

Tooth-size Discrepancy and Bolton's Ratios: a literature review

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Objectives: To review the literature on Bolton's tooth-size discrepancies (TSD) with specific attention to the prevalence of TSD, and the possible influence of different classes of malocclusion, gender and racial group. Also examined were the validity of the standard deviations from Bolton's samples as an indicator of significant TSD, methods of measurement of TSD and their reproducibility. Based on the review, suggestions are made as to how future work could be improved.

Results and conclusions: Studies have reported from 20 to 30% of people with significant tooth-size anterior discrepancies and 5–14% for overall TSD. Bolton's original sample was appropriate for indicating what ratio is most likely to be associated with an excellent occlusion, but was not suited to indicating the size or prevalence of significant TSD. Most studies use samples that are not likely to be representative of orthodontic patients in the UK or, indeed, elsewhere. Although some statistically significant differences have been reported, gender and racial group seem unlikely to have a clinically significant influence on Bolton's tooth-size ratios. Class III malocclusions may have larger average ratios. Computerized methods of measurement are significantly more rapid. Most studies performed or reported their error analysis poorly, obscuring the clinical usefulness of the results. Studies are needed to properly explore the reproducibility of measurement of TSD and to appropriately determine what magnitude of TSD is of clinical significance.

Key words: Bolton's ratios, literature review, tooth-size discrepancy

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Introduction

A tooth-size discrepancy (TSD) is defined as a disproportion among the sizes of individual teeth.¹ In order to achieve a good occlusion with the correct overbite and overjet, the maxillary and mandibular teeth must be proportional in size. The mesio-distal widths of teeth were first formally investigated by G.V. Black² in 1902. He measured a large number of human teeth and set up tables of mean dimensions, which are still used as references today.

Many authors^{3–6} studied tooth width in relation to occlusion following Black's investigation. The best-known study of tooth-size disharmony in relation to treatment of malocclusion was by Bolton⁷ in 1958. He evaluated 55 cases with excellent occlusions. Bolton developed 2 ratios for estimating TSD by measuring the summed mesio-distal (MD) widths of the mandibular to the maxillary anterior teeth (Figure 1).

The data from this sample were then used to indicate the deviation from the ideal of any measured ratio and thus the size of the discrepancy. Bolton concluded that these ratios should be 2 of the tools used in orthodontic diagnosis, allowing the orthodontist to gain insight into the functional and aesthetic outcome of a given case

without the use of a diagnostic setup. In a subsequent paper, Bolton⁸ expanded on the clinical application of his tooth size analysis. Bolton's standard deviations from his original sample have been used to determine the need for reduction of tooth tissue by interdental stripping or the addition of tooth tissue by restorative techniques.

Smith *et al.*⁹ stated that specific dimension relationships must exist between the maxillary and mandibular teeth to ensure proper interdigitation, overbite and overjet. Within certain limits, this would seem self-evident, yet amongst orthodontists, opinions vary widely concerning the frequency of significant TSD and the need to measure it in clinical practice.

This review therefore aims:

- to review the literature on Bolton's TSD with specific attention to the prevalence of TSD;
- to review the influence of different classes of malocclusion, gender and of racial group;
- to examine the validity of the standard deviations from Bolton's samples as an indicator of significant TSD;
- to examine methods of measurement of TSD and their reproducibility.

$$\text{Overall ratio} = \frac{\text{Sum of MD widths of mandibular 12 teeth (first molar – first molar)}}{\text{Sum of MD widths of maxillary 12 teeth (first molar – first molar)}} \times 100$$

$$\text{Anterior ratio} = \frac{\text{Sum of mandibular anterior 6 teeth}}{\text{Sum of maxillary anterior 6 teeth}} \times 100$$

Figure 1 Bolton's ratios for estimating TSD

Suggestions are made as to how future work could be improved.

Methods and materials

Ideally a formal, 'Cochrane-type' systematic review would have been undertaken. However, this was not possible due to the very varied approach applied to this subject by previous authors; hence, only a systematic style could be adopted at this stage.

Search mechanisms and inclusion criteria

An electronic search using Medline was carried out using the following free-text terms: Bolton ratio, tooth-size discrepancy, Bolton discrepancy, tooth-size ratios and tooth-size measurement. In addition, a hand search was conducted in the *American Journal of Orthodontics* (now the *American Journal of Orthodontics and Dentofacial Orthopaedics*) from 1960 to 2005; the *Angle Orthodontist* from 1960 to 2005; the *European Journal of Orthodontics* from 1980 to 2005 and the *Journal of Orthodontics* (formerly the *British Journal of Orthodontics*) from 1973 to 2005. Only papers in English were included. The principal inclusion criteria were an investigation of prevalence of TSD or a quantitative investigation of the speed or reproducibility of a method of measurement of TSD. The independent searches by 2 persons produced 47 potential papers and a core of 31 were agreed by the 2 authors as meeting the criteria. Papers were commonly excluded because they reported measurement of tooth sizes, but not tooth-size discrepancy. Other papers on method of measurement were excluded because they described, but did not quantify a method in terms of speed or reproducibility. It was

considered helpful to refer to 2 papers in this review, in spite of such drawbacks.

Results

The prevalence of tooth-size discrepancies

The prevalence of TSD in the general population has been quoted as being 5%.¹ However, the basis for this figure was not explained and it appears to be defined as the proportion of cases that will fall outside 2 standard deviations from Bolton's mean ratios.

In 1989, Crosby and Alexander¹⁰ reported that 22.9% of subjects had an anterior ratio with a significant deviation from Bolton's mean (greater than 2 of Bolton's standard deviations). This is clearly a much higher figure than Proffit's 5%. They also noted that there was a greater percentage of patients with anterior TSD than patients with such discrepancies in the overall ratio. These findings are common to many investigations. Table 1 summarizes cardinal features of previous investigations of the prevalence of TSD. The percentages of patients with 'significant' TSD are those with Bolton ratios falling more than 2 of Bolton's standard deviations from Bolton's mean values, although later discussion in this paper will question the appropriateness of this common definition of significance.

In the study by Freeman *et al.*¹¹ it is noteworthy that the overall discrepancy was equally likely to be relative excess in the maxilla or the mandible, whereas the anterior discrepancy was nearly twice as likely to be a relative mandibular excess (19.7%) than a relative maxillary excess (10.8%). Santoro¹² and Araujo and Souki¹³ found similar prevalence values to Freeman.¹¹

Bernabě *et al.*¹⁴ studied TSD in 200 Peruvian adolescents with untreated occlusions. Importantly, this

Table 1 Summary of studies of the prevalence of tooth-size discrepancy

Author	Population	Sample size	% Anterior TSD	% Overall TSD
Crosby and Alexander ¹⁰	Orthodontic	109	22.9	–
Freeman <i>et al.</i> ¹¹	Orthodontic	157	30.6	13.5
Santoro <i>et al.</i> ¹²	Orthodontic	54	28.0	11.0
Araujo and Souki ¹³	Orthodontic	300	22.7	–
Bernabě <i>et al.</i> ¹⁴	School	200	20.5	5.4

sample was selected from a school, not from an orthodontic clinic, so may not have been representative of patients undergoing orthodontic treatment.

None of the studies in Table 1 or Table 2 was carried out on a sample from the UK and the results from each study may not apply in other countries. In spite of these reports of a relatively high incidence of TSD, a widespread subjective view amongst clinicians is that this is an infrequent problem in clinical practice. There are several potential reasons for this disparity in perception, which will be explained later.

Methods of measuring tooth-width for Bolton ratios and their reproducibility

It is important to have a method of measurement that is quick and easy to use if it is to be widely employed. Equally, no method of measurement is robust without good documentation of the reproducibility. The traditional methods of measuring mesio-distal widths of teeth on dental casts can be described as manual methods and have either employed needle-pointed dividers or a Boley gauge (Vernier callipers). In 1995, Shellhart *et al.*¹⁵ evaluated the reliability of the Bolton analysis when performed with these 2 instruments and also investigated the effect of crowding on measurement error. They found that clinically significant measurement errors could occur when the Bolton tooth-size analysis is performed on casts that have at least 3 mm of crowding, a factor that should lead clinicians to undertake a TSD analysis in substantially crowded cases only when the teeth have been aligned.

Recent technological advances have allowed the introduction of digital callipers, which can be linked to computers for rapid calculation of the anterior and posterior ratios and the required correction to produce Bolton's mean ratio. Alternatively, digitized or scanned

images of the study casts can be measured on-screen. Ho and Freer¹⁶ proposed that the use of digital callipers with direct input into the computer program can virtually eliminate measurement transfer and calculation errors, compared with analysis that requires dividers, rulers and calculators, although the same measurement error may be associated with the positioning of the callipers on the teeth. This is very analogous to the findings of investigations of manual and digitizer measurement of cephalometric lateral skull radiographs. However, a reproducibility study was not part of their paper.

Tomassetti *et al.*¹⁷ performed a study using manual measurements with a Vernier calliper and 3 computerized methods. Quick Ceph was the quickest method followed (in order) by HATS, OrthoCad and Vernier callipers. However, Quickceph gave results which gave the greatest mean discrepancy from Vernier callipers (although not statistically significant) and which were least correlated with the Vernier calliper results. Although these findings are helpful, the authors did not measure the reproducibility of each method by means of replicate measurements.

Zilberman *et al.*¹⁸ also compared the measurement using digital callipers with OrthoCAD. Measurement with digital callipers produced the most accurate and reproducible results, but these were not much improved relative to the results with OrthoCAD. Digital callipers seem to be a more suitable instrument for scientific work, but OrthoCAD's accuracy was considered clinically acceptable.

Arkutu¹⁹ evaluated commonly used means of assessing a Bolton's discrepancy to the gold standard, which was defined as the measurement with a Vernier calliper to 0.1 mm. Anterior and overall ratios were calculated using 4 methods:

Table 2 Summary of studies of TSD: statistically significant for gender, malocclusion and racial/ethnic differences in average TSD values

Author	Country	Gender difference	Malocclusion differences	Racial/ethnic differences
Sperry <i>et al.</i> ²¹	USA		Yes	
Crosby and Alexander ¹⁰	USA		No	
Nie and Lyn ²²	China	No	Yes	
Araujo and Souki ¹³	Brazil	No	Yes	
Ta <i>et al.</i> ²³	China		Yes	
Alkofide and Hashim ²⁴	Saudi Arabia	No	Yes	
Liano <i>et al.</i> ²⁵	Italy		No	
Uysal <i>et al.</i> ²⁶	Turkey		No	
Lavelle ²⁸	USA	Yes		Yes
Richardson and Malhotra ²⁹	USA	No		
Al-Tamimi and Hashim ³⁰	Saudi Arabia	No		
Smith <i>et al.</i> ⁹	USA	Yes		Yes

- ‘eyeballing’ (simply looking);
- a quick check by comparing the size of the laterals and second premolars;
- callipers and stainless steel ruler (0.5 mm);
- Vernier callipers (0.1 mm).

Sensitivity and specificity tests were performed and the study found that, when compared with actual measurement with callipers, these rapid, visual tests are poor at detecting a lack of Bolton discrepancy and very poor at correctly identifying a significant Bolton’s discrepancy. This may further explain the subjective clinical view that significant TSD is much less common than several studies have reported.

Some well-known studies of TSD did not report the measurement error at all¹¹. Crosby and Alexander,¹⁰ Araujo and Souki¹³ and Bernabě *et al.*¹⁴ reported very incomplete measurement of error. Houston²⁰ wrote that if any quantitative study is to be of value, it is imperative that such error analysis be undertaken and reported. The reproducibility of all these methods of measurement has not been adequately explored.

Tooth-size discrepancies in different classes of malocclusion

The variables: malocclusion type, gender and racial/ethnic group are summarized in Table 2. Sperry *et al.*²¹ demonstrated that the frequency of relative mandibular tooth size excess (for the overall ratio) was greater in cases of Angles Class III. Crosby and Alexander¹⁰ studied the prevalence of TSD among different malocclusion groups with between 20 and 30 subjects in each group. For the anterior ratio, 16.7% of the Class I patients had a significant discrepancy, whereas this figure was 23.4% in the Class II division 1 group. This difference is highlighted because it might be considered potentially significant, but in fact there were no statistically significant differences in the prevalence of TSD among the malocclusion groups. Nie and Lin²² conducted a study of this aspect of TSD in a sample of 360 cases. A significant difference was found for all the ratios between the malocclusion groups, showing that the anterior, posterior and overall ratios were all greatest in Class III and lowest in Class II. Araujo and Souki¹³ concluded that individuals with Angle Class III malocclusions had a significantly greater prevalence of TSD than did those with Class I individuals who, in turn, had a greater prevalence than those with Class II malocclusion. This statistically significant trend to larger ratios in Class III patients was also reported by Ta *et al.*²³ in a southern Chinese population and by Alkofide and

Hashim²⁴ in a Saudi population. Liano *et al.*²⁵ concluded that there was no association between TSD and the different malocclusion groups, but with only 13 subjects in their Class III group, statistically significant differences were improbable. The study by Uysal *et al.*²⁶ was interesting in that there were no differences between malocclusion types, but all malocclusion groups had significantly higher average ratios than the group of 150 untreated normal occlusions. This last group is exceptionally large, but is a rare feature of studies investigating TSD.

In summary, relative mandibular tooth excess was found in Class III malocclusions in 5 studies^{13,21–24} and relative maxillary excess in Class II malocclusion,²² whilst no significant differences were found by others.^{10,25,26} If the studies that found a larger ratio in Class III patients are valid and are measuring a degree of discrepancy that is also clinically significant, then this is an additional hurdle to overcome in correcting a Class III incisor relationship.

Tooth-size discrepancies and gender

Several studies have found that male teeth are larger than female teeth. Bishara *et al.*²⁷ is representative of these studies. They compared boys and girls within and between 3 populations from Iowa, Egypt and Mexico. Canines and molars were significantly larger in boys than in girls. Regrettably, however, the TSD ratios were not measured in this or in many other studies. It is important to note that the possibility of gender differences in TSD is different from differences in absolute tooth size. Lavelle²⁸ did compare maxillary and mandibular tooth-size ratios between males and females. He showed that the total and anterior ratios were both greater in males than in females. However, these sex differences were small, all being less than 1%. Richardson and Malhotra²⁹ found that the teeth of black North American males were larger than those of females for each type of tooth in both arches, but there were no differences in anterior or posterior inter-arch tooth-size proportions. Al-Tamimi and Hashim³⁰ also found no sexual dichotomy in Bolton ratios in a relatively small sample of 65 Saudi subjects. In contrast Smith *et al.*⁹ found that males had larger ratios than females. However, these differences (0.7% for overall ratio and 0.6% for anterior ratio) were small, being much less than 1 standard deviation from Bolton’s sample.

Most studies have therefore found no differences in the mean Bolton ratios between the sexes and in those studies which have found a difference, it has been small, with males having slightly larger ratios.

Tooth-size discrepancies and ethnic/racial groups

Bolton⁷ based his study upon a heterogeneous Caucasian population sample and, hence, provides no information relating to other racial groups. It has been suggested that TSD differs between various racial or ethnic groups. Studies are again summarized for their key findings in Table 2. Lavelle,²⁸ studied tooth-size and ratios in Caucasoids, Negroids and Mongoloids. These 3 terms for these racial groups are originally anthropological and are based on skull dimensions. They can be considered equivalent to the terms white, black and far eastern as used in many English-speaking countries. Both the overall and anterior average ratios were greater in Negroids than in Caucasoids, those for Mongoloids being intermediate. The subjects were chosen to have excellent occlusions, so the means are a good guide to the ideal mean ratio to give a good fit for a racial group.

A more recent study by Smith *et al.*⁹ on inter-arch tooth-size relationship of 3 populations found that whites displayed the lowest overall ratio (92.3%), followed by Hispanics (93.1%), and blacks (93.4%). The anterior ratio, however, was statistically significantly larger in Hispanics (80.5%) than blacks (79.3%). There appears to be a trend to larger overall ratios in black populations, but these differences are all relatively small. There have been few good studies of this potential factor.

Discussion of Bolton's sample

Bolton's⁷ original research was carried out on 55 cases with excellent occlusions. The use of cases with good occlusion is very appropriate for determining the average ratio associated with, and permitting, an excellent occlusion. However, it follows that it is not suitable for determining the size or prevalence of discrepancy that would rule out an excellent occlusion. This would explain the high proportion of orthodontic patients with ratios beyond 2 standard deviations of Bolton's mean ratios in Table 1. By definition, no case in Bolton's sample had a discrepancy that was sufficiently large to prevent a good occlusion in his estimation. It has been suggested that Bolton's mean ratios in general are more applicable to white females because the values subsequently found in this group most closely matched Bolton's ratios and a majority of orthodontic patients during the 1950s were from this group. The previous section in this review suggests that significant gender differences may not exist and that significant racial or ethnic differences may be small.

The effects of extraction

In his second paper, Bolton⁸ discussed the effect of premolar extraction on the overall ratio. Bolton correctly stated that premolar extraction would mathematically reduce the suggested overall mean ratio value of 91.3%. After the extraction of 4 premolars, patients in whom no TSD existed would have an overall mean ratio of 88%. Saatci and Yukay³¹ and Tong *et al.*³² both investigated whether the extraction of 4 premolars as a requirement of orthodontic therapy is a factor in the creation of TSD. Pre-treatment mesio-distal dimensions of mandibular and maxillary teeth were measured, recorded on a computer program and subjected to Bolton's analysis. They then performed hypothetical tooth extraction of all premolar combinations by computer on each patient. Their results are in agreement with the opinion expressed by Bolton⁸ that the removal of the larger mandibular second premolars often improves the overall Bolton ratio. This factor is not large, but may tip the balance in some extraction decisions.

What size of tooth-size discrepancy is of clinical importance?

Smith *et al.*⁹ stated that specific dimensional relationships must exist between the maxillary and mandibular teeth to ensure proper interdigitation, overbite and overjet at the end of orthodontic treatment. This much can be readily accepted, but the important question remains as to what size of discrepancy is clinically significant in making an acceptable occlusion unachievable unless tooth size is altered by interdental stripping or restorative addition.

Table 1 confirms that a significant percentage of any random or orthodontic population will have a discrepancy >2 of Bolton's standard deviations from Bolton's mean, especially for the anterior ratio. More fundamental than this is the question of the absolute size of discrepancy thought to be incompatible with an acceptable occlusal fit. Bernabě *et al.*¹⁴ chose 1.5 mm as their limit of acceptable discrepancy, quoting Proffit¹ and compared this figure of 1.5 mm with Bolton's standard deviations as thresholds for clinical significance. Approximately 30% of the sample had more than 1.5 mm overall arch discrepancy. This percentage is much larger than the figures for overall TSD in Table 1 and the authors concluded that the 2 standard deviation range from the Bolton mean, far from overestimating the prevalence of TSD, seriously underestimated the prevalence. However, a TSD of 1.5 mm is only 0.75 mm per side, and many clinicians would hesitate to add or

reduce tooth tissue for a problem of this size, especially for the overall arch estimation, and would reserve such measures for larger discrepancies. The use of Bolton's original standard deviations or a relatively modest absolute discrepancy, such as 1.5 mm may partially explain why the prevalence of discrepancies that are deemed to be significant in studies is much higher than the subjective view of many clinicians.

A potentially very interesting study into this question was carried out by Heusdens *et al.*³³ They evaluated the effect of the introduction of a deliberate TSD on a typodont occlusion. The typodonts were set up to produce the 'best' occlusion possible in the light of the extractions or deliberate introduction of TSD. Crucially, and perhaps understandably, the effect on occlusion was measured by the size of the PAR score achieved in the set-up. They reported that extraction therapy only slightly affected the PAR score of the final occlusion, which is to be expected. Much more surprisingly, they concluded that a TSD of 12 mm from Bolton's average could still permit a satisfactory occlusion as measured by PAR and that, therefore, TSD was not a real factor in the inability to produce a good occlusion. It is intuitive to believe that a discrepancy of 12 mm cannot permit a good occlusion by most standards. This study is an interesting and potentially informative approach, but probably reveals more about the potential insensitivity of the weighted PAR index than it does about the degree of TSD that is clinically significant. A better approach to validation of the threshold of significance might be to use the method of Heusdens *et al.*, but to use peer assessment, rather than the numerical PAR score to determine a view of the quality of resulting occlusion.

Tooth thickness is an additional aspect of tooth size, which can influence occlusal fit. Bolton⁸ pointed out that the ratio permitting an ideal occlusion would be influenced by the labio-lingual thickness. Rudolph *et al.*³⁴ investigated this and showed for example that Bolton's mean ratios were a better indicator of potential ideal occlusion if the maxillary incisors were thinner. Measurement of tooth thickness would be an additional complexity in any measurement of Bolton's ratios, but this factor may explain part of the range of ratio which can permit a good occlusion.

Conclusions

- The Bolton standard deviation is probably not a good guide to the prevalence of a clinically significant tooth-size discrepancy.
- Investigators should focus more on the actual size of the discrepancy, rather than the Bolton ratios alone.

The size of discrepancy that is clinically significant requires further investigation, but might appropriately be investigated by peer assessment, for example.

- Gender and racial group are unlikely to have a clinically significant effect on TSD.
- Class III malocclusions probably have higher average ratios.
- The prevalence of significant TSD in a UK population of orthodontic patients remains uncertain as is also the case for other populations.
- The advent of computer programs and electronic callipers greatly facilitates the measurement of Bolton ratios and should greatly increase the use of measurement of TSD in clinical practice.
- Reproducibility of measurement of TSD has been poorly investigated.

Authors and contributors

Siti Adibah Othman was responsible for searching for the literature from which data was obtained, gathering data, drafting the paper and contributed to the writing of the article. Mr Nigel Harradine was responsible for contributing to the writing of the article, critical revision and final approval of the article. Mr Nigel Harradine is the guarantor.

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