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Space analysis: a comparison between sonic digitization (DigiGraph™ Workstation) and the digital caliper

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SUMMARY The introduction of the DigiGraph™ Workstation permits the use of sonic digitization to measure lateral cephalometric values, mesiodistal tooth size and arch perimeter discrepancy as a one-stop diagnostic record taking set-up. This study compared the reproducibility of mesiodistal total tooth widths and arch perimeter values, on plaster casts, given by the DigiGraph™ Workstation and by digital calipers. Forty-seven sets of plaster casts of Southern Chinese children (mean age 12.5 years) comprised the sample. Arch perimeter was measured using calipers in six segments from the distal of the first permanent molar to its antimere in each arch. The total mesiodistal widths of all teeth, excluding second and third molars, were also measured. The difference between the available arch perimeter and the total tooth widths was taken as the arch perimeter discrepancy. Sonic digitization of the study casts was completed according to instructions of the DigiGraph™ software. Paired *t*-tests and *F*-tests were used to compare the two methods.

Compared with manual measurement, there was an over-estimation of the total tooth widths by 1 mm in the mandible and 0.5 mm in the maxilla, and an arch perimeter discrepancy of 1.6 mm in the mandible and 0.4 mm in the maxilla when using the sonic method. The sonic digitization was not as reproducible as the digital caliper and its clinical usefulness in evaluating the space problem of an individual malocclusion should be interpreted with caution.

Introduction

Space analysis is an essential procedure in the diagnosis and treatment planning of malocclusions. The analysis of space problems, in relation to aetiology, methods of measurement, and treatment strategies have been extensively dealt with in the literature (Lundström, 1948; Moorrees, 1959; Huckaba, 1964; Mills, 1964; Fastlicht, 1970; Van der Linden, 1974; Doris *et al*., 1981; Howe *et al*., 1983; Radnzic, 1988).

The space problem can be viewed as the deficit between the sum of the mesiodistal widths of the teeth within an arch, from first permanent molar to first permanent molar, and the available arch perimeter to accommodate the teeth (Lundström, 1948; Hunter, 1978). Many methods and instruments have been used to measure mesiodistal tooth size and the available arch perimeter.

Mesiodistal tooth sizes have usually been measured from the mesial and distal anatomic contact points directly on study casts with instruments such as dividers, calipers, or Boley's gauge with a vernier scale, the Reflex metrograph, an image analysis system or different *x*–*y* co-ordinate digitizing systems. The arch perimeter has been measured with these methods, after dividing the arch into segments or by mathematical formulae starting from the mesial or distal contact point of the first permanent molar. The formulae commonly used were the parabola, the catenary curve or the fourth-degree polynomial function (Lu, 1964; Rudge, 1981).

Comparisons between different space analysis methods are occasionally found in the literature (Rudge *et al*., 1983). However, comparisons using different instruments measuring only mesiodistal tooth sizes or only arch perimeter are more commonly found. Hunter and Priest (1960) studied the difference between dividers and Boley's gauge, while Brook *et al.* (1986) compared the image analysis system with a dial caliper. Looking at the literature with regard to arch perimeter, Rudge *et al.* (1983) compared measurements made using an *x–y* digitizer with the Reflex metrograph, while Musich and Ackerman (1973) compared the brass wire method with the catenary curve formed by a hanging chain. Battagel (1996) compared the manual measurement using the 'overlap method' measured by the Reflex microscope with the catenary curve formula.

With the advent of the DigiGraph™ Workstation (DigiGraph™, Dolphin Imaging Systems, Valencia, California, USA; Figure 1), sonic digitization provides a new measuring technique for registering linear distances. The original concept for the DigiGraph™ Workstation was to eliminate or minimize the need for radiation exposure in obtaining lateral cephalometric measurements for patient diagnosis. It also includes a module for space analysis utilizing study casts. In this way, comprehensive patient records for diagnosis and treatment planning may be obtained.

Recently published papers by Chaconas *et al.* (1990), Prawat *et al.* (1995) and Doll *et al.* (1996) have investigated the accuracy of sonic digitization in measuring lateral cephalometric values for both angular and linear measurements. These studies compared direct sonic digitization on patients with conventional radiographic measurements, but they produced contradictory results.

Currently, no data are available for the evaluation of the sonic method provided by the DigiGraph™ Workstation compared with other space analysis methods. This present study investigated the reproducibility of sonic digitization with manual measurement using a digital caliper.

Figure 1 The DigiGraph™ Workstation.

Materials and methods

The sample comprised randomly selected study casts from a previous morphometric study completed at the Faculty of Dentistry, Hong Kong, in 1982. The selected group consisted of 47 sets of study casts of Southern Chinese children. The mean age was 12.5 years with a male to female ratio of 29:18. The selected study casts were included if they matched the following main criteria: in the permanent dentition, no interproximal caries, no obvious distortion, no missing teeth, and demonstrating a 'good occlusion'.

The casts were prepared to fit securely onto a modified digitizing platform on the DigiGraph™ Workstation, as the original digitizing platform was not sufficiently secure. This preparation involved drawing three alignment lines on the heels of each set of study casts. Two Pindex® holes (Whaladent International, New York, USA) were then drilled onto the base of the study casts (Figure 2) and two plastic Pindex® pins were cemented onto the pin holes. Before the sonic digitization process, each set of casts were positioned onto the platform (Figure 3) which consisted of a rectangular acrylic plate with two rigidly fixed matching Pindex® pins and supporting acrylic bars. This provided a reproducible and fixed position for the casts during the sonic digitization process.

Space analysis method

The space analysis method used was that described by Lundström (1948) and later

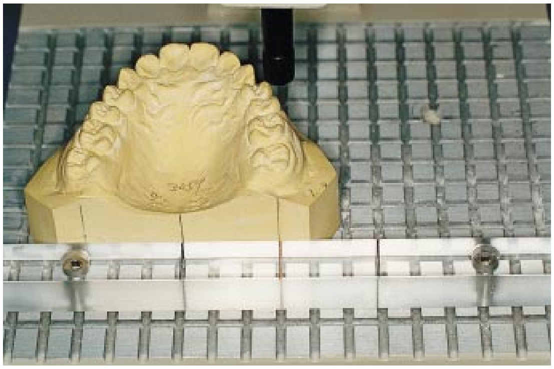

Figure 2 Preparation of the study casts using the Pindex machine.

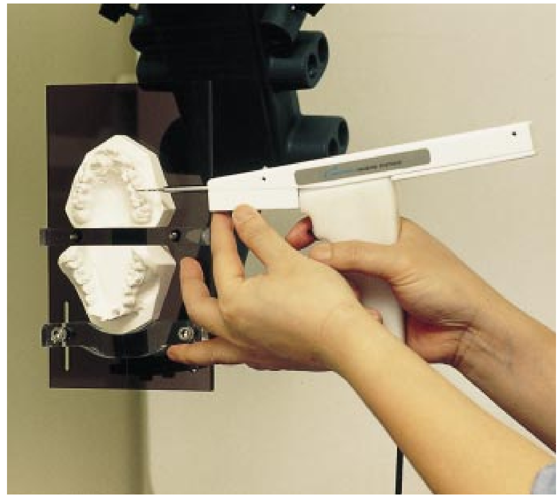

Figure 3 Digitization using the modified platform.

adapted by Vego (1962). The mesiodistal tooth widths of individual tooth, from the first molar to its antimere, were measured in each arch (Figure 4) from the respective mesial and distal anatomic contact points (Moorrees, 1957). The arch perimeter was calculated by dividing the maxillary or mandibular arch into six segments and these segments were then added together (Figure 4). The difference between the arch perimeter and the total mesiodistal tooth widths is the arch perimeter discrepancy. Hence:

Arch perimeter discrepancy = Arch perimeter – Total mesiodistal tooth widths.

Digitization of the casts on the DigiGraph™ Workstation was completed on the landmarks using the space analysis module in the DigiGraph™ software (Figure 5). The measurements were taken by positioning the tip of the digitizing handpiece on the chosen landmark, while pressing the button on the handpiece. Manual measurement (Figure 6) was performed using the method described previously by digital caliper (Digit-Cal SM, TESA S.A., Switzerland).

Replicate measurements, by the same single examiner, were made on all study casts with a time interval of 1 week. A total of four series of measurements (2 DigiGraph™, 2 caliper) were recorded with six different categories: mandibular total tooth sum; mandibular arch perimeter; mandibular arch discrepancy; maxillary total tooth sum; maxillary arch perimeter and maxillary arch perimeter discrepancy.

Data analysis and statistical tests

For each method of measurement normal descriptive data and correlation coefficients for the following parameters were calculated: total mesiodistal tooth widths; arch perimeter and arch perimeter discrepancy in both jaws. Paired *t*-tests were used to assess any systematic error. The method errors for each of the categories of measurement and the coefficient of reliability were calculated according to Houston (1983) using the following equation:

$$\text{Method Error } (S_e) = \sqrt{\frac{S_d^2}{2}}$$

where S_d^2 represents the square of the standard deviation of the differences between replicate measurements.

$$\text{Coefficient of reliability} = 1 - \frac{S_e^2}{S_t^2}$$

where S_t^2 represents the total variance of the measurements and S_e^2 represents the variance due to random errors.

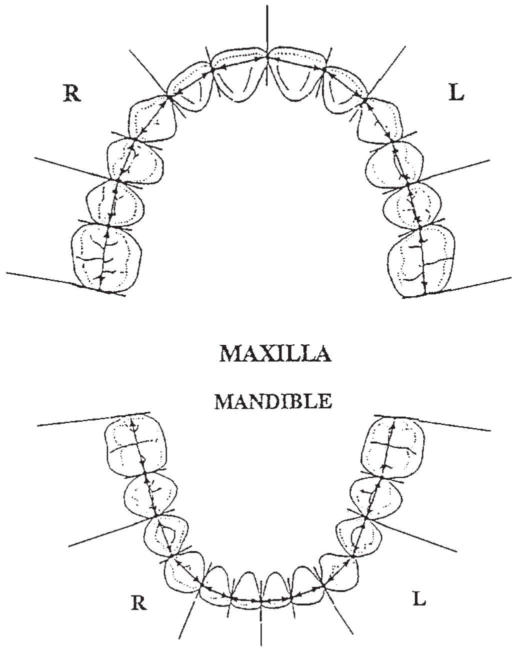

Figure 4 Landmarks for measurement of the mesiodistal tooth widths and the arch perimeter segments.

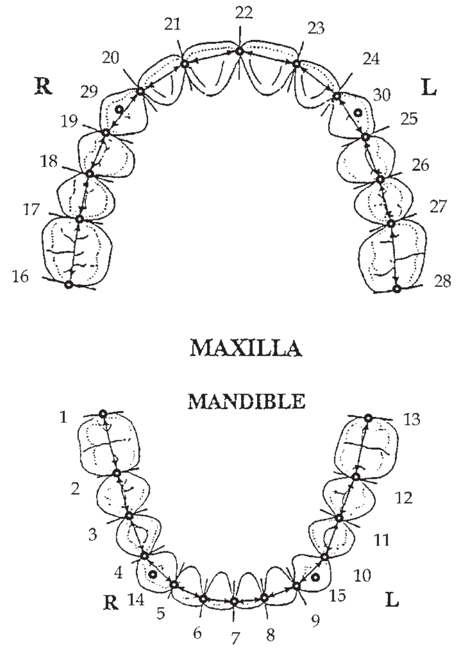

Figure 5 DigiGraph™ digitization landmarks sequence. Points 14, 15, 29 and 30 are the cusp tip of the canines.

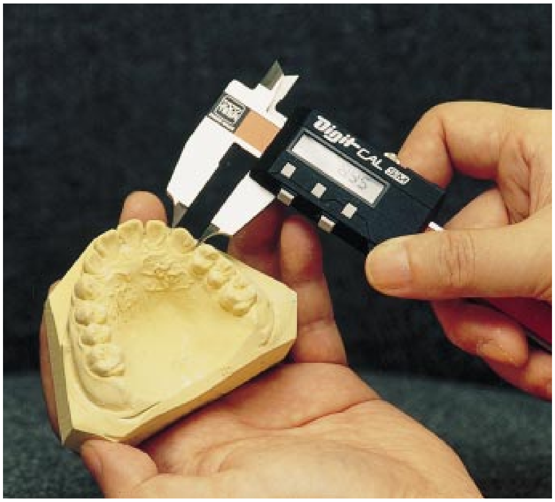

Figure 6 Measurement of the study casts using the caliper.

The method for assessing reproducibility between the two methods was performed using confidence interval construction (Bland and Altman, 1986; Altman, 1994). The limits of agreement as proposed were calculated accordingly.

Results

Table 1 shows the reproducibility between replicate measurements for both methods using *F*-tests on the squared standard deviations of the mean difference between the two methods. All *F*-test values were larger than 45 and the corresponding *P*-values were all smaller than 0.01, indicating a statistically significant difference between the standard deviations at the 1 per cent level. The standard deviations for the DigiGraph™ Workstation ranged from 1.57 to 3.1 mm which was greater than the caliper's values which ranged from 0.22 to 0.38 mm.

Table 2 shows the systematic error between a single set of DigiGraph™ and caliper measurements, and their correlation coefficient squared. The largest mean difference (systematic error) was 1.71 mm and the smallest 0.14 mm, for the mandibular and maxillary arch perimeter

Table 1 Reproducibility between DigiGraph™ Workstation and caliper (n = 47).

	DigiGraph™ Standard deviation of mean differences between replicates (mm)	Caliper Standard deviation of mean differences between replicates (mm)	F-values	P-values
Mandibular tooth sum	3.04	0.23	172.93	<0.01
Mandibular arch perimeter	2.41	0.31	59.04	<0.01
Mandibular arch perimeter discrepancy	3.10	0.38	65.92	<0.01
Maxillary tooth sum	2.53	0.36	49.90	<0.01
Maxillary arch perimeter	1.57	0.22	49.70	<0.01
Maxillary arch perimeter discrepancy	2.47	0.36	45.73	<0.01

Table 2 Systematic differences between DigiGraph™ Workstation and caliper (n = 47).

	DigiGraph™		Caliper		Mean difference (mm)	t-values	P-values	r^2
	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)				
Mandibular tooth sum	89.71	3.85	88.67	3.67	1.04	3.37	<0.01	0.71
Mandibular arch perimeter	89.31	4.74	89.99	4.05	–0.68	2.33	0.02	0.83
Mandibular arch perimeter discrepancy	–0.39	2.86	1.32	2.02	–1.71	4.29	<0.01	0.17
Maxillary tooth sum	97.19	4.06	96.68	4.11	0.51	1.62	0.11	0.74
Maxillary arch perimeter	98.79	4.12	98.41	3.88	0.38	1.49	0.14	0.83
Maxillary arch perimeter discrepancy	1.59	2.38	1.73	1.82	–0.14	0.37	0.71	0.08

SD = standard deviation; r^2 = correlation coefficient squared.

discrepancy, respectively. The r^2 were highest for both arch perimeter readings—0.83 (mandible and maxilla)—but lowest for both arch perimeter discrepancy readings—0.17 (mandible) and 0.08 (maxilla). All systematic errors were statistically significant except maxillary arch perimeter and maxillary arch perimeter discrepancy. Figure 7 is a graphical representation of the above results and the error bars represent the 95 per cent confidence intervals of the mean differences. The error bars for all the maxillary measurements crossed the x-axis, while the others did not.

By calculating the standard deviation of the mean differences of the paired DigiGraph™ and caliper readings twice, 95 per cent of the paired measurements will be included. This represents the limits of agreement between the two measurement methods as suggested by Bland and Altman (1986). Table 3 shows the limits of agreement as calculated. The largest range was found for the arch perimeter discrepancy categories: 3.8 to –7.2 mm and 5 to –5.3 mm for the mandibular and maxillary arch, respectively. This shows that the arch perimeter discrepancy measurement between methods can vary from +5 mm to –5 mm for both arches. For the arch perimeter, the range was ±4 mm for the mandible and ±3.5 mm for the maxilla. For the mesiodistal total tooth sum the range was ±4 mm for both arches.

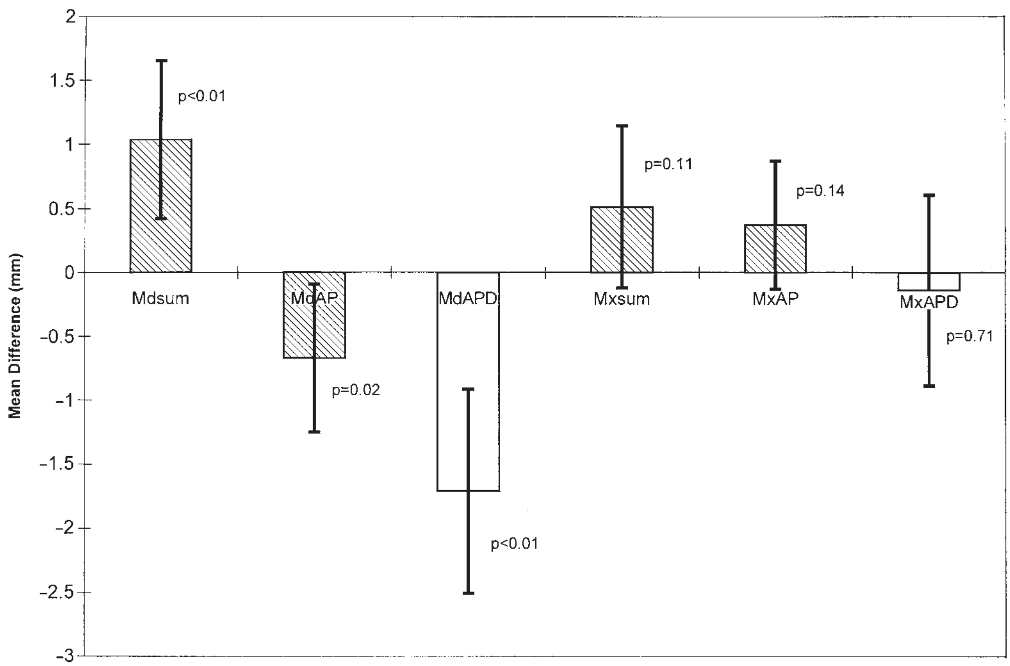

Figure 7 Systematic differences between the DigiGraph™ and the caliper. Mdsum, Mxsum: mandibular and maxillary tooth sum; MdAP, MxAP: mandibular and maxillary arch perimeter; MdAPD, MxAPD: mandibular and maxillary arch perimeter discrepancy.

Table 3 Limits of agreement between DigiGraph™ Workstation and caliper (n = 47; Bland and Altman, 1986).

	Lower limit (mm)	Mean difference (mm)	Upper limit (mm)
Mandibular tooth sum	–3.2	1.0	5.2
Mandibular arch perimeter	–4.7	–0.7	3.3
Mandibular arch perimeter discrepancy	–7.2	–1.7	3.8
Maxillary tooth sum	–3.9	0.5	4.9
Maxillary arch perimeter	–3.1	0.4	3.8
Maxillary arch perimeter discrepancy	–5.3	–0.1	5.0

All figures abbreviated to 1 decimal place for clinical relevance.

Table 4 shows the method errors (random errors) of each category of measurement for both DigiGraph™ and caliper readings. They were calculated using Houston's (1983) formula. A trend can be found for each arch in this analysis of the DigiGraph™ readings. The random errors were comparable for mesiodistal total tooth widths and the arch perimeter discrepancy 2.15 and 2.19 mm for the mandible, and 1.79 and 1.74 mm for the maxilla. The smallest error was associated

Table 4 Method error (ME) and coefficient of reliability (CR) calculated using Houston's formula (1983) ($n = 47$).

	DigiGraph™		Caliper		F-values	P-values
	ME (mm)	CR (%)	ME (mm)	CR (%)		
Mandibular tooth sum	2.15	69.15	0.16	99.80	13.17	<0.01
Mandibular arch perimeter	1.71	87.02	0.22	99.70	7.68	<0.01
Mandibular arch perimeter discrepancy	2.19	41.12	0.27	98.22	8.12	<0.01
Maxillary tooth sum	1.79	80.63	0.25	99.62	7.06	<0.01
Maxillary arch perimeter	1.11	92.77	0.16	99.84	7.05	<0.01
Maxillary arch perimeter discrepancy	1.74	46.44	0.26	98.00	6.76	<0.01

with the arch perimeter recordings, being –1.71 for the mandible and 1.11 for the maxilla. In contrast, the largest error with the caliper method was for the arch perimeter discrepancy, being –0.27 and 0.26 for the mandible and maxilla, respectively. The coefficient of reliability was lower with the DigiGraph™ readings when compared with the caliper readings. The lowest coefficient for both methods being associated with the arch perimeter discrepancy, which was 40–50 per cent for the DigiGraph™ and 98 per cent for the caliper. By using the F-ratio test between the variance of the two methods the result showed that all were statistically significantly different at the 1 per cent level.

Discussion

The selection of 47 sets of good occlusion study casts aimed to reduce the number of parameters that could affect the outcome as confounding variables and provide a less variable sample. Such interactions may arise from factors such as a deep curve of Spee or proclined incisors which may affect the elucidation of arch perimeter discrepancy. The modification of the digitizing platform on the DigiGraph™ Workstation also aimed to reduce variability on the placement provided by the original platform.

Traditionally, the criteria for comparison are to compare the correlation coefficients between the readings measured by different methods. However, Bland and Altman (1986), and Altman (1994) suggested that the standard deviation of the mean differences between the two methods should be compared along with the limits of agreement for 95 per cent of the measured readings between the two methods as a practical clinical guide for the comparability of the two methods.

From the reproducibility results shown in Table 1, there was a complete lack of agreement between the replicate measurements of the DigiGraph™ Workstation compared with the caliper, for all six categories of measurement. All F-test and P-values were smaller than 0.01. Consistently, measurements with the caliper had much smaller standard deviations; the weakest of the caliper readings was 0.38 as compared with the best of the DigiGraph™'s 1.57 mm. This is in good agreement with Prawat *et al.* (1995), who found that 19 linear measurements out of 21 had a difference in variability between the manual and the sonic method. Doll *et al.* (1996), using the Jarabak analysis, also reported higher standard deviations by the sonic method.

Statistically significant systematic errors existed between the two methods for half of the categories of measurements (Table 2). The largest error (1.71 mm) was for the mandibular arch perimeter discrepancy. This may be due to the consistently large readings given by the DigiGraph™ Workstation on individual teeth, particularly the incisors in the mandibular arch. No systematic error was found in the maxillary arch between the two methods.

Several sources may contribute to the systematic errors. They may result from consistent over-estimation of the mesiodistal widths of the incisors in the mandibular arch using the sonic method or by fields of non-linearity on the sparkler-microphone array digitizer system. Alternatively, it may be due to different resolutions or scaling errors along the *x*-, *y*- and *z*-axes (Eriksen and Solow, 1991). It is also possible that the three-dimensional data were truncated to planar data by software reduction.

The absence of systematic error found for the maxillary arch categories of measurement may well be the result of larger incisors, which the DigiGraph™ Workstation could measure more accurately.

Random errors, as determined by Houston's formula (1983), were also higher for the DigiGraph™ Workstation when compared with the caliper method. Arch perimeter measurements undertaken with the calipers were 0.16 mm (maxilla) and 0.22 mm (mandible). This is in good agreement with Dahlberg's (1940) value quoted by Battagel (1996) of less than 0.3 mm, and also with the value of 0.22 mm reported by Bhatia and Harrison (1987). In contrast, the random errors associated with measurements undertaken using the DigiGraph™ were significantly higher, at 1.1 mm (maxilla) and 1.7 mm (mandible). These were much larger than the 0.26 mm observed by Battagel (1996) using catenary curve calculation. The coefficients of reliability for caliper measurements were, on average, 99.7 per cent, which compared well with the 99 per cent given by Battagel (1996) using the 'overlap method'.

Sources of random errors are harder to explain since ultrasonic sonography has been used extensively in other medical disciplines with good results (Christie, 1981; Campbell *et al*., 1982; Lessoway *et al*., 1990). Since resolution is related to the frequency of the sound source used (Sarti and Kimme-Smith, 1987), there is reason to suspect the frequency of the sound used in the DigiGraph™ Workstation. If the frequency used by the DigiGraph™ is in the audible range, then the resolution of the frequency may not be high enough to resolve objects smaller than the wavelength of the sound frequency, which in this case may be in the millimetre range. Other sources of random error may include the fluorescent light used in the office environment, atmospheric variations, background noise level, or the stability of the operator's hand during the digitization process. Another important factor is landmark location. This is illustrated by the findings of Bhatia and Harrison (1987) who demonstrated that the method error changed from 0.67 mm, for marked points, to 0.22 mm for unmarked landmarks, in measurements of study casts with the travelling microscope.

The limits of agreement suggested by Altman (1994) provide a good indication to the clinical usefulness of the DigiGraph™ Workstation. From our current results, the two methods differed widely as illustrated by the arch perimeter discrepancy which demonstrated a range from approximately 4 to –7 mm (mandible) and for the maxilla 5 to –5 mm. This indicates an unacceptable range in clinical diagnosis as a treatment plan can change from non-extraction to extraction therapy with a variability between the methods of approximately ±5 mm. The data from this study showed that the sonic method was not so reproducible as the manual measurement. Systematic errors existed in half of the categories of measurement and there were large overall random errors.

The available data indicate that the DigiGraph™ Workstation would benefit from more refinement before the machine can reliably be used to diagnose space problems in individual malocclusions.

Conclusions

1. The DigiGraph™ Workstation consistently over-estimates mesiodistal tooth widths by 1 mm in the mandible and by 0.5 mm in the maxilla.
2. There is an over-estimation of the arch perimeter discrepancy by 1.7 mm in the mandible and by 0.1 mm in the maxilla. The DigiGraph™ Workstation tends to give a 'more crowded' measurement.
3. Fifty per cent of the total measurements using sonic digitization were significantly different from the caliper measurements.
4. With a variation of ±5 mm in the arch perimeter discrepancy values in both arches,

the results given by the space analysis module of the DigiGraph™ Workstation should be interpreted with caution.

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