European Journal of Orthodontics 25 (2003) 77–85

Development of a non-radiographic cephalometric system

Satoshi Nagasaka, Takeshi Fujimura and Kensuke Segoshi
Department of Orthodontics, Tsurumi University School of Dental Medicine, Yokohama City, Kanagawa Prefecture, Japan

SUMMARY The purpose of the present study was to develop a three-dimensional (3D) non-radiographic cephalometric system based on Simon's three planes. In pursuit of cephalometry without irradiation of patients, readiness of data and simplicity of the system, a portable 3D computer-aided, contact-method cephalometric system, equipped with newly developed cephalometric software for chairside use, was developed. The feasibility of its clinical use was examined based on comparison of the measurements obtained with those from conventional radiographic cephalometry on a human dry skull, as well as on three living subjects.

From a total of nine measurements, a statistically significant difference was seen in six measurements: FMPA, U1/FH, FMIA, ANB, IMPA, and A-Np for the dry skull; in four measurements: FPA, FMPA, U1/FH, and Pog-Np for subject A; in five measurements: FMPA, U1/FH, FMIA, AN/FH, and A-Np for subject B; and in seven measurements: FMA, FMPA, U1/FH, FMIA, ANB, IMPA, and AN/FH for subject C. A clinically significant difference was found only in one measurement, U1/FH for the dry skull, in four measurements FPA, FMPA, U1/FH, and Pog-Np for subject A, in one measurement AN/FH for subject B, and in three measurements U1/FH, FMIA, and AN/FH for subject C.

While demonstrating workability as a chairside tool and whilst there is a need for further refinement in measurement accuracy, this newly developed cephalometric system shows potential applicability, not only in the clinic as an auxiliary to or as a substitute for existing radiographic cephalometry, but also outside the clinic as an epidemiological tool.

Introduction

Cephalometry has been heavily reliant on radiography since Broadbent (1931) and Hofrath (1931) first introduced cephalometric radiography into orthodontics. Cephalometric radiographs taken under standardized conditions have provided valuable clinical and research information about craniofacial morphology (Brodie, 1941; Downs, 1948; Ricketts, 1981). Cephalometric radiography, however, is not without its drawbacks, such as radiation exposure, bulkiness of the equipment, geometric distortion, fuzzy image, and a need for tracing and measuring, etc. Despite the efforts made to reduce radiation exposure, such as 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 (L'Abee and Tan, 1982; British Society for the Study of Orthodontics and 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), radiation exposure still remains an intrinsic problem of cephalometric radiography.

There has been an attempt to bring a non-radiographic alternative to conventional cephalometric radiography using the DigiGraph™ Workstation (Alexander *et al*., 1990; Chaconas *et al*., 1990). This system utilizes direct sonic digitization of patients to obtain various cephalometric measurements. Sonic signals are emitted from the digitizing probe placed on each facial or intraoral cephalometric landmark and picked up by the system's overhead microphones. The DigiGraph™ is, however, neither compact nor portable and it has been suggested that its measurements be interpreted with caution (Tsang and Cooke, 1999).

Simon (1922) first introduced his three-plane theory for the diagnosis of dental anomalies. His idea has been an important conceptual tool for orthodontists in objective evaluation of cranio-dento-facial morphology in orthodontic diagnosis. The purpose of the present study was to develop a three-dimensional (3D) non-radiographic cephalometric system based on Simon's three planes. A 3D direct cephalometric system, which has the advantage of no radiation exposure and is compact enough to be portable, simple to use at the chairside and quick to provide measurement results, is presented. Examined both on a dry skull and three living subjects, the new system appears promising with respect to data reliability and clinical feasibility.

Materials and methods

Components of the system

The system comprises the following major constituents (Figure 1).

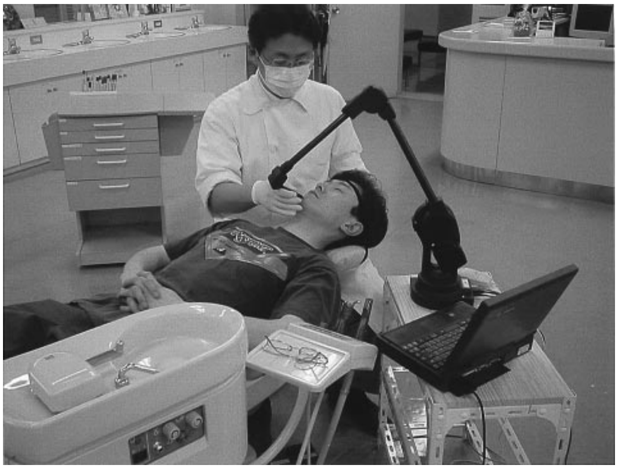

Figure 1 Set-up for digitizing in the clinic.

1. 3D digitizer (MicroScribe-3DXL®, Immersion Corp., San Jose, CA, USA)
2. Original software program
3. Notebook-type personal computer (Sharp Corp., Osaka, Japan) with an operating system Microsoft Windows® 95 (Microsoft Corp., Redmond, WA, USA)

The outline of the digitizer Microscribe-3DXL®

The MicroScribe-3DXL® is a 3D digitizer of mechanical linkages ending in a stylus that allows the user to specify x, y, and z positions and roll, pitch, and yaw orientations. The digitizer consists of a free-standing, self-contained digitizing arm with high-resolution optical encoders and an embedded microprocessor and electronics to communicate with a host computer via a standard RS-232 serial port. The position and orientation of the stylus is uniquely determined by the configuration of the five-linkage arm. The on-board microprocessor determines this configuration by reading the optical encoders and reports this information to the host computer. The device also takes input from optional pedals and buttons that can be plugged into its back panel. When in the home position, the digitizer measures approximately 600 mm in height, 200 mm in width, and 400 mm in depth.

Measurement method: Contact method
Spherical workspace: 825 mm
Accuracy: 0.30 mm … manufacturer's quotation

0.23 mm … this is a result of the performance test (Fujimura *et al.*, 2001) based on Japanese Industrial Standard, JIS B 7440-2: 1997 and the International Organization for Standardization, ISO 10360-2: 1994. A maximum linear measurement error of 0.23 mm was adopted as acceptable.

Software program

The established three cranial reference planes were the Frankfort Horizontal (FH), the orbital and the mid-sagittal planes (Figure 2).

An original software program was developed so that the digitized 3D co-ordinates of each cranio-dento-facial landmark could be converted to those located in an intra-cranial Cartesian co-ordinate system containing the following three planes: the FH, the orbital, and the mid-sagittal planes, which are constructed to be vertically orientated to one another. The program also allows projection of each landmark onto each of the three planes and calculation of angular and linear measurements corresponding to those obtained by the conventional methods on cephalograms. The FH plane was constructed by connecting the orbitales and the midpoint of the two porions and the orbital plane as a plane connecting both orbitales at right angles to the FH plane. The mid-sagittal plane was made to be a plane containing the midpoint between the left and right orbitales and vertically orientated to both the FH and orbital planes. The present system is a modification of Simon's three-plane system where the raphe points were employed to determine the median plane.

Intra-cranial Cartesian co-ordinates: the origin, x-*,* y-*, and* z-*axes* (Figure 3). The origin was established at the point of intersection of a line connecting the left and right orbitales and a vertical line connecting nasion to that point. The y-axis was a line connecting the left and right orbitales. The z-axis was established by drawing two lines: line 1, connecting the midpoint of left and right porions and left orbitale, and line 2, connecting

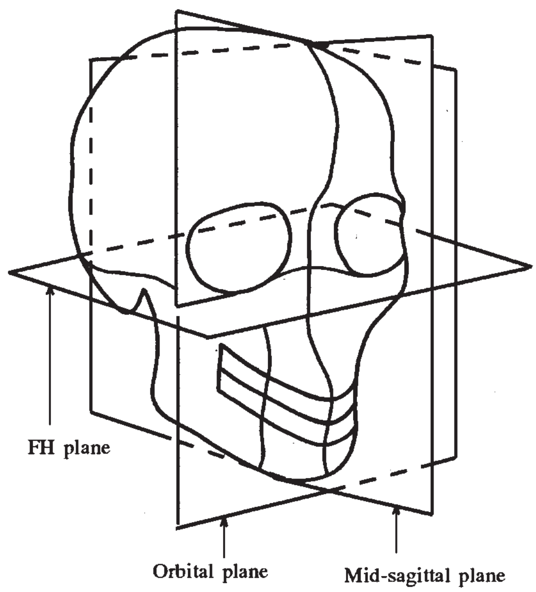

Figure 2 The three cranial reference planes based on Simon's three-plane theory: FH, orbital, and mid-sagittal planes.

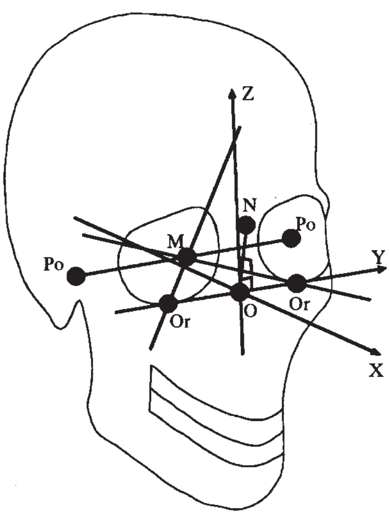

Figure 3 The intra-cranial Cartesian co-ordinates: the origin, x-, y, and z-axes. The origin (O) was established at the point of the intersection of the line connecting the left and right orbitales (Or) and the vertical line connecting nasion (N) to that point. The y-axis is the line connecting the left and right orbitales (Or). The z-axis was established by drawing two lines: line 1, connecting the midpoint (M) of the left and right porion (Po) and the left orbitale (Or); line 2, connecting the midpoint (M) of the left and right porion (Po) and the right orbitale (Or). A line that was vertically orientated to lines 1 and 2 was the z-axis which passed through the origin (O). The x-axis was vertically orientated to both the y- and x-axes.

the midpoint of left and right porions and right orbitale. A line that was vertically orientated to lines 1 and 2 was designated the z-axis, which passed through the origin. The x-axis was vertically orientated to both the y- and x-axes.

Projection method. The idea and the method of projecting a spatial point onto a two-dimensional (2D) plane can be explained by the theory that to project 3D co-ordinates of a spatial landmark point onto a predetermined 2D reference plane is to locate a point of intersection of this 2D plane with a vertical line extending from the landmark to this plane.

1. Construct three 2D planes: (1) a horizontal FH plane, (2) a frontal orbital plane, and (3) a mid-sagittal plane.
2. Determine the vertical line extending from the spatial landmark point to the respective planes.
3. Determine the point of intersection of the line and each plane.

Mathematics. The 3D co-ordinates of a spatial landmark point 'M' can be given as follows:

$$\mathrm{M}\ (\mathrm{M}x, \mathrm{M}y, \mathrm{M}z)$$

Any of the three 2D planes can be given as follows:

$$\mathrm{A}x + \mathrm{B}y + \mathrm{C}z + \mathrm{D} = 0$$
(A, B, C, and D are constants.)

The three vertical lines can be given as follows:

$$X = \mathrm{M}x + \mathrm{A}t,\ Y = \mathrm{M}y + \mathrm{B}t,\ Z = \mathrm{M}z + \mathrm{C}t$$

The parameter 't' is:

$$t = -(\mathrm{AM}x + \mathrm{BM}y + \mathrm{CM}z)/(\mathrm{A}^*\mathrm{A} + \mathrm{B}^*\mathrm{B} + \mathrm{C}^*\mathrm{C})$$

Therefore, the 3D co-ordinates of a point of intersection are given by:

$$X = \mathrm{M}x + \mathrm{A}t = \mathrm{M}x + \mathrm{A}^* - (\mathrm{AM}x + \mathrm{BM}y + \mathrm{CM}z)/(\mathrm{A}^*\mathrm{A} + \mathrm{B}^*\mathrm{B} + \mathrm{C}^*\mathrm{C})$$

$$Y = \mathrm{M}y + \mathrm{B}t = \mathrm{M}y + \mathrm{B}^* - (\mathrm{AM}x + \mathrm{BM}y + \mathrm{CM}z)/(\mathrm{A}^*\mathrm{A} + \mathrm{B}^*\mathrm{B} + \mathrm{C}^*\mathrm{C})$$

$$Z = \mathrm{M}z + \mathrm{C}t = \mathrm{M}z + \mathrm{C}^* - (\mathrm{AM}x + \mathrm{BM}y + \mathrm{CM}z)/(\mathrm{A}^*\mathrm{A} + \mathrm{B}^*\mathrm{B} + \mathrm{C}^*\mathrm{C})$$

Employing the above geometric theory, the software was programmed so that the 3D co-ordinates of 59 different landmarks could be processed and projected onto the three different planes. This generated a total of 62 linear and angular measurements which could be compared with those obtained from conventional cephalograms in addition to 31 facial linear measurements and their ratios on the orbital plane.

Notebook-type computer. The software can be operated on any DOS/V computer with the following specification:

CPU: More than 486DX2(100 MHz)
RAM: More than 32 MB
HDD: More than 10 MB
OS: MS-Windows 95/98/NT

Landmarks and measurements. While five landmarks, left porion, right porion, left orbitale, right orbitale, and nasion, are indispensable points to be digitized that are used to determine three 2D reference planes with this program, other landmarks may be selectively digitized depending on the measurements required. For the present examination, nine measurement items (Table 1) were chosen from lateral cephalometric analyses (Miyashita, 1986; Athanasiou, 1995) as they are not only of clinical use but are also suitable for data comparison between the digitizer system and conventional cephalometry. They include both angular and linear measurements. For acquisition of these nine measurements, 19 landmarks (Table 2) including the above five indispensable ones were digitized.

Examination of measurement validity

In order to examine the validity of the data obtained through the investigated system, a human adult dry skull and three male adults whose average age was 36 years

Table 1 The nine measurements obtained on the mid-sagittal plane.

1. Facial Plane Angle (FPA)
2. Frankfort Mandibular Plane Angle (FMPA)
3. U1- FH (mean of 3 and 4)
4. Frankfort Mandibular Incisor Angle (FMIA)
5. ANB
6. IMPA
7. AN/FH
8. Distance between Point A and McNamara (Np) Line
9. Distance between Pogonion (Pog) and Np

Table 2 Nineteen landmarks digitized for acquisition of nine measurements.

1. Left Porion
2. Right Porion
3. Left Orbitale
4. Right Orbitale
5. Nasion
6. Pogonion
7. Menton
8. Left T2 (the most posterior inferior point on the body of mandible)
9. Right T2 (the most posterior inferior point on the body of mandible)
10. Left U1 Edge Point
11. Left U1 Cervical Point
12. Right U1 Edge Point
13. Right U1 Cervical Point
14. Left L1 Edge Point
15. Left L1 Cervical Point
16. Right L1 Edge Point
17. Right L1 Cervical Point
18. Point A
19. Point B

were digitized and their nine measurements were compared with the corresponding results obtained from the conventional lateral cephalogram (Tables 3–6). All subjects consented to take part in the study after being fully informed about radiation and its possible effect. The study was also approved by the Tsurumi University Ethical Committee.

Digitization of a human dry skull

A human dry skull on which the 19 landmarks were marked with pieces of round, sticky lead foil approximately 2 mm in diameter was stabilized by being placed on its hardened plaster impression on a table. It was then fixed with a rubber band surrounding the head with the mouth being closed at maximum intercuspation during digitization. Three examiners who had previously practised the digitization procedure placed the stylus of the digitizer on the centre of each lead mark and digitized the 19 landmarks on the dry skull. This was repeated six times.

Digitization of the subjects

Each of the three adult subjects was requested to lie on his back on a horizontally reclined dental chair. Their head was fastened to the headrest, using a band around the head, for fixation during digitization. The system was set up at the chairside close to the headrest so that the stylus of the digitizer handled by the examiner could easily reach any landmark on the subject's head. The subjects were requested to remain still with their mouth closed in maximum intercuspation during digitization.

Table 3 Comparison between the cephalogram and digitizer measurements obtained by the same three examiners on a human dry skull.

		n	Mean	Difference	SD	*P* value
FPA (°)	Cephalogram	18	88.06		0.59	
	Digitizer	18	87.90	0.15	0.26	0.33
FMPA (°)	Cephalogram	18	20.48		0.60	
	Digitizer	18	19.86	0.62	0.14	0.00*
U1/FH (°)	Cephalogram	18	96.95		2.01	
	Digitizer	18	85.32	11.63	2.15	0.00*
FMIA (°)	Cephalogram	18	53.40		2.03	
	Digitizer	18	55.04	–1.64	0.99	0.00*
ANB (°)	Cephalogram	18	7.87		0.25	
	Digitizer	18	7.69	0.18	0.15	0.01*
IMPA (°)	Cephalogram	18	106.16		1.64	
	Digitizer	18	105.10	1.06	1.04	0.03*
AN/FH (°)	Cephalogram	18	94.58		0.72	
	Digitizer	18	94.47	0.11	0.19	0.52
A–Np (mm)	Cephalogram	18	4.55		0.56	
	Digitizer	18	4.01	0.54	0.16	0.00*
Pog–Np (mm)	Cephalogram	18	–3.86		0.93	
	Digitizer	18	–3.62	–0.24	0.32	0.32

*Significant values ($P < 0.05$).

Table 4 Comparison between the cephalogram and digitizer measurements obtained by the same three examiners on living subject A.

		n	Mean	Difference	SD	*P* value
FPA (°)	Cephalogram	18	86.42		0.49	
	Digitizer	18	88.34	–1.92	1.14	0.00*
FMPA (°)	Cephalogram	18	27.07		0.70	
	Digitizer	18	24.90	2.16	2.27	0.00*
U1/FH (°)	Cephalogram	18	94.56		3.30	
	Digitizer	18	86.98	7.58	1.62	0.00*
FMIA (°)	Cephalogram	18	78.51		3.65	
	Digitizer	18	79.84	–1.33	2.25	0.20
ANB (°)	Cephalogram	18	0.22		1.07	
	Digitizer	18	0.25	–0.04	0.66	0.90
IMPA (°)	Cephalogram	18	74.64		3.63	
	Digitizer	18	75.26	–0.61	2.74	0.57
AN/FH (°)	Cephalogram	18	85.97		1.32	
	Digitizer	18	85.49	0.48	1.47	0.31
A–Np (mm)	Cephalogram	18	–4.42		1.76	
	Digitizer	18	–4.36	–0.06	1.53	0.91
Pog–Np (mm)	Cephalogram	18	–7.77		1.17	
	Digitizer	18	–3.27	–4.50	2.25	0.00*

*Significant values ($P < 0.05$).

Table 5 Comparison between the cephalogram and digitizer measurements obtained by the same three examiners on living subject B.

		n	Mean	Difference	SD	*P* value
FPA (°)	Cephalogram	18	78.97		1.08	
	Digitizer	18	78.56	0.41	0.96	0.24
FMPA (°)	Cephalogram	18	33.79		1.33	
	Digitizer	18	31.85	1.94	2.28	0.00*
U1/FH (°)	Cephalogram	18	91.64		1.72	
	Digitizer	18	88.88	2.76	1.22	0.00*
FMIA (°)	Cephalogram	18	60.28		1.98	
	Digitizer	18	62.50	–2.21	1.64	0.00*
ANB (°)	Cephalogram	18	4.37		0.48	
	Digitizer	18	4.68	–0.32	1.08	0.27
IMPA (°)	Cephalogram	18	86.11		2.40	
	Digitizer	18	85.66	0.45	3.52	0.66
AN/FH (°)	Cephalogram	18	83.86		1.38	
	Digitizer	18	81.76	2.10	0.92	0.00*
A–Np (mm)	Cephalogram	18	–6.40		1.57	
	Digitizer	18	–7.35	0.95	0.65	0.03*
Pog–Np (mm)	Cephalogram	18	–20.03		10.21	
	Digitizer	18	–19.40	–0.64	1.25	0.80

*Significant values ($P < 0.05$).

Each digitization of the 19 landmarks took a few minutes, giving rise to nine angular and linear measurements that could be displayed on the monitor. The same subjects were digitized six times by each of the three different orthodontists. It should be remembered that even when digitization targets are bony landmarks, the stylus has to be placed on the overlying soft tissue in order to determine the hard tissue landmarks. For soft tissue landmarks the stylus needs to be kept in contact with the soft tissues, exerting as little pressure as possible.

X-ray cephalometry of a dry skull

Six lateral cephalograms were taken at different times on a human dry skull with 19 landmarks marked with a tiny lead marker for radio-opacity. The measurements of the six lateral cephalograms were made by manual tracing with a pencil and were measured with a pair of callipers, a ruler, and a protractor. Nine angular and linear measurements were obtained. This was conducted once for each of the six cephalograms by each of the three different orthodontists.

Table 6 Comparison between the cephalogram and digitizer measurements obtained by the same three examiners on living subject C.

		n	Mean	Difference	SD	*P* value
FPA (°)	Cephalogram	18	84.97		0.91	
	Digitizer	18	86.51	–1.54	0.88	0.00*
FMPA (°)	Cephalogram	18	32.91		0.85	
	Digitizer	18	31.09	1.82	1.94	0.00*
U1/FH (°)	Cephalogram	18	87.87		1.20	
	Digitizer	18	93.79	–5.92	1.07	0.00*
FMIA (°)	Cephalogram	18	74.71		2.67	
	Digitizer	18	79.37	–4.66	2.07	0.00*
ANB (°)	Cephalogram	18	2.20		0.38	
	Digitizer	18	1.73	0.47	0.29	0.00*
IMPA (°)	Cephalogram	18	72.51		2.64	
	Digitizer	18	69.55	2.96	1.46	0.00*
AN/FH (°)	Cephalogram	18	87.78		4.88	
	Digitizer	18	83.64	4.14	1.40	0.00*
A–Np (mm)	Cephalogram	18	–5.38		1.00	
	Digitizer	18	–6.12	0.74	1.33	0.07
Pog–Np (mm)	Cephalogram	18	–6.27		7.44	
	Digitizer	18	–6.60	0.33	1.49	0.86

*Significant values ($P < 0.05$).

X-ray cephalometry of the subjects

One lateral cephalogram was taken for each of the three subjects in order to obtain nine angular and linear measurements. The conventional manual tracing and measuring was carried out six times for each cephalogram by each of the three different orthodontists.

Comparison of data between radiography and digitization

Since the cephalogram measurements were considered to be the only reliable and presently available standard for comparison, they were regarded as the control data. In both the dry skull and the three subjects, cephalometric measurements were collected from each of the three examiners for each cephalometric measurement to form a control group of 18 time measurements, against which the corresponding digitizer results were compared. For statistical comparisons, a *t*-test was conducted using the SPSS (Statistical Package for the Social Sciences by SPSS, Inc. Chicago, IL, USA) software. A value of $P < 0.05$ was considered to be significant. Any clinical significance in the mean difference between the two types of data was also examined by comparing the mean difference of each measurement with that from standard norms such as the Downs–North Western (Downs, 1952; Graber, 1952), Ricketts (Rickets *et al.*, 1971), and McNamara (McNamara, 1984) analyses. If the mean difference between the cephalogram and the digitizer for each measurement in the present study was smaller than the equivalent of half the value of the norm SD (Table 7), it was considered that there was no clinically significant difference between the two types of data. As this was a pilot study with a small sample intended mainly to introduce the concept of a newly developed system, statistically averaging the results for the living subjects was not undertaken for the next phase of the investigation since it would be more meaningful with a larger sample.

Results

The results for the dry skull are shown in Table 3 and those for the subjects in Tables 4–6. Although both for the dry skull and the subjects, a statistically significant difference was seen in the majority of the measurements obtained through the working system, there seemed to be no clinically significant difference, except in one measurement for the dry skull and a few for the subjects. From the total of nine measurements, a statistically significant difference was seen in six measurements:

Table 7 Norm values of nine measurement items available at Tsurumi University School of Dental Medicine (Nagaoka and Kuwahara, 1993).

	Mean	SD	1/2 SD
FPA (°)	87.3	3.1	1.6
FMPA (°)	27.1	5.2	2.6
U1/FH (°)	111.0	5.5	2.8
FMIA (°)	58.0	6.0	3.0
ANB (°)	2.1	2.1	1.1
IMPA (°)	93.0	6.2	3.1
Maxillary depth (AN/FH) (°)	89.0	3.0	1.5
Np (mm)	–1.3	2.5	1.3
Pog–Np (mm)	–5.5	4.2	2.1

FMPA, U1/FH, FMIA, ANB, IMPA, and A-Np for the dry skull; in four measurements: FPA, FMPA, U1/FH, and Pog-Np for subject A; in five measurements: FMPA, U1/FH, FMIA, AN/FH, and A-Np for subject B; and in seven measurements: FMA, FMPA, U1/FH, FMIA, ANB, IMPA, and AN/FH for subject C. A clinically significant difference was seen only in one measurement: U1/FH for the dry skull; in four measurements: FA, FMPA, U1/FH, and Pog-Np for subject A; in one measurement: AN/FH for subject B; and in three measurements: U1/FH, FMIA, and AN/FH for subject C.

Discussion

Dry skull (Table 3)

Although a statistically significant difference was detected in six measurements between the cephalogram and the digitizer, the actual value of the mean difference was much smaller than the equivalent value of half the SD in eight measurement items out of nine from the Tsurumi University norm (Table 7), which suggests that these statistically significant mean differences may be clinically insignificant except for the measurement U1/FH. One possible reason for the highly significant difference in U1/FH is considered to be the fact that the different landmarks used for determination of the long axis of the incisor are very closely located to each other compared with those used for other measurements in the present study. This can be confirmed by the theory that the more closely located two different landmark points are, the greater the angular measurement error tends to become, provided that the digitizing or measuring error is the same, which is explained in Figure 4 and Table 8. It is noteworthy that the angular error increases to 5.28 degrees when the inter-landmark distance is 10 mm, supposing a linear error of 0.92 mm. This type of error is expected to occur not only in digitization but also in cephalogram tracing and measuring, which is confirmed by the fact that the SD values of 2.01 and 2.15 respectively for U1/FH are greater than those for other skeletal measurements. It seems also true of measurements of FMIA and IMPA in which the cephalogram shows similarly larger SD values, 2.03 and 1.64 and the digitizer showing greater SD values, 0.99 and 1.04. It should be stressed that the digitizer shows smaller SD values than the cephalogram for eight out of nine measurements, which confirms the digitizer's better repeatability. For measurements of the dry skull, the system is quite reliable.

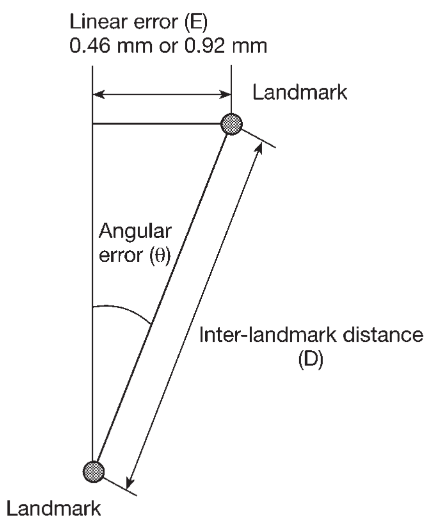

Figure 4 A geometric illustration describing the theoretical relationship between the inter-landmark distance (D) and the possible angular measurement error (θ) when the linear measurement error (E) is set at a certain level e.g. 0.46 mm or 0.92 mm. The relationship among the three factors can be expressed by the formula $\sin\theta = E/D$.

Table 8 Relationship between inter-landmark distance and possible angular measurement error in two different situations of linear measurement error.

Inter-landmark distance (mm)	Angular measurement error (°)	
	for 0.46 mm of linear error	for 0.92 mm of linear error
10.0	2.64	5.28
20.0	1.32	2.64
30.0	0.88	1.76
40.0	0.66	1.32
50.0	0.53	1.05
60.0	0.44	0.88
70.0	0.38	0.75
80.0	0.33	0.66
90.0	0.29	0.59

Subjects (Tables 4–6)

For all three subjects the digitizer showed smaller SD values than the cephalograms for a greater number of measurements: five items out of nine in subject A (Table 4), six items out of nine in subject B (Table 5), and seven items out of nine in subject C (Table 6). Considering that the SD value is a barometer of repeatability, the digitizer can be regarded as superior to the cephalogram in repeatability for measuring both the subjects and dry skull. Remarkably increased SD values were found for Pog-Np: 10.21 in subject B (Table 5), 7.44 in subject C (Table 6), 4.88 in AN/FH of subject C (Table 6), 3.65 in FMIA of subject A (Table 4), 3.63 in IMPA of subject A (Table 4), and 3.52 in IMPA of subject B (Table 5). Compared with the dry skull, as might have been expected, the subjects tended to show a greater mean difference and higher SD values. This is considered to be due to two reasons: one is the presence of the soft tissue drape and the other is the presumable head mobility of the living subject during digitization despite the utmost effort made for its fixation.

In subject A (Table 4), four measurements showed a statistically significant mean difference while only two showed a clinically significant mean difference. In subject B (Table 5), five measurements showed a statistically significant mean difference while only one showed a clinically significant difference. For subject C (Table 6), seven measurements out of nine showed a statistically significant difference and three a clinically significant difference. In all three subjects, U1/FH and AN/FH were the only two items showing a clinical difference for more than one subject, namely, in two subjects. For the very first step of experimental measuring of subjects, the reliability of the new system was considered to be quite promising although further testing with a larger sample is required.

Two subjects out of the three had fewer measurements showing a statistical significance than the dry skull. This is quite interesting considering that living subjects are considered to have more problems with regard to accuracy such as the soft tissues, the necessity for head fixation, etc.

The resultant overall superiority of the digitizer over the cephalogram could be partly due to the difference in the measuring method, that is, the digitizer is a direct measuring device whereas the cephalogram is an indirect method. In the former, one step of the tracing procedure is eliminated as a matter of course. However it should be noted that in measuring the subjects the digitizer also has a disadvantage in that soft tissue is always present between the stylus and the bony landmark. It is quite difficult to tell, however, which of these two factors contributes more to error.

One noticeable result was that the mean difference in U1/FH was both statistically and clinically significant for the dry skull and two of the three subjects. In relation to this, it should be remembered that a cervical point of the tooth and not the apex is presently used for determination of the anterior tooth axis because the digitizer cannot reach its apex. However, there could be other reasons for this significant difference. Among them are the morphological and positional characteristics of the central incisor such as shortness of the crown height, thickness, and width of the incisor edge, contours of the cervical area, and the incisal edge and rotation of the crown. All these factors seem to adversely affect stable, accurate, and firm application of the digitizer's stylus to the objective landmark point. On the other hand, measurements for the lower incisor such as FMIA and IMPA show much smaller mean differences. This is probably attributable to the fact that digitization of the lower incisor edge was conducted on a limited area of the labial surface in proximity to the incisal edge because of the normal overbite relationship exhibited by the subjects, which reduced the probability of error. The thickness of the upper incisor edge might be another cause in addition to the shortness of the crown, but further investigation is needed. It should be borne in mind that although the cephalometric method is the most practical control, it is neither perfect nor ideal.

In measuring the subject, fixation of the head is always a matter of concern. In this method, since the system is portable, the subject can lie on their back rather than sitting or standing. In this way the whole body is stabilized, which acts to stabilize the subject's head rested on the headrest of the dental chair. A band fastened around the head and a headrest also increases stability.

The fact that an intrinsic problem of the system is that the stylus of the digitizer cannot gain direct contact with any bony landmark, due to the presence of the soft tissue drape, does not negate the data obtained through this new system, nor does it invalidate the system itself. Considering that the system is just a prototype, there is room for further refinement and improvement. However, the significance of the present study lies in its concept of a direct measuring method employing simple portable equipment that can non-radiographically yield the subject's cephalometric data at the chairside. A successful development of the system is expected not only to advance patient-centred treatment but also to benefit epidemiological studies on cranio-dento-facial morphology.

Conclusions

While demonstrating workability as a chairside tool and being in need of further refinement in measurement accuracy, this newly developed cephalometric system shows potential applicability not only in the clinic, as an auxiliary to, or a substitute for, radiographic cephalometry but also outside the clinic as an epidemiological tool.

Address for correspondence

Satoshi Nagasaka
Department of Orthodontics
Tsurumi University School of Dental Medicine
2-13 Tsurumi, Tsurumi-ku
Yokohama City
Kanagawa Prefecture 230-8501
Japan

Acknowledgements

This research was supported in part by a Grant-in-aid for Scientific Research (No. 08672398, No. 09672126, No. 11557167) from the Ministry of Education, Science, Sports and Culture of Japan.

References

Alexander R G, Gorman J C, Grummons D C, Jacobson R L, Lemchen M S 1990 The DigiGraph Work Station Part 2: Clinical management. Journal of Clinical Orthodontics 24: 402–407

Athanasiou A E 1995 Orthodontic cephalometry. Times Mirror International Publishers Limited, London

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

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 *et al*. 1990 The DigiGraph Work Station Part 1: Basic concepts. Journal of Clinical Orthodontics 24: 360–367

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

Downs W B 1952 Role of cephalometrics in orthodontic case analysis and diagnosis. American Journal of Orthodontics 38: 162–182

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

Fujimura T, Nagasaka S, Kuwahara Y 2001 Performance assessment of a three-dimensional digitizer for its application to dentofacial measurement. Tsurumi University Dental Journal 27: 121–128

Graber T M 1952 New horizons in case analysis-clinical cephalometrics. American Journal of Orthodontics 38: 603–624

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

Hofrath H 1931 Die bedeutung der gontgenferm und abstandsaufnahme fur die diagnostik der kieferanomalien. Fortschritte der Kieferorthopädie 1: 232–258

L'Abee 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

McNamara J A 1984 A method of cephalometric evaluation. American Journal of Orthodontics 86: 449–469

Miyashita K 1986 An atlas of roentgen anatomy and cephalometric analyses. Quintessence Inc., Tokyo

Nagaoka K, Kuwahara Y 1993 Normal standards for various roentgen cephalometric and cast model analyses in present day Japanese adults: Part I. Journal of Japan Orthodontic Society 52: 467–480

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

Ricketts R M, Bench R W, Hilgers J J, Schulhof R 1972 An overview of computerized cephalometrics. American Journal of Orthodontics 61: 1–28

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

Simon P W 1922 Fundamental principles of a systematic diagnosis of dental anomalies. The Stratford Company, Boston

Tsang K H S, Cooke M S 1999 Comparison of cephalometric analysis using a non-radiographic sonic digitizer (DigiGraph Workstation) with conventional radiography. European Journal of Orthodontics 21: 1–13

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

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

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