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Accuracy and validity of space analysis and irregularity index measurements using digital models

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Background: Digital copies of study models may avoid the storage and retrieval issues of plaster study models, but measurements made on digital models may not be as accurate as measurements made on traditional study models.
Aim: To determine the reliability and validity of tooth size–arch length discrepancies (TALD), irregularity indices and arch lengths (four- and six-segment analyses) measured directly on study models with digital calipers with the same measurements measured on digital copies of the study models with proprietary software.
Methods: The irregularity indices and TALDs (four- and six-segments) were measured on 50 sets of pretreatment plaster models. The plaster models were measured using manual calipers with a digital readout. The models were then couriered to OrthoCAD and digital copies emailed to the authors. The digital models were measured with the proprietary software provided with the digital models. Repeat measurements of the TALDs and the irregularity indices were subjected to intraclass correlations (ICC) to assess the reliability. The least squares means of variation was used to assess validity and the impact of measuring arch length (four- and six-segments) on the digital models, and the implications on the TALDs.
Results: There were high correlations (ICC) ranging from 98.6–99.9 per cent for both the irregularity indices and the TALDs. The choice of manual over computer and four-segment over six-segment analysis had a significant effect when measuring lower arch lengths ($p < 0.05$), but they had no effect on the upper arch findings.
Conclusions: Reliable measurements of the irregularity index and the TALD can be made on digital models. Computer measurements of TALDs on digital models were more consistent than manual measurements of TALDs on plaster models. Six-segment analyses of lower arch lengths on digital and plaster models gave more consistent findings than the four-segment analyses.
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Introduction

Digital copies of study models have recently been added to practice management software packages to avoid the storage and retrieval issues of plaster study models. Unlike traditional plaster models, digital models can be available at a number of different locations in seconds.[1] Furthermore, the transfer of patients' records, using electronic copies of the study models and other records, is facilitated. However, like all issues related to computing, digital models cannot be accessed when computers are not operational, and this may be a source of frustration to the clinician.

A variety of methods has been used to assess plaster study models, ranging from inspection of the casts to direct measurement with a Boley gauge, dividers or electronic calipers. The accuracy of measurement with electronic calipers appears to be superior to direct intra-oral measurements.[2] The reliabilities of sonic digitisation, photocopies and scanned images of plaster models have also been explored.[3–8]

Several software products are now available to measure, capture and store tooth size and arch length discrepancies (TALD), the Bolton ratio, the irregularity index, overbite and overjet. Moreover, 'sectioning' of

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digital models allows three-dimensional changes in structures, such as the alveolar ridge and palate, to be evaluated. This technology has lead to the development of 'invisible aligners' and computer-aided indirect bonding.[9,10]

Study models are primarily used to evaluate intra- and inter-arch relationships. Of the parameters used to describe intra-arch relationships, the irregularity index[11] and TALD measurements may significantly influence the orthodontist's diagnostic and treatment planning decisions. In spite of their shortcomings, measurements made on plaster models are generally regarded as the 'gold standard'. Although doubt has been cast on the accuracy of measurements taken from digital models as compared with measurements made on traditional study models, the differences may not be clinically significant. For example, Zilberman et al.[12] demonstrated greater accuracy of direct measurements from plaster models with electronic calipers compared with measurements from digital models of the same malocclusions. They reported that both methods gave valid and reproducible tooth size, intercanine width and inter-molar width measurements. Peer assessment rating scores, the American Board of Orthodontics objective grading system and Bolton analyses derived from digital models were also found to be as valid and reliable as the same analyses from plaster study models.[13–15] Santoro et al.[16] demonstrated that measurements taken from digital models were routinely smaller than direct measurements with calipers, except for overjet. Tran et al.,[17] on the other hand, demonstrated that measurements from digital models were slightly larger than direct measurements, but concluded that the differences were not clinically significant. He suggested that measurements from both sources could be interchanged. Other investigators have reported statistically significant differences between measurements taken from plaster and digital models, but have questioned whether the differences would be clinically significant.[18–20]

Arch length and TALD in particular, have been measured a number of ways.[21–23] If changes in arch depth are to be correlated with stability findings, a tangential line from the mesial of the first permanent molar to the midpoint between the central incisors has been advocated.[23] To assess the space needed for alignment of teeth, the brass wire technique may be used,[24,25] or arch length may be measured in four quadrants from the mesial of one molar to mesial of contralateral molar.[22] Alternatively, the arch may be measured in six sections, treating the canine as a separate unit.[21] The four- and six-segment approaches have possible limitations. The four-segment approach may give an inaccurate estimate of arch form, and measurement points in the canine regions are often difficult to identify. The cumulative measurement error may be higher with the six-segment approach because of the greater number of measurements.

The irregularity of teeth does not necessarily give an accurate estimate of the TALD, although some occlusal indices use the displacement of contact points to determine the need for treatment.[26,27] The irregularity index sums the displaced anterior contact points from one canine to the contralateral canine to provide an objective measure of the degree of anterior crowding.[6] This index is often used to describe tooth alignment in treatment and retention studies.

The purpose of this study was to compare measurements taken from plaster study models with identical measurements taken from digital copies of the same plaster models using a proprietary software programme. Specifically, we aimed to determine: the accuracy of measuring the irregularity index and components of the TALD; the validity of measuring the TALD and the irregularity index with digital models as compared with plaster models; and to compare the accuracy of arch lengths measured in four-segments with arch lengths measured in six-segments for digital and plaster study models.

Materials and methods

Approval to conduct this study was obtained from the Human Research Ethics Committee of The University of Western Australia. All assessments were carried out in accordance with the guidelines of the National Health and Medical Research Council of Australia.

Fifty sets of study models were selected from the records held in the Orthodontic Department at The University of Western Australia. The study models satisfied the following inclusion criteria: all permanent teeth had erupted, excluding the third molars; the study models were of school age children; the teeth had a normal crown forms with no interproximal restorations, unrestored carious cavities or interproximal/occlusal attrition. A sample size



Figure 1. Arch length measured in four-segments on the lower digital model.



Figure 2. Arch length measured in six-segments on the lower digital model.



Figure 3. Irregularity index measured on the lower digital model.

calculation was undertaken and approximately 50 models were needed to detect a difference of 0.5 mm in the space analysis variables based on the variance estimated from previous studies, a Type I error of 0.05 and a power of 80 per cent.

The models were coded for identification, and measured in a random order using a digital caliper by a single examiner (RG). The models were then sent by express courier to a firm providing digital models (Cadent Inc, Fairview, NJ, USA). Digital copies of the models were emailed to the authors and the plaster casts returned by express courier. The digital models were measured with the proprietary software (Orthocad, Cadent Inc, Fairview, NJ, USA) provided with the digital models. Two weeks later, 10 sets of models were randomly selected and remeasured both manually and digitally.

Measurement procedures

A manual caliper with an electronic digital readout was used to measure the plaster study models (Manual method). The software provided with the digital models was used to make identical measurements on the digital study models (Computer method). All measurements were recorded to the nearest 0.1 mm. The following dimensions were measured:

1. Mesio-distal crown length. The greatest mesio-distal length, measured parallel to the occlusal plane.[7]

2. Four-segment arch length. Posterior segment: from the mesial contact point of one first permanent molar to the mesial contact of the ipsilateral canine; Anterior segment: from the mesial contact point of the canine to the mesial contact point of ipsilateral central incisor or if the incisor was displaced to the mesial contact point of the central incisor in the line of the arch (Figure 1).

3. Six-segment arch length. Posterior segment: from the mesial contact of one first permanent molar to the distal contact point of the ipsilateral canine; Middle segment: from the distal contact point of the canine to the mesial contact of the same canine; Anterior segment: from the mesial contact point of the canine to the mesial contact point of ipsilateral central incisor or if the incisor was displaced to the mesial contact point of the central incisor in the line of the arch (Figure 2).[16]

4. Irregularity index. The sum of the displacements of the anatomical contact points of the incisors from adjacent teeth, measured from the mesial contact point of one canine to the mesial contact point of the contralateral canine (Figure 3).[6]

Statistical analysis

All measurements were recorded on a Microsoft Excel spreadsheet (Microsoft, Redmond, WA, USA) and analysed using SAS software (SAS Institute, Cary, NC, USA). Descriptive statistics of the arch lengths, tooth widths and the irregularity indices for both plaster and digital models were calculated. Variance components statistical models were used to assess the repeatability for the manual and digital recordings of the TALDs and the irregularity indices on the upper and lower models. The within patient variability, between patient variability variance component estimates and the repeatability coefficient or intraclass correlation coefficient (ICC) were calculated. Intuitively, if the measurements on an individual are the same then this value will be 1. The more the measurements differ, the closer this measure will become to 0. A linear mixed model approach was used to examine: the impact of fixed factors measuring the space analysis in either four- or six-segments; the measurement type (computer or manual); and the

Table I. Arch length, tooth size and TALD for plaster and digital models, in millimetres.

Type	Number of segments	Arch	Arch length Mean (SD)	TALD Mean (SD)	Tooth size Mean (SD)
Plaster (N=50)	4	Lower	63.6 (2.82)	-2.1 (2.42)	65.7 (3.55)
	6	Lower	65.1 (3.28)	-0.6 (1.66)	
	4	Upper	74.8 (4.24)	-0.6 (1.70)	74.8 (4.00)
	6	Upper	74.3 (4.49)	-0.5 (1.75)	
Digital (N=50)	4	Lower	65.3 (3.11)	-1.0 (1.98)	66.3 (3.22)
	6	Lower	65.9 (3.00)	-0.4 (1.50)	
	4	Upper	75.8 (4.32)	-0.3 (1.20)	76.1 (3.61)
	6	Upper	75.8 (4.27)	-0.3 (1.59)	

Table II. Irregularity index, in millimetres.

Type	Arch	Mean (SD)	Range
Plaster (N=50)	Upper	7.8 (5.09)*	1.5 - 25.7
Digital (N=50)		7.8 (4.89)*	2.1 - 26.2
Plaster (N=50)	Lower	7.0 (3.19)†	0.8 - 15.0
Digital (N=50)		7.1 (3.07)†	1.1 - 15.4

* $p = 0.73$
† $p = 0.13$

Table III. Repeatability of manual and computer measurements of TALD and irregularity index.

Variable	Type of measurement	Location	ICC
TALD	Manual	Lower	97.88
	Manual	Upper	99.05
	Computer	Lower	98.60
	Computer	Upper	98.65
Irregularity Index	Manual	Lower	99.40
	Manual	Upper	99.81
	Computer	Lower	99.87
	Computer	Upper	99.78

ICC, intraclass correlation coefficient

interaction of the two factors on the outcomes of arch length and TALD. The random factor of 'patient' was also included in the model. Significant fixed effects are presented along with tables of least squares (predicted) means and pairwise comparisons of each treatment group combination.

Results

The descriptive statistics for the components of the TALDs and the irregularity indices measured on the digital and plaster models are given in Tables I and II. The arch lengths and tooth sizes appear to be consistently larger when the digital models were used. However, when the irregularity index was measured, there does not appear to be any statistically significant difference between the methods of measurement: Upper plaster model vs upper digital model, $p = 0.73$; Lower plaster model vs lower digital model, $p = 0.13$ (Table II).

Table III presents the results for the intra-examiner repeatability for both manual and computer measurements of TALD and incisor irregularity. There were high correlations (ICC) ranging from 98.6 to 99.9 per cent.

When upper arch length was considered, the computer measurements of the digital models gave a systematically larger mean arch length than the manual measurements ($p < 0.001$). The number of segments had no impact on the findings. For the lower arch length a statistically significant interaction ($p = 0.007$) between the digital and manual methods and the number of segments was observed, indicating that the difference in mean arch length between manual and computer was not consistent for the four- and six-segment measurements. Table IV and Figure 4 show this more clearly: the difference between the four-segment computer and four-segment manual methods (Estimated difference: 1.75) is larger than

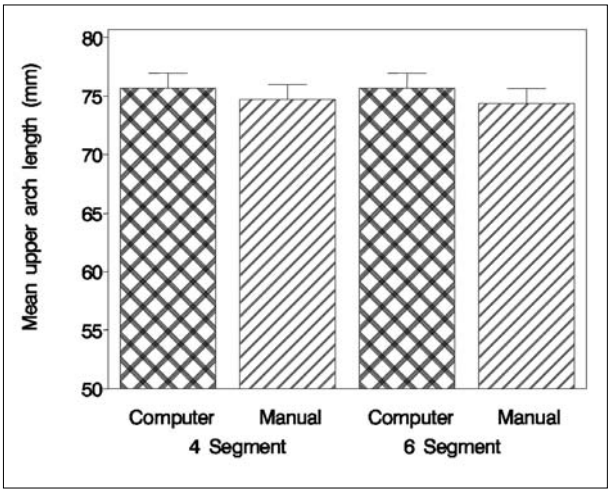


Figure 4. Comparison of manual and computer measurements of upper arch length (four- and six-segment methods), least squares means ± 2 SE.

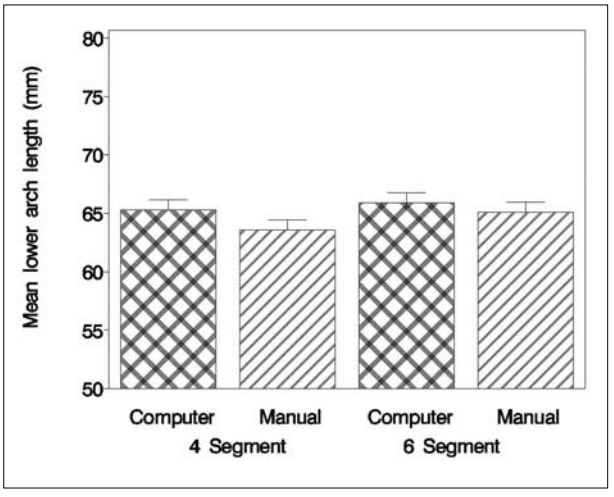


Figure 5. Comparison of manual and computer measurements of lower arch length (four- and six-segment methods), least squares means ± 2 SE.

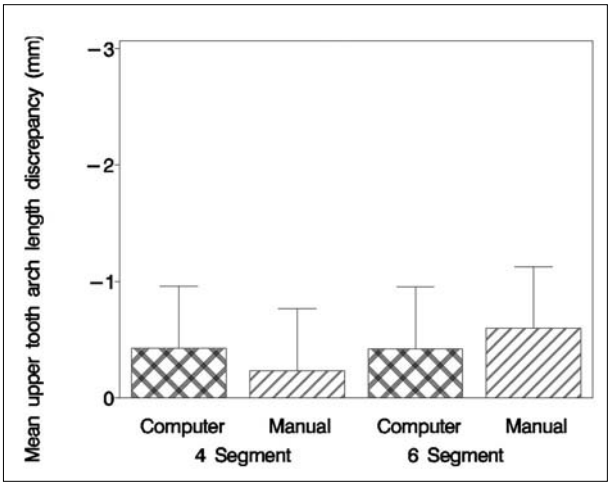


Figure 6. Comparison of manual and computer measurements of upper TALD (four- and six-segment methods), least squares means ± 2 SE.

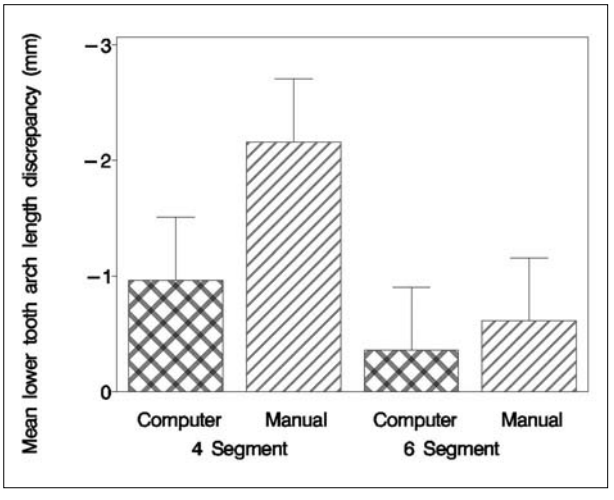


Figure 7. Comparison of manual and computer measurements of lower TALD (four- and six-segment analyses), least squares means ± 2 SE.

the difference between the six-segment computer and the six-segment manual methods (Estimated difference: 0.83).

A statistically significant interaction (p = 0.004) between the method (manual or computer) and the number of segments (four or six) was observed when the lower arch TALD was considered (Table V). This indicates that the differences between the manual and computer results are not consistent for the four-segment and six-segment measurements. This is seen more clearly by the predicted means in Table V and Figure 6. It is noticeable that although components of the TALD (arch length and tooth size) are consistently larger when measured with digital models, the manual TALD measurements are generally higher than the computer measurements: the difference is much larger for the four-segment analysis than for the six-segment analysis. In fact, the difference between the manual and computer methods for the six-segment data is not statistically significant (p = 0.261). When the upper arch was measured there were no significant effects on the method of measurement or choice of four- or six-segments as seen in Table V and Figure 7.

Table IV. All pairwise comparisons of least squares means of arch length, in millimetres.

	Measurement methods	Arch length estimated difference	SE	*p*
Lower	C, 4-segments v C, 6-segments	-0.61	0.239	**0.012**
	C, 4-segments v M, 4-segments	1.75	0.240	**<0.000**
	C, 4-segments v M, 6-segments	0.22	0.239	0.3582
	C, 6-segments v M, 4-segments	2.36	0.240	**<0.000**
	C, 6-segments v M, 6-segments	0.83	0.239	**0.000**
	M, 4-segments v M, 6-segments	-1.53	0.240	**<0.000**
Upper	C, 4-segments v C, 6-segments	0.00	0.214	0.984
	C, 4-segments v M, 4-segments	0.95	0.215	**<0.000**
	C, 4-segments v M, 6-segments	1.30	0.214	**<0.000**
	C, 6-segments v M, 4-segments	0.95	0.215	**<0.000**
	C, 6-segments v M, 6-segments	1.29	0.214	**<0.000**
	M, 4-segments v M, 6-segments	0.35	0.215	0.109

C, computer method
M, manual method
Statistically significant values in bold

Discussion

We found that measurements of tooth size and arch length from digital models were consistently larger than the same measurements taken from plaster models. These findings agree with other studies,[17,19] although Santoro[16] found that measurements from digital models were smaller than those made directly from plaster models with calipers. We sent the plaster models to be scanned rather than mailing impressions, which may undergo dimensional changes and may be responsible for the consistently smaller measurements Santoro reported.[16] However, others have reported that the distortion of impression materials added little to the errors associated with measurements of the teeth on digital models.[13]

We consider that the accuracy of measurements taken from both plaster models and digital models appears to be excellent. Measurements from both sources could be used to assess the irregularity index and for space analysis: there was no suggestion of any kind of bias. The ICC findings given in Table III show excellent repeatability for both methods of measurement. In our study the accuracy of the measurements taken from the digital models is consistent with the accuracy reported in other studies.[13,16–19] We used the ICC to measure repeatability because the Pearson's correlation coefficient does not account for differences in absolute differences between different patients and this may introduce bias.

We found differences in the TALD measurements taken from the plaster models, particularly when the four-segment method was used on the lower models. Manual measurements in the lower arch were slightly smaller than the computer measurements, and the difference between the manual and computer measurements was larger with the four-segment analysis as compared with the six-segment analysis (Table V, Figure 5). The difference between the six-segment data for the manual and computer methods was not statistically significant. Irrespective of the method of measurement, the six-segment analyses were significantly more consistent than the four-segment analyses.

There were no statistically significant differences between the computer and manual methods of measurement and the four- and six-segment analyses of the upper models (Table V). The two computer measurements were more consistent than the manual measurements. The four significant findings in the lower models may be due to the finding that the lower arches were more crowded, relative to the total arch circumference, than the upper arches. Any shortcomings in measuring the TALD appear to be limited to the lower model. Measurements of the lower models may be complicated by a significant curve of Spee, slightly greater TALD and shorter overall arch length compared with the upper arch. It could be postulated that small variations in TALD

Table V. All pairwise comparisons of least squares means of TALD, in millimetres.

	Measurement methods compared	TALD estimated difference	SE	*p*
Lower	C, 4-segments v C, 6-segments	-0.61	0.229	**0.009**
	C, 4-segments v M, 4-segments	1.19	0.230	**<0.000**
	C, 4-segments v M, 6-segments	-0.35	0.229	0.130
	C, 6-segments v M, 4-segments	1.80	0.230	**<0.000**
	C, 6-segments v M, 6-segments	0.26	0.229	0.261
	M, 4-segments v M, 6-segments	-1.54	0.230	**<0.000**
Upper	C, 4-segments v C, 6-segments	-0.00	0.217	0.985
	C, 4-segments v M, 4-segments	-0.19	0.219	0.380
	C, 4-segments v M, 6-segments	0.17	0.217	0.434
	C, 6-segments v M, 4-segments	-0.19	0.219	0.390
	C, 6-segments v M, 6-segments	0.17	0.217	0.422
	M, 4-segments v M, 6-segments	0.36	0.219	0.099

C, computer method
M, manual method
Statistically significant values in bold

will have greater relative impact on the shorter lower arch length and to some extent the curve of Spee may compensate for this difference. We also found that arch length was difficult to measure with the four-segment approach on the lower models because the lower models were difficult to orientate.

It has been suggested that statistically significant differences between measurements using digital and plaster models should not influence treatment planning decisions.[13,18,20] In a study of 200 case assessments with digital and plaster models 43 cases were considered for extraction. Of the 43 cases, 18 came from measurements made on digital models and 25 from measurements made on plaster models. The overall proportions of agreement ranged between approximately 77 per cent and 87 per cent for digital/plaster models. These findings were not considered to be statistically significant and/or the study was not large enough to attain sufficient statistical power.[20] On one hand, it could be argued that variations of 1–2 mm in the tooth size–arch length discrepancy fall within the range of measurement errors and should not affect treatment planning decisions, but on the other hand 1–2 mm in a borderline extraction case may tip the scale towards either an extraction or a nonextraction treatment plan.

The lower arch acts as a template for both the establishment and maintenance of upper arch alignment.[28,29] Significant efforts have also been directed to explain changes in lower incisor alignment in both untreated and treated subjects.[23,30,31] Reliable and accurate measurement of lower arch length is therefore critical. Because of the importance of the lower arch to diagnosis and shortcomings in the four-segment method of measuring arch length, we recommend that the six-segment analysis is used because it more accurately reflects the curve of the dental arch. Digital models offer a convenient and cost-effective method for recording, measuring and storing study models. Small differences between manual and computer measurements of arch length and tooth size were not considered to be clinically significant.

Conclusions

Accurate and valid measurements of the irregularity index, tooth size and arch length can be made on digital models.

Small, but statistically significant, differences between manual measurements on traditional study models and computer-aided measurements on digital models were found. The computer-aided measurements of the TALD were more consistent than manual measurements of TALD on plaster models. These differences were not considered to be clinically significant.

The six-segment analysis of dental arch length was more accurate than the four-segment analysis,

particularly when plaster study models were measured manually with digital calipers. Differences between the six-segment and four-segment analyses may not be clinically significant.

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