretation of cephalometric measurements difficult. If different operators perform sonic digitization on the same patient, the situation would be further complicated by inter-operator error. In this instance, periodic intra- and inter-examiner calibrations are definitely required for the DigiGraph™ Workstation so as to ensure comparable readings.

Conclusions

Significant differences between the two methods were found for all except one cephalometric measurement. The standard deviations of the differences between measurement values for both methods were large. The 95 per cent limits of agreement between the two methods were, in general, poor. The reproducibility of radiographic measurement, especially the incisor-related measurements, was significantly better than that of the DigiGraph™ Workstation. It is therefore recommended that measurements obtained with the DigiGraph™ Workstation be interpreted with caution.

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References

Adams J W 1940 Correction of error in cephalometric roentgenograms. Angle Orthodontist 10: 3–13

Altman D G 1991 Practical statistics for medical research. Chapman & Hall, London

Atchison K A 1986 Radiographic examinations of orthodontic educators and practitioners. Journal of Dental Education 50: 651–655

Atchison K A, Luke L S, White S C 1991 Contribution of pretreatment radiographs to orthodontists' decision making. Oral Surgery, Oral Medicine, Oral Pathology 71: 238–245

Bankvall G, Hakansson H A R 1982 Radiation-absorbed doses and energy imparted from panoramic tomography, cephalometric radiography, and occlusal film radiography in children. Oral Surgery, Oral Medicine, Oral Pathology 53: 532–540

Baumrind S, Frantz R C 1971a The reliability of head film measurements 1. Landmark identification. American Journal of Orthodontics 60: 111–127

Baumrind S, Frantz R C 1971b The reliability of head film measurements 2. Conventional angular and linear measures. American Journal of Orthodontics 60: 505–517

Baumrind S, Miller D, Molthen R 1976 The reliability of head film measurements 3. Tracing superimposition. American Journal of Orthodontics 70: 617–644

Björk A 1947 The face in profile: an anthropological X-ray investigation on Swedish children and conscripts. Svensk Tandläkare Tidskrift 40 (Supplement no. 5B): 1–180

Bland J M, Altman D G 1986 Statistical methods for assessing agreement between two methods of clinical measurement. Lancet i: 307–310

British Society for the Study of Orthodontics and the British Society of Dental and Maxillofacial Radiology 1985 Report of a Joint Working Party. The reduction of the dose to patients during lateral cephalometric radiography. British Journal of Orthodontics 12: 176–178

Broadbent B H 1931 A new X-ray technique and its application to orthodontics. Angle Orthodontist 1: 45–66. Reprinted 1981 Angle Orthodontist 51: 93–114

Brodie A G 1941 On the growth pattern of the human head from the third month to the eighth year of life. American Journal of Anatomy 68: 209–262

Chaconas S J, Engel G A, Gianelly A A, Gorman J C 1990a The DigiGraph™ Work Station Part 1: Basic concepts. Journal of Clinical Orthodontics 24: 360–367

Chaconas S J, Jacobson R L, Lemchen M S 1990b The DigiGraph™ Work Station. Part 3: Accuracy of cephalometric analyses. Journal of Clinical Orthodontics 24: 467–471

Chan C K, Tng T H, Hägg U, Cooke M S 1994 Effects of cephalometric landmark validity on incisor angulation. American Journal of Orthodontics and Dentofacial Orthopedics 106: 487–495

Cohen A M 1984 Uncertainty in cephalometrics. British Journal of Orthodontics 11: 44–48

Cooke M S, Wei S H Y 1991 Cephalometric error: A comparison between repeat measurements and retaken radiographs. Australian Dental Journal 36: 38–43

Doll G M, Zentner A, Hohensee A, Gärtner H, Sergl H G 1996 Sonic digitizing versus radiographic cephalometry—a clinical comparison. European Journal of Orthodontics 18: 410 (Abstract)

Downs W B 1948 Variation in facial relationships: their significance in treatment and prognosis. American Journal of Orthodontics 34: 812–840

Eliasson S, Julin P, Richter S, Stenström B 1984 Radiation absorbed doses in cephalography. Swedish Dental Journal 8: 21–27

Franklin J B 1952 Certain factors of aberration to be considered in clinical roentgenographic cephalometry. American Journal of Orthodontics 38: 351–368

Gravely J F, Benzies P M 1974 The clinical significance of tracing error in cephalometry. British Journal of Orthodontics 1: 95–101

Hallett G E M 1959 Inherent errors in cephalometric films and their reduction. Transactions of the British Society for the Study of Orthodontics pp. 1–10

Halse A, Hedin M 1978 May fast film-screen combinations be used for cephalometry? British Journal of Orthodontics 5: 189–192

Hofrath H 1931 Die bedeutung der röntgenfern und abstandsaufnahme für die diagnostik der kieferanomalien. Fortschritte der Orthodontik 1: 232–258

Houston W J B 1983 The analysis of errors in orthodontic measurements. American Journal of Orthodontics 83: 382–390

Houston W J B, Maher R E, McElroy D, Sheriff M 1986 Sources of error in measurements from cephalometric radiographs. European Journal of Orthodontics 8: 149–151

Jones G A 1987 Considerations for the apprehensive X-ray patient. General Dentistry 35: 102–103

L'Abée E M, Tan H T 1982 Improved radiation hygiene in lateral cephalometry and a method to obtain good reproduction of the soft tissue profile. Journal of Clinical Orthodontics 16: 381–386

McNicol A, Stirrups D R 1985 Radiation dose during the dental radiographic techniques most frequently used during orthodontic treatment. European Journal of Orthodontics 7: 163–171

Midtgård J, Björk G, Linder-Aronson S 1974 Reproducibility of cephalometric landmarks and errors of measurements of cephalometric cranial distances. Angle Orthodontist 44: 56–61

Miller P A, Savara B S, Singh I J 1966 Analysis of errors in cephalometric measurements of three-dimensional distances on the maxilla. Angle Orthodontist 36: 169–174

Moyers R E 1988 Handbook of orthodontics (4th edn). Year Book Medical Publishers Inc., Chicago

Nanda R S, Ghosh J, Bazakidou E 1996 Three-dimensional facial analysis using a video imaging system. Angle Orthodontist 66: 181–188

Prawat J S, Nieberg L, Cisneros G J, Acs G 1995 A comparison between radiographic and sonically produced cephalometric values. Angle Orthodontist 65: 271–276

Preston-Martin S, White S C 1990 Brain and salivary gland tumors related to prior dental radiography: implications for current practice. Journal of the American Dental Association 120: 151–158

Ricketts R M 1981 Perspectives in the clinical application of cephalometrics. Angle Orthodontist 51: 115–150

Savara B S, Tracy W E, Miller P A 1966 Analysis of errors in cephalometric measurements of three-dimensional distances on the human mandible. Archives of Oral Biology 11: 209–217

Sikorski P A, Taylor K W 1984 The effectiveness of the thyroid shield in dental radiology. Oral Surgery, Oral Medicine, Oral Pathology 58: 225–236

Taylor T S, Ackerman R J, Hardman P K 1988 Exposure reduction and image quality in orthodontic radiology: a review of the literature. American Journal of Orthodontics and Dentofacial Orthopedics 93: 68–77

Tng T T H, Chan T C K, Hägg U, Cooke M S 1994 Validity of cephalometric landmarks. An experimental study on human skulls. European Journal of Orthodontics 16: 110–120

Thurow R C 1951 Cephalometric methods in research and private practice. Angle Orthodontist 21: 104–116

Tyndall D A, Turner S P 1990 Radiographic materials, methods, film ordering patterns among orthodontic educators and private practitioners. American Journal of Orthodontics and Dentofacial Orthopedics 97: 159–167

Tyndall D A, Washburn D B 1986 Rare-earth filters in panoramic radiography: a means of reducing patient dose without compromising image quality. Dentomaxillofacial Radiology 15: 19–25

Tyndall D A, Matteson R E, Soltmonn R E, Hamilton T L, Proffit W R 1988 Exposure reduction in cephalometric radiology: a comprehensive approach. American Journal of Orthodontics and Dentofacial Orthopedics 93: 400–412

Valachovic R W, Lurie A G 1980 Risk benefit considerations in pedodontic radiology. Pediatric Dentistry 2: 128–146

Whitcher B L, Gratt B M, Sickles E A 1979 Leaded shields for thyroid dose reduction in intraoral dental radiography. Oral Surgery, Oral Medicine, Oral Pathology 48: 567–570

Whitcher B L, Gratt B M, Sickles E A 1980 A lead apron for use in panoramic dental radiography. Oral Surgery, Oral Medicine, Oral Pathology 49: 467–470

White S C 1992 Assessment of radiation risk from dental radiography. Dentomaxillofacial Radiology 21: 118–126

Wootton R 1993 Radiation protection of patients. Cambridge University Press, Cambridge