Dental crowding: a comparison of three methods of assessment

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SUMMARY This study was designed to explore a new method for the assessment of dental crowding from study models, which would be both valid and reproducible. This was then tested against two previously reported strategies.

A single examiner compared the following methods: visual examination, brass wire/ callipers, and a reflex microscope with its customized computer program. Sixty study models (30 maxillary and 30 mandibular) were measured using each technique on two separate occasions.

The results showed the reflex microscope method to be the most reproducible, followed by the visual examination and brass wire methods. When testing for validity, as there is no absolutely accurate standard of arch measurement, the individual methods must be compared with one another. From the results, it was seen that the mean values for dental crowding using the reflex microscope, in both the upper and lower arches, were very close to a value which equalled the average obtained from the two means of the visual examination and brass wire methods. The results also indicated that the visual examination and brass wire methods showed a positive bias towards over- and underestimating the degree of crowding, respectively.

Introduction

Correct alignment of teeth is a fundamental goal of orthodontic treatment. The accurate assessment of dental crowding and the space required to alleviate it is critical for correct orthodontic diagnosis and treatment planning. An index of crowding would also be helpful in other respects: public health programmes, epidemiological studies and any description of post-treatment changes that rely on the ability to monitor precisely arch alignment (Little, 1975). Furthermore, a valid and reproducible index of crowding would prove useful for audit and research purposes.

The degree of crowding within the arch is determined by subtracting the space required from the space available and may be expressed directly in millimetres or by means of a crowding index.

Crowding may be quantified in one of two ways:

1. A simple analysis, that is, a measure of the degree of labio-lingual displacement of any slipped contact points. Variations of this method have been described by different workers (Barrow and White, 1952; Moorrees and Reed, 1954; Van Kirk and Pennell, 1959; Poulton and Aarronson, 1961; Richardson, 1965; Buckley, 1972; Little, 1975; Norderval *et al.*, 1975; Richmond, 1987). Many of these were originally based on attempts to quantify mandibular anterior crowding, but have been subsequently adapted for full arch assessment.

2. Arch length analysis, that is, a measurement of the discrepancy between total tooth size (the sum of the mesio-distal widths of all the teeth within the arch) and the space available (arch perimeter). This technique has been used by the majority of workers for quantifying dental crowding. Arch perimeter has been recorded from study models in a variety of ways, which have included the use of brass

or multistrand wire (Nance, 1947; Carey, 1958; Huckaba, 1964; Hart, 1988), straight-line segments (Moorrees and Reed, 1954; Lundström, 1955), indirect arch wire techniques (Beazley, 1971; White, 1977), the arcogramme (Herren *et al.*, 1973), cateno-meter (Musich and Ackerman, 1973) and photographic enlargements (Betteridge, 1976). More recently, various workers have designed computer programs to be used in association with electronic digitization (Burstone, 1979; Rudge, 1982; Howe *et al.*, 1983), the reflex metograph (Richmond, 1987; Jones and Richmond, 1989) or the application of chosen mathematical formulae (Pepe, 1975; Richards *et al.*, 1990).

Individual tooth widths have also been recorded by a variety of methods, which have included the use of callipers (Norderval *et al.*, 1975; Hart, 1988), microscope (Herren *et al.*, 1973), travelling microscope (Bhatia and Harrison, 1987) and reflex metrograph (Richmond, 1987).

The use of an arch length analysis method is, however, associated with a number of problems. Whilst accurate measurement of mesio-distal tooth widths is relatively easy, the determination of arch perimeter is not (Herren *et al.*, 1973; Adkins *et al.*, 1990). There have been two major limiting factors in measuring the available arch perimeter. The first involves problems of accuracy and validity, which are intimately related to dental arch form. Until more is known about the factors that are responsible for determining and maintaining arch form, it will not be possible to forecast accurately which arch shape is best suited for an individual, thus the use of pre-formed arches brings into question the validity of the method. The second problem is one of reliability; as there is a large amount of subjective judgement involved, the method for estimating arch perimeter should be highly reproducible. Reduction of the curved arch perimeter to straight-line segments invariably underestimates the space available (Bjerregaard *et al.*, 1980; Adkins *et al.*, 1990). If a brass wire, flexible ruler or digitizing cursor is used, the

outcome is heavily dependent upon the exact bucco-lingual position traced.

The use of a simple crowding analysis attempts to overcome the major limiting factors in measuring arch perimeter highlighted above; however, with the exception of Little's Ir-regularity Index (1975), the technique has been criticized for not offering a truly quantitative scoring method. The method described by Little (1975), which records the degree of labio-lingual displacement of any slipped contact points, is associated with a tendency to assign an unusually high score to cases involving severe labio-lingual displacement of one or more anterior teeth (Harris *et al.*, 1987). The concept of recording crowding by measuring tooth overlap in the mesio-distal direction described briefly by Norderval *et al.* (1975) does not seem to have been followed up, despite the fact that this method most accurately describes the crowding phenomenon. In the assessment of dental crowding, although the need for a valid and reproducible method has been acknowledged (Musich and Ackerman, 1973), it would appear that none of the reported techniques has been tested in this respect.

The aim of the present study was, therefore, to explore a new method for the assessment of dental crowding, which would be both valid and reproducible. Crowding was measured without the need to record arch perimeter, using a reflex microscope and customized computer program based on the concept of determining the mesio-distal overlap between adjacent teeth in the arch. This was then tested against two previously reported methods, one involving a simple analysis and the other an arch length analysis, for the assessment of dental crowding.

Materials and methods

Materials

Maxillary and mandibular dental study casts of 30 subjects were selected from patients awaiting orthodontic treatment. These fulfilled the following criteria. (i) Both study casts were of good quality and showed varying degrees of crowding, rotations and bucco-lingual displace-ments. In some instances, tooth eruption was

incomplete due to crowding and in others primary molars were retained, either uni- or bilaterally. (ii) No previous orthodontic treatment had been undertaken.

Method

Sixty study models (30 maxillary, 30 mandibular) were measured by a single examiner (A.S.J.) twice, by each of the three methods of measurement. After an initial training period in each of the techniques, repeat measurements were performed after an interval of 2 weeks.

Three methods of measuring dental crowding were compared.

Visual estimation. Visual estimation of the degree of crowding was made, using a clear ruler, with a millimetre scale. The amount of crowding was assessed by measuring the discrepancy, in millimetres, between the space available in the arch between the contact points of adjacent teeth and the mesio-distal width of the displaced tooth, taking care to conform to the individual's arch form.

Brass wire/calliper method (Carey, 1958; Huckaba, 1964). A brass wire of 0.5 mm diameter was contoured to lie over the incisal edges of the anterior teeth and the centres of the contact areas of the teeth in the buccal segments. The site where the wire crossed the distal contact point of the first permanent molars was marked. The arch perimeter was then measured between these marks. The individual mesio-distal widths of the teeth (first permanent molar to first permanent molar, inclusive) were measured between the mesial and distal contact points using dividers. From the sum of the tooth widths in each arch and the recorded arch perimeter, the arch length discrepancy was calculated.

The reflex microscope and customized computer program. Tooth widths were measured directly using a reflex microscope interfaced to an IBM compatible personal computer, in which only the mesial and distal contact points, from the first permanent molar to first permanent molar inclusive, were recorded. No attempt was made to record arch perimeter directly; the latter was calculated by the computer program from the

Table 1 Dahlberg error associated with measurement of the upper and lower arches (mm).

Variable	Visual examination	Brass wire/ callipers	Reflex microscope
Upper			
Total tooth width	–	0.9	–
Arch perimeter	–	1.3	1.1
Dental crowding	1.2	1.6	0.8
Lower			
Total tooth width	–	1.0	–
Arch perimeter	–	1.0	0.8
Dental crowding	0.9	1.5	1.0

total tooth width minus the mesio-distal overlaps between adjacent teeth. From this calculation, the amount of crowding in each arch was expressed in millimetres. Precise details on the calculation of dental crowding from the overlap method have been reported previously (Johal, 1995; Battagel, 1996).

Statistical analysis

The means of the two series of recordings were determined, for each of the three methods used, and their standard deviations and ranges calculated. The random error (Table 1) was calculated using Dahlberg's formula (Dahlberg, 1940). Systematic error (Table 2) was tested using a paired *t*-test, at the 10 per cent level of significance, as recommended by Houston (1983). The intra-examiner reproducibility of the first and second series of readings, for measurement of arch perimeter and dental crowding, were also evaluated by calculating Pearson *r* correlation coefficients (Table 3). When testing the validity of the three methods used to determine the degree of dental crowding, a standard is needed against which to compare the results. As there is no absolutely accurate standard of arch measurement, the individual methods were compared with one another.

Results

The error of measurement

Random error (Table 1). From the random error associated with the measurement of arch perimeter, comparing the use of brass wire and the reflex microscope, there appears to be little difference in the results, both having a large error (greater than 1.0 mm).

The random error associated with the measurement of dental crowding shows that, in the upper arch, the value obtained was approximately doubled when using the brass wire/callipers compared with the reflex microscope. Visual examination revealed a random error which was exactly mid-way between the values obtained by the other two techniques. A smaller difference was seen for the measurement of dental crowding in the lower arch, with the visual examination method being associated with the lowest random error.

Systematic error (Table 2). The systematic error demonstrated differences that were most apparent between the upper and lower arch measurements. There was significant systematic error associated with recording both arch perimeter and dental crowding in the upper arch, when using the reflex microscope, which was not present with the brass wire/calliper method. In the lower arch, however, there was no significant error associated with the measurement of arch perimeter or dental crowding with the reflex microscope or the visual examination methods, but there was significant error in using the brass wire/calliper technique.

Pearson correlation coefficients (Table 3)

The measurement of dental crowding. A similar pattern was evident for both the upper and lower dental arches. The reflex microscope showed the highest correlation coefficients (0.97 mm upper arch; 0.92 mm lower arch), visual examination was associated with lower values (0.92 mm upper arch; 0.90 mm lower arch), whilst the brass wire/calliper method demonstrated the lowest values (0.84 mm upper arch; 0.83 mm lower arch).

Table 2 Systematic error, determined by a paired *t*-test, at the 10 per cent level of significance.

Variable	Visual examination	Brass wire/ callipers	Reflex microscope
Upper arch perimeter	–	0.63 n.s.	2.25 sig.
Upper dental crowding	–1.86 sig.	0.48 n.s.	3.52 sig.
Lower arch perimeter	–	0.59 n.s.	–1.38 n.s.
Lower dental crowding	0.2 n.s.	1.76 sig.	1.44 n.s.

n.s represents a non-significant *t*-value ; sig. represents a significant *t*-value.

Table 3 Pearson correlation coefficients for the measurement of dental crowding and arch perimeter (mm).

	Visual examination	Brass wire/ callipers	Reflex microscope
Dental crowding			
Upper arch	0.92	0.84	0.97
Lower arch	0.90	0.83	0.92
Arch perimeter			
Upper arch		0.95	0.97
Lower arch		0.96	0.96

The measurement of arch perimeter. The correlation coefficients for measurement of arch perimeter by the brass wire and reflex microscope methods were more closely related. In the upper arch, the reflex microscope proved to be only slightly more reproducible ($r = 0.97$) than the brass wire technique ($r = 0.95$). In the lower arch, however, both methods proved to be equally reproducible, with a correlation coefficient of 0.96.

Statistical results

Arch perimeter (Table 4). Table 4 illustrates that the mean values obtained for arch perimeter, recorded by the brass wire method (upper arch, 98.1 mm; lower arch, 87.4 mm) were higher than those values obtained from the reflex microscope (upper arch, 94.1 mm: lower arch,

Table 4 Mean values for arch perimeter, for both upper and lower arches (mm).

Method	Minimum	Mean ± SD	Maximum
Upper brass wire	87.0	98.1 ± 6.4	109.5
Upper reflex microscope	83.2	94.1 ± 5.7	106.4
Lower brass wire	77.5	87.4 ± 4.6	97.0
Lower reflex microscope	76.0	84.9 ± 5.2	99.9

Table 5 Mean values for dental crowding, for both upper and lower arches (mm).

Method	Minimum	Mean ± SD	Maximum
Upper visual examination	0.8	8.2 ± 3.7	13.8
Upper brass wire/callipers	−4.8	4.5 ± 4.2	11.5
Upper reflex microscope	−0.9	6.3 ± 4.1	14.3
Lower visual examination	2.8	7.4 ± 3.0	15.5
Lower brass wire/callipers	1.3	6.2 ± 3.5	17.5
Lower reflex microscope	2.0	6.8 ± 3.4	16.1

84.9 mm). Paired t-tests were used to compare the mean arch perimeter measurements obtained from the use of the brass wire and reflex microscope, for both arches; no difference was found.

Dental crowding (Table 5). Table 5 summarizes the mean values obtained for dental crowding in both the upper and lower dental arches. The visual examination method recorded the highest mean values (upper arch, 8.2 mm; lower arch, 7.4 mm) whereas the brass wire/calliper method was associated with the lowest mean value for crowding (upper arch, 4.5 mm; lower arch, 6.2 mm). A one-way analysis of variance was used to compare the mean crowding values, obtained by the different measuring methods, which were shown to be statistically significant.

Discussion

Limitations of the study

The limitation of a single examiner comparing three methods of measurement for the assessment of dental crowding is that, in the presence of a significant systematic error, care is then needed in extrapolating these findings and making generalized conclusions. However, the potential advantage of a single operator undertaking the study is that the intra-observer error is likely to be smaller than the inter-observer error, as all the measurements are undertaken with the same objective in mind, avoiding the problem of multiple operators each with their own interpretations.

Comparison of the reflex microscope with other techniques

It was interesting to see that the reflex microscope method recorded a mean value for dental crowding which in the upper arch was just below the average for the other two techniques (mean value 6.3 mm) and in the lower arch was equal to the average value (mean value 6.8 mm).

Table 5 illustrates that certain cases recorded spacing (negative values) in the arch with the brass wire/calliper and reflex microscope methods, whereas the visual examination of these cases recorded crowding. This suggested that the visual examination of dental casts showed some positive bias towards over-recording the amount of crowding present.

It was also apparent that the brass wire/calliper method tended to under-record the degree of crowding, compared with the other two techniques. This is evidenced by the fact that a greater number of cases were recorded as showing spacing in the arch and that the results of upper arch perimeter recordings by the brass wire method were associated with higher values compared with those obtained with the reflex microscope (Table 4).

The reflex microscope with its customized computer program was used to determine the degree of dental crowding, in order to overcome some of the potential problems which exist with both the simple crowding and arch length analysis methods previously described in the literature, and with a view to addressing the

question of the need for validity of the technique (Musich and Ackerman, 1973).

Measurement of arch perimeter. There are two major limiting factors in measuring available arch perimeter. The first involves problems of accuracy and validity, which are intimately related to the dental arch form. The second limiting factor is one of reliability as the method for estimating arch perimeter should be highly reproducible.

With the reflex microscope's computer program, no attempt was made to record arch perimeter directly: this overcomes the potential drawback of the brass wire/calliper method. In the latter method, the degree of dental crowding is calculated by subtracting the sum of the total tooth widths (space required) from the arch perimeter (space available). The reported limitation of the brass wire method is summed up by Huckaba (1964), 'in cases in which the teeth are badly crowded or overlapped, the mean arch alignment is used'. This means that the examiner must use individual judgement in the determination of this mean alignment which, in turn, is related to the interpretation of the arch form presented by the individual case. However, the greater the crowding the more the arch form is obscured. This may offer a possible explanation as to why the mean arch perimeter masurements in both upper and lower arches were consistently higher than those recorded by the reflex microscope (Tables 3 and 4). Musich and Ackerman (1973) and Rudge *et al.* (1983) also found that mean arch perimeter values were higher with the brass wire method when compared with the means obtained from the use of the catenometer and the direct electronic digitization of study models, respectively.

Richmond (1987), Jones and Richmond (1989) and Jones (1990), in examining the fit of a computer-generated parabolic curve to assess dental crowding, reported that there was some positive bias towards recording space or reduced crowding in pre-treatment cases. In addition, a great variation as regards reproducibility between observers and duplicate measurements was reported, with the authors expressing reservations regarding the use of symmetrical curves in the assessment. Thus, the advantages of

a technique which does not employ direct arch perimeter measurement become apparent.

Measurement of individual tooth widths. The reflex microscope technique overcomes many of the potential disadvantages of using a pair of callipers, as with the brass wire method, or a clear ruler in the visual examination technique, but does involve the identification of many individual points on the model, with its attendant errors.

The determination of dental crowding. The reflex microscope approach calculates the degree of crowding from only one measurement, that is, the distance between pairs of contact points. In contrast, the other two methods both require two separate measurements, in order to calculate the arch discrepancy. This offers a possible explanation as to why higher error values were associated with the visual and brass wire/calliper recordings.

Other potential advantages. In cases presenting with deciduous predecessors, unerupted or partially erupted permanent teeth, the recording of the maximum mesio-distal tooth width becomes inaccurate. The reflex microscope, with its customized computer program, is designed to overcome this problem by calculating a value for the unerupted tooth from a table of mesio-distal widths (independently for males and females) based on the figures reported by Moyers *et al.* (1976).

Possible problems associated with the reflex microscope technique

1. The reflex microscope is expensive and a suitable computer program must be devised
2. If the teeth are severely tilted, for example mesially or distally angulated to any significant degree, the maximum mesio-distal width is difficult to record. The reason for this is that the model is rigidly clamped to a fixed, horizontal microscope base, which ideally needs to be movable to focus normally to each tooth.

The use of the reflex microscope and the customized computer program in the assessment

of dental crowding is not intended for routine clinical use, but is likely to be of benefit primarily for research and audit purposes, where such a method can provide more sophisticated information about the occlusion.

The visual technique

The potential drawbacks which exist for the use of a visual examination in the estimation of the degree of dental crowding include the following.

1. A high degree of subjective assessment is involved in the technique.
2. There is error associated with the recording of the mesio-distal widths of displaced teeth and the measurement of the space available between adjacent teeth in the arch. This error arises not only as a result of the potential inconsistency of landmark identification (the mesial and distal contact points of the teeth), but also as a result of the limited accuracy of the millimetre ruler being used, which is no greater than 0.5 mm.
3. The dental arch is curved and the use of straight-line ruler measurements in the assessment of the available space in the arch will reflect less space than is actually present. This may explain why the visual examination revealed consistently higher mean values for the degree of dental crowding than the other two methods.

Despite the fact that the visual estimation of dental crowding has been shown to have many potential limitations, the results of this study are quite encouraging. The visual examination method showed a range of 4 mm for the case with the greatest disagreement, between the first and second series of measurements, with the closest case showing perfect agreement. These results compare favourably with those reported by Beazley (1971), in which the respective ranges were 5.5 and 2.5 mm. The overall impression was that the visual examination method, despite being highly reproducible, showed a tendency to overestimate the degree of dental crowding, the mean values for dental crowding being higher than those obtained by the other two methods.

The brass wire/calliper method

In the assessment of arch length discrepancy using the brass wire/calliper method, a range of 6 mm was seen for the case with the greatest disagreement, between replicate measurements. Such a large variation was thought to be mainly the result of the operator's evaluation of the 'mean' arch form. The case that presented with the greatest agreement showed a range of 0.5 mm. These results compare favourably with those reported by Beazley (1971), in which the respective ranges were 12.5 mm (greatest disagreement) and 5.5 mm (greatest agreement), and Rudge et al. (1983), in which the respective ranges were 9.3 and 0.6 mm. The present study showed a high degree of reproducibility in the measurement of arch perimeter using brass wire. It was likely that the measurement of arch perimeter was more reproducible than the measurement of dental crowding because estimating the latter involves determining each individual tooth width. This may be associated with an error of up to 0.5 mm (the smallest increment on the ruler), and this error becomes a significant proportion of the total, given that the average tooth width is approximately 7 mm. In determining arch perimeter, an error in measurement of 0.5 mm is not as significant given that even the smallest arch was recorded as being over 80 mm. It would therefore appear that the measurement of dental crowding by the brass wire/calliper method showed a tendency to underestimation, attributable mainly to the large mean arch perimeter recordings obtained and poor reproducibility.

Conclusions

1. The reflex microscope and its customized computer program provides a valid and reproducible measure of dental crowding.
2. Visual examination of study casts shows some positive bias towards over-recording the amount of crowding.
3. The brass wire method is associated with a positive bias towards recording space or a reduction in crowding.

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References

Adkins M D, Nanda R S, Currier S C 1990 Arch perimeter changes in rapid palatal expansion. American Journal of Orthodontics and Dentofacial Orthopedics 97: 194–199

Barrow G, White J 1952 Developmental changes of the maxillary and mandibular dental arches. Angle Orthodontist 22: 41–46

Battagel J M 1996 The assessment of crowding without the need to record arch perimeter. Part I: Arches with acceptable alignment. British Journal of Orthodontics 23: 137–144

Beazley W W 1971 Assessment of mandibular arch length discrepancy utilizing an individualised arch form. Angle Orthodontist 41: 45–54

Betteridge M A 1976 Index for measurement of lower labial segment crowding. British Journal of Orthodontics 3: 113–116

Bhatia S N, Harrison V E 1987 Operational performance of the travelling microscope in the measurement of dental casts. British Journal of Orthodontics 14: 147–153

Bjerregaard J, Bundgaard A M, Melsen B 1980 The effect of the mandibular lip bumper and maxillary bite plate on tooth movement, occlusion and space conditions in the lower dental arch. European Journal of Orthodontics 2: 257–265

Buckley L A 1972 Relationship between malocclusion and periodontal disease. Journal of Periodontology 43: 415–417

Burstone C J 1979 The uses of computers in orthodontic practice (Part 2). Journal of Clinical Orthodontics 13: 539–551

Carey C W 1958 Treatment planning and the technical program in the four fundamental treatment forms. American Journal of Orthodontics 44: 887–898

Dahlberg G 1940 Statistical methods for medical and biological students. Interscience Publications, New York

Harris E F, Vaden J L, Williams R A 1987 Lower incisor space analysis: A contrast of methods. American Journal of Orthodontics and Dentofacial Orthopedics 92: 375–380

Hart A J 1988 Mandibular second permanent molar extraction: effect on lower incisors. MSc Thesis, University of London

Herren P, Schmoker R, Jordi T 1973 Arch shape and space balance determined by arcogramme technique. Transactions of the European Orthodontic Society, pp. 61–73

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

Howe R P, McNamara J A, O'Connor K A 1983 An examination of dental crowding and its relationship to tooth size and arch dimension. American Journal of Orthodontics 83: 363–373

Huckaba G W 1964 Arch size analysis and tooth size prediction. Dental Clinics of North America: 431–440

Johal A S 1995 Dental crowding a comparison of three methods of assessment. MSc Thesis, University of London

Jones M L 1990 The Barry Project—a further assessment of occlusal treatment change in a consecutive sample: Crowding and arch dimensions. British Journal of Orthodontics 17: 269–285

Jones M L, Richmond S 1989 An assessment of the fit of a parabolic curve to pre- and post-treatment dental arches. British Journal of Orthodontics 16: 85–93

Little R M 1975 The irregularity index: a quantitative score of mandibular anterior alignment. American Journal of Orthodontics 68: 554–563

Lundström A 1955 Early loss of deciduous teeth in the aetiology of malocclusion. American Journal of Orthodontics 41: 819–826

Moorrees C, Reed B 1954 Biometrics of crowding and spacing of the teeth of the mandible. American Journal of Physiological Anthropology 12: 77–88

Moyers R E, Van der Linden F P G M, Riolo M L, McNamara J A 1976 Standards of human occlusal development. Monograph No. 5, Craniofacial Growth Series, Center for Human Growth and Development, University of Michigan, Ann Arbor, pp. 45

Musich D R, Ackerman J A 1973 The catenometer: a reliable device for estimating dental arch perimeter. American Journal of Orthodontics 63: 366–375

Nance H N 1947 Limitations of orthodontic treatment—II. American Journal of Orthodontics and Oral Surgery 33: 253–301

Norderval K, Wisth P J, Bøe O E 1975 Mandibular anterior crowding in relation to tooth size and craniofacial morphology. Scandinavian Journal of Dental Research 83: 267–273

Pepe S H 1975 Polynomial and catenary curve fits to human dental arches. Journal of Dental Research 54: 1124–1132

Poulton D R, Aarronson S A 1961 Relationship between occlusion and periodontal status. American Journal of Orthodontics 47: 690–699

Richards L C, Townsend G C, Brown T, Burgess V B 1990 Dental arch morphology in South Australian twins. Archives of Oral Biology 35: 983–989

Richardson M E 1965 The relationship between the relative amount of space present in the deciduous dental arch and the rate and degree of space closure susequent to the

extraction of a deciduous molar. Dental Practitioner 16: 111–118

Richmond S 1987 Recording the dental cast in three dimensions. American Journal of Orthodontics and Dentofacial Orthopedics 92: 199–206

Rudge S J 1982 A computer program for the analysis of study models. European Journal of Orthodontics 4: 269–273

Rudge S J, Jones P T, Hepenstal S, Bowden D E J 1983

The reliability of study model measurement in the evaluation of crowding. European Journal of Orthodontics 5: 225–231

Van Kirk L E, Pennell E H 1959 Assessment of malocclusion in population groups. American Journal of Orthodontics 45: 752–758

White L W 1977 Accurate arch discrepancy measurements. American Journal of Orthodontics 72: 303–308