Accuracy and eligibility of Bonwill-Hawley arch form established by CBCT image for dental crowding measurement: a comparative study with the conventional brass wire and caliper methods.

Wenyu Meng
First Hospital of Lanzhou University

Hui Xue
the Affiliated Suzhou Hospital of Nanjing Medical University

Weining Wang
School of Stomatology, Lanzhou University

Yifei Huo
School of Stomatology, Lanzhou University

Xiaoming Wang ( wangxiaoming@lzu.edu.cn )
School of Stomatology, Lanzhou University

Research Article

Keywords: Model analysis, Dental crowding, Brass wire method, Caliper method, Bonwill-Hawley arch form

Posted Date: August 1st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1890703/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

Objectives

The purpose of this study was to develop a novel Bonwill-Hawley method (Bonwill-Hawley arch form based on CBCT image) for the assessment of dental crowding, and to investigate and compare the accuracy and eligibility with the conventional brass wire and caliper methods under different crowding conditions.

Material and methods

60 patients with the pair of plaster casts and CBCT data were collected. All the casts were marked and transformed into digital models using iTero scanner, and imported into OrthoCAD software to measure the required space. Using the conventional brass wire (M1) and caliper methods (M2), the available space and dental crowding were measured and calculated basing on digital models, respectively. Correspondingly, the axial planes in the level of dental arches were oriented and captured from the CBCT images to draw the Bonwill-Hawley arch forms (M3), which were used to measure and calculate the available space and dental crowding. For each method, intra and inter-examiner reliabilities were elevated with intra-class correlation coefficients (ICCs). Wilcoxon test and Kruskal-Wallis test were performed for statistically analyzing the discrepancy among different groups.

Results

Both intra and inter-examiner reliability were generally excellent for all parameters obtained by the three methods, except for the dental crowding measured using M1 (ICC: 0.473/0.261). The dental crowding measured using M2 were significantly increased in mild, moderate and severe-crowding groups compared with M1. However, no significant difference was detected between M1 and M3 in severe-crowding group (maxilla, p = 0.108 > 0.05; mandible, p = 0.074 > 0.05). With the deteriorate of crowding condition, the discrepancy of dental crowding between M1 and M2, or M1 and M3 were significantly decreased (maxilla, M2-M1, mild VS serve, p = 0.003 < 0.05; maxilla, M3-M1, mild VS serve, p = 0.003 < 0.05; mandible, M2-M1, mild VS serve, p = 0.000 < 0.001; mandible, M3-M1, mild VS serve, p = 0.043 < 0.05).

Conclusion

Dental crowding measured using the novel Bonwill-Hawley method was relatively greater than the caliper method, but not exceeding the brass wire method, which wound gradually come close to the brass wire method with the deteriorate of crowding condition.

Clinical relevance
The Bonwill-Hawley method basing on CBCT image proved to be a reliable and acceptable choice for orthodontists to analyze the dental crowding.

**Introduction**

Successful orthodontic treatment is based on comprehensive diagnosis and treatment planning, and model analysis is a vital part for correct diagnosis. Dental crowding in our patient population is majority, and the accurate space analysis for orthodontic diagnosis is especially crucial. Dental crowding is the discrepancy calculated by subtracting the space required (the sum of the mesial-distal widths of all the teeth within the arch) from the space available (arch perimeter). The mesial-distal tooth widths were relatively unified and accurate, while the investigation of arch perimeter can get great inconsistent results when using different measuring methods. For a long time, orthodontists proposed various methods to calculate the arch perimeter as accurate as possible, such as the visual estimation, brass wire method, caliper method, and the reflex microscope combining customized computer program method. Owing to the rapid and simple requirement in clinical operation, orthodontists tended to select the brass wire method or caliper method for arch length analysis. Nevertheless, the brass wire method required operator pre-forming the ideal dental arch for an individual, which is heavily dependent on the subjective judgement of the operator, and the result was limited in reproducibility. The caliper method reduced the curve arch to straight-line segments, which usually underestimates the true arch perimeter. Herein, a more valid and reproducible measuring method for calculating the arch available space is necessary to improve the disadvantages of previous methods.

Bonwill-Hawley arch form was the method proposed by Bonwill in 1887 to individually adjust the length and width of archwire. Later in 1905, Hawley furtherly modified the method by combining the width of six anterior teeth to serve as the radius of a circle, of which the arc between the bilateral canines was approximately coincided with the anterior segment of aligned dental arch, and the straight lines extending from anterior arc represented the middle and posterior segments with aligned premolars and molars. Thus, the arch dimensions were varied among individuals because of the different sizes of the anterior teeth among patients. Moreover, a recent study demonstrated that the Bonwill-Hawley arch was significantly related with the individual base bone arch in length and width. Thus, the clinical reference established by the Bonwill-Hawley arch form was important to determine the ideal contour of individual dental arch, which was helpful to improve the root-alveolar relationship and long-term stability of treatment. However, for the complex mathematical geometry, Bonwill-Hawley arch form was rarely used to analyze the dental crowding in the pre-treatment period. In addition, to our knowledge, the discrepancy between the Bonwill-Hawley method and the conventional brass wire and caliper methods for crowding measurement is still unknown.

At present, various digital model systems were applied in orthodontic field. Using the intraoral scanner, operators can translate the traditional plaster models into three-dimensional digital models, which avoid the drawbacks of damage, loss, and storage requirement. Relating studies have concluded that these
systems can get satisfactory accuracy, and are valid alternative to plaster models in orthodontic application. Moreover, some digital model systems also provide accompanied software for model analyzing, such as the 3Shape™ (Copenhagen, Denmark) and orthoCAD (Align Technology Inc., San Jose, CA, USA), both of which can automatically and accurately finish the measuring work, including the dental crowding. These digital model systems effectively improved the reliability and reproducibility of the conventional brass wire and caliper methods for model analysis, and reduced the measuring time. Besides the digital model systems, CBCT scanning has become a common item of orthodontic preoperative examination, and the accompany digital softwares are widely used in visualization analysis of the craniofacial structures with high resolution and precise measurement, including the three dimensional measurement and reconstruction of the jawbone, teeth, soft tissue and airway, but the application in dental crowding analysis remains rare.

Therefore, this study aims to explore a novel Bonwill-Hawley method using CBCT image for the assessment of dental crowding, which would be tested against the conventional brass wire and caliper methods to identify the accuracy and eligibility under different crowding conditions.

**Material And Methods**

**Sample collection:**

This research was approved by the Ethics Committee of Lanzhou University (Approval No. LZUKQ-2022-028). All the processes were conducted in full accordance with the World Medical Association Declaration of Helsinki. At the same time, all the patients were informed of the study destination and processes, and all of them were consent to sign the treatment consent form voluntarily.

We designed to category the subjects into three groups according to the degree of dental crowding (minor crowding, arch length discrepancy ≥0 mm and ≤3 mm; moderate crowding, arch length discrepancy >3 mm and <8 mm; and severe crowding, arch length discrepancy ≥8 mm), and measured via the conventional brass wire and caliper methods, as well as the novel Bonwill-Hawley method. Thus, the effective sample size was estimated by G*Power (version 3.1.9.7) according to the previous study (80% power; 0.8 effect size; α= 0.05 significance level; two-tailed)\(^{13-15}\), and the methods errors determined using Dahlberg’s formula did not exceed 0.5mm for all the measurements, indicating the comparable standard deviation between three methods, as assessed on the digital casts and CBCT images\(^{1,14,16}\). As a result, the minimum of 15 subjects in each group were required to detect a significant difference. The sample size was increased by 25%, resulting in 20 patients in each group, to account for the validity of results as previous studies reported\(^{14,17}\).

Then, dental plaster casts and corresponding CBCT scans (Smart3D-X, parameters: 100kv, 6mA, 26.9s, field view of 23 x 18cm, and voxel size of 0.25mm) of 60 subjects were collected from the archives of the Department of Orthodontics, School of Stomatology, Lanzhou University. These subjects were selected according to the following inclusion criteria: (1) Complete permanent dentition and no missing teeth from
the first molar to the first molar in the upper and lower arches; (2) All teeth showed normal morphology and no obvious dental attrition or defect; (3) No periodontal disease or gingival defects; (4) The plaster casts were fabricated in satisfying quality and contained tooth crowding, rotations and bucco-lingual displacements, no space exist; (5) No orthodontic, functional orthopedic treatment, cleft lip palate, and orthognathic surgery history; (6) Clear imaging by CBCT. Exclusion criteria included: (1) Plaster models from patients with mixed dentition; (2) Patients with tooth missing from the first molar to the first molar or obvious dental alterations; (3) Patients who were in mixed dentition, or with cleft lip/palate and facial deformity; (4) Subjects who received orthodontic treatment. (5) Blurring image by CBCT.

Crowding measurement:

To minimize the influence of disagreement in the identification of measuring points on dental casts, the mesial contact points of the canines, first premolars, and the first permanent molars were identified and attached with metal balls 1.5 mm in diameter, according to the published study. Then, the plaster casts were digitized using the iTero® Scanner (Align Technology Inc., San Jose, CA, USA).

The arch required space is the sum of individual mesio-distal widths of the teeth (the second premolar to the second premolar on bilateral sides), which were measured according to the mesial and distal contact points using the Diagnostics-Teeth Width function of OrthoCAD software (Figure 1A), and the dental crowding would be quantified by subtracting the space required from the space available. The space available was calculated via the following brass wire and caliper methods:

Brass wire method (M1): Using the Diagnostics-Space function of OrthoCAD software, a virtual wire was fitted to lie over the incisal edges of anterior teeth and the centers of the dental arches. The 7 curve nodes were adjusted at the sites where the metal balls attached. Thus, the available space (M1) would be automatically calculated (Figure 1B).

Caliper method (M2): The arch was divided into four straight-line segments, where the bilateral canines belonged to the anterior segments. Segmental measurement was conducted using the Diagnostics-Measurements function of OrthoCAD software, and the recognition and matching for positioning point were identified by the metal balls. The available space (M2) was the sum of the four segments (Figure 1C).

To three dimensionally standardize the image position and draw the Bonwill-Hawley arch form in CBCT image using Dolphin Imaging 3D software, we followed the method proposed by Crossley, A. M. et al with some modification (Figure 2A). The axial plane of the CBCT was oriented by bisecting the mesio-buccal cusps of first molars and the incisal edges of central incisors in maxillary and mandibular arches on the right side, with the left side checked to coincide with the axial plane (Figure 2B). The coronal plane was defined perpendicular to the axial plane, coinciding with the posterior walls of bilateral maxillary tuberosities (Figure 2A&C). The sagittal plane was defined perpendicular to the axial and coronal planes, bisecting the incisive foramen (Figure 2A&D). The axial slice for the maxillary and mandibular dental arches were parallel to the axial plane and located at the levels of the maximum mesial-distal diameters
of the upper and lower central incisors (Figure 3). The detail description of the Bonwill-Hawley method was as follows:

**Bonwill-Hawley method (M3):** The Bonwill-Hawley arch form was drawn using CorelDraw graphics 2017 software according to the published approaches\(^5,6\). As shown in Figure 3, the sagittal (red) and coronal (green) planes had been established in previous step. The mesial-distal widths of the central and lateral incisors, as well as the canines were measured and recorded with additional 1mm for each tooth on the horizontal line (white). The half of the total width between bilateral canines was calculated to act as the radius (line AA’ or BA’) of the first circle (yellow), defined point A’ as the center, tangent to the horizontal line (red) at point A (the contacting site of central incisors). Then, the second circle was drawn with point A as the center and AA’ as the radius, and intersected with the first circle at points C and C’. Furtherly, the extension of line segment BC or BC’ intersected with the horizontal line (red) at point B’ and B” (BB’=BB”). The third circle (pink) was drawn with the center located on the sagittal plane (red) and BB’ as the radius, which was tangent to the horizontal line (red) at point A, and intersected with the sagittal plane (red) at point D. The fourth circle (blue) was drawn with point D as the center and BB’ as the radius, which intersected with the third circle (pink) at points E and E’. Finally, line segments EC or EC’ were connected with the anterior arc CC’ to form a Bonwill-Hawley arch form (yellow). The arch between the mesial borders of right and left first molars was marked with translucent green curve for further measurement. The axial slice drawn with Bonwill-Hawley arch form was imported into the Image J software, calibrated according to the scale, and measured the length of translucent green curve as the available space (M3).

In the above three methods, two well-trained examiners (Wenyu-Meng and Yifei-Huo) completed the parameters on all the subjects within 2 weeks, Wenyu-Meng repeated the measurements on each parameter after 2 months. The observers were blinded to the information including previous model measurements, initial diagnosis and treatment plan.

**Statistical analysis:**

For measuring accuracy, Wilcoxon test and intra-class correlation coefficient (ICC) were used to evaluate intra and inter-examiner reliability of each method and parameter on 60 subjects\(^11\). Kruskal-Wallis test was applied to compare the discrepancies among different measuring methods and crowding classifications\(^13\). For data interpretation, the value of 0.75 for ICC was clinically acceptable, and the level of significance was set at \(p < 0.05\)^18.

**Results**

Intra-examiner and inter-examiner reliability proved to be acceptable in all the three measuring methods as reflected by ICC, and all the relating measurements ranged from 0.810 to 0.992. Nevertheless, the intra-examiner and inter-examiner ICCs of maxilla available space and dental crowding measured using the brass wire method (M1) were relatively lower compared with the caliper method (M2) and Bonwill-Hawley
method (M3). The Wilcoxon test also showed no significant difference in all the measurements for both the intra-examiner and inter-examiner tests (P > 0.05) (Tables 1 and 2).

As for the available space and dental crowding differences among the three methods, Kruskal-Wallis test showed the mean differences, standard deviations, and detected statistical significances for all the measurements among different methods (Table 3, Fig. 4). M1 presented maximum value of available space both in upper and lower arches, compared with M2 (Max, M1 = 75.93 ± 1.32mm VS M2 = 72.87 ± 1.62mm, p = 0.000 < 0.001; Mand, M1 = 63.56 ± 1.36mm VS M2 = 60.61 ± 1.18mm, p = 0.000 < 0.001) and M3 (Max, M1 = 75.93 ± 1.32mm VS M3 = 74.08 ± 1.40mm, p = 0.015 < 0.05; Mand, M1 = 63.56 ± 1.36mm VS M3 = 61.86 ± 1.33mm, p = 0.021 < 0.05). For the dental crowding, M1 presented minimum value in upper and lower arches, compared with M2 (Max, M1 = 5.92 ± 1.33mm VS M2 = 8.98 ± 1.70mm, p = 0.000 < 0.001; Mand, M1 = 5.73 ± 1.41mm VS M2 = 8.67 ± 1.86mm, p = 0.000 < 0.001) and M3 (Max, M1 = 5.73 ± 1.41mm VS M3 = 7.78 ± 1.61mm, p = 0.018 < 0.05; Mand, M1 = 5.73 ± 1.41mm VS M3 = 7.42 ± 1.19mm, p = 0.015 < 0.05). However, no significant difference was detected between the M2 and M3 groups (available space, dental crowding, M2 VS M3, p > 0.05), and the value of available space and dental crowding in M3 group was closer to M1 than M2 group. The above results suggested us different measuring methods could cause remarkable discrepancy in the result of model space analysis, and the Bonwill-Hawley method could narrow the gap between virtual arc (brass wire method) and line segmentations (caliper method) in crowding calculation.

To further identify the variety and effective of the three methods, we compared the differences under different crowding classifications using Kruskal-Wallis test (Table 4, Fig. 5). In any crowding classification of upper or lower arch, the mean values of dental crowding presented significant differences between the M1 and M2 groups (M1 VS M2, p < 0.05); there were also significant differences between the M1 and M3 groups in mild and moderate classifications (M1 VS M3, p < 0.05), but no significant differences were detected in severe classification (Max, M1 VS M3, p = 0.108 > 0.05; Mand, M1 VS M3, p = 0.074 > 0.05). Nevertheless, the discrepancy of dental crowding between M2 and M3 groups was statistically insignificant (M2 VS M3, p > 0.05), except for the mandibular mild classification (M2 VS M3, p = 0.000 < 0.001). The result showed that the discrepancy of crowding calculation between virtual arc (brass wire method) and line segmentations (caliper method) occurred under any crowding conditions, but the Bonwill-Hawley method could generate closer crowding result to the brass wire method compared with the caliper method.

To further investigate the detail discrepant variation between the virtual arc and line segmentations during crowding calculation, we subtracted the value measured by the brass wire method (M1) from the caliper method (M2) and Bonwill-Hawley method (M3) respectively (Table 5, Fig. 6). Kruskal-Wallis test showed neither statistically significant difference existed between the mild and moderate crowding groups (p > 0.05), nor between the moderate and severe crowding groups (p > 0.05) in the upper and lower arches. However, the differences between M1 and M2 were significantly decreased when comparing the mild with the severe groups (Max, M2-M1, mild = 3.44 ± 0.68 VS severe = 2.35 ± 0.32, p = 0.003 < 0.01; Mand, M2-M1, mild = 4.19 ± 0.48 VS severe = 2.22 ± 0.65, p = 0.000 < 0.001), and similar trends also presented...
between M1 and M3 (Max, M3-M1, mild = 2.80 ± 0.23 VS severe = 1.56 ± 0.54, p = 0.003 < 0.01; Mand, M3-M1, mild = 1.98 ± 0.37 VS severe = 1.38 ± 0.56, p = 0.043 < 0.05). The above results indicated that the obvious measuring different between the virtual arc and line segmentations mainly existed in mild and moderate crowding arches.

Discussion

The Bonwill-Hawley arch form was widely used as the custom arch forms to bend the stainless steel archwire in Tweed-Merriifield technique, which was suitable for the individual characteristic form of tooth and alveolar bone\textsuperscript{19}. Thus, Bonwill-Hawley arch form can be applied as a relatively ideal template to simulate the terminal target form of dental arch. This study was novel because it was the first to evaluate the accuracy and eligibility of Bonwill-Hawley arch form established by CBCT image for dental crowding measurement, and compare with the conventional brass wire and caliper methods.

A good dental crowding calculating method must generate consistent results across time and different examiners. The ICC value for categorizing the intra or inter-examiner as excellent reliability was over 0.75 in model analysis\textsuperscript{9,20}. In this study, the two observers were well pre-trained to reference point definition before formal measuring. To further guarantee the good reproducibility, we collected all maxillary and mandibular models with different crowding severity, and attached 7 metal balls on dental arch to assist the observers to identify the measuring points, which was applied by the previous study to improve scanner accuracy for digital models\textsuperscript{7}. Moreover, according to Michael F. Leifert’s study, space analysis evaluation on digital models was prove to be reliably used to analyze arch length discrepancies when compared with plaster model\textsuperscript{21}. In this study, for the conventional brass wire and caliper methods, we used digital models and corresponding measurement software instead of manual measurement\textsuperscript{16}, which reduced the error caused by the physical barrier of plaster cast when locating caliper tip\textsuperscript{18}, and by the brass wire incompletely straightened\textsuperscript{21}. As for the Bonwill-Hawley method in this study, both intra-examiner and inter-examiner reliability were also generally excellent for all measurements made on CBCT image. After comparing the accuracy of three-dimensional image of the upper and lower dental arches acquired from the CBCT and high-precision optical scanner, Kim, S. R. et.al. demonstrated that the accuracy and repeatability of the two approaches showed little difference\textsuperscript{22}. By digitizing the plaster casts with CBCT and dedicated optical device, Becker, K.et.al. found that the median distances between CBCT and optically digitized casts were 0.064 ± 0.005 mm, and the accuracy and eligibility of CBCT was sufficient for digital planning and forensic purpose\textsuperscript{8}. Taken together, in this study, the results of intra-examiner reliabilities of the three method for crowding measurement were proved to be clinically acceptable.

The inter-examiner reliabilities were relatively lower than the intra-examiner, but the ICC values still greater than 0.8 and were also excellent, except for the dental crowding measured by brass wire method. For the reason of ICC in dental crowding measured by the brass wire method less than 0.75, we attributed it to the amplification of cumulative error generated from the required and available spaces\textsuperscript{16}, because the
crowding value was determined by subtracting the space required from the space available\textsuperscript{2,23}. Moreover, previous study had demonstrated the limitation of the brass wire method in reproducibility, which required individual arch forming and involved large amount of subjective judgement\textsuperscript{2,21}. While the digital model analysis was proved to be more reliable than the manual one with less variability, the examiner still needed to rotate in three-dimension over the 2D screen for heavily tilted teeth, and a different angle of view might cause identification and positioning error\textsuperscript{9,24}. Nevertheless, both in intra and inter-examiner comparison, Wilcoxon test detected no statistical significant difference in all the variables, indicating the measuring results were validity. Thus, we set the results generated by the wire method as reference standard to compare the difference generated by the caliper method and Bonwill-Hawley method.

Best to the knowledge of the authors, few studies investigated the detail difference between the brass wire and caliper methods, not to mention the Bonwill-Hawley method. For the conventional space calculating methods, brass wire method was recognized as the currently closest one to the arch real length available over basal bone\textsuperscript{21}, but the caliper method was also widely used for more convenient operation\textsuperscript{18}. The brass wire method conducted the arch measurement with a whole curved wire. Johal, A. S. et.al previously demonstrated that the measurement of dental crowding by the brass wire method showed a tendency to underestimation compared with the real situation\textsuperscript{2}. The permanent canines were frequently impacted or erupted buccally or palatally to the dental arch because of the delayed eruption sequence than lateral incisor and first premolar\textsuperscript{25}. Moreover, even in the non-crowding arch, the eruption path of canines were slightly buccal in relation to the dental arches\textsuperscript{26}. Thus, canines located at the transition points of the dental arch, and divided the dental arch into four segments for the calculation of available space, as conducted by the caliper method\textsuperscript{23,27}. In this study, the caliper method generated a significantly decreased crowding value compared with the brass wire method. The Bonwill-Hawley method combined the advantages of brass wire and caliper methods, with arc coinciding to the anterior and line segments coinciding to the middle and posterior regions of dental arch. In present study, we compared the discrepancy of the results of available space or dental crowding between the three methods. Although no significant difference was detected between the Bonwill-Hawley and caliper methods for both the available space and dental crowding in upper and lower arches, the Bonwill-Hawley method got all the measuring results between the brass wire and traditional caliper methods, suggesting the closer results to the valid dental crowding condition. A significant correlation had been reported between the shape of the mandibular apical base and Bonwill-Hawley arch form in Class \(\text{II} \) malocclusion patients\textsuperscript{6}. Thus, we supposed that the diagnosis and design of orthodontics using Bonwill-Hawley method were beneficial to take the condition of basal bone into consideration, which was helpful to reduce the risk of relapses and dehiscence/fenestration.

The extent of dental crowding could definitely cause significant measuring error on model analysis\textsuperscript{9}. Shellhart\textsuperscript{28} reported that dental arch measuring discrepancies were influenced by dental crowding condition, which varied as much as 1.5 mm on a plaster cast with mild crowding\textsuperscript{9}. Thus, we further investigated the measuring discrepancy among the above three methods under different dental crowding
classifications. Both in mild/moderate crowding groups, dental crowding measured by the caliper and Bonwill-Hawley methods were obviously greater than the brass wire method, and the difference increased to as much as 3.44/3.11 mm between the caliper and brass wire methods in upper arch, and 4.19/3.41 mm in lower arch; similar 2.80/2.37 mm increments were detected between the Bonwill-Hawley and brass wire methods in upper arch, and 1.98/1.77 mm in lower arch. However, in severe crowding group, the significant differences between the Bonwill-Hawley and brass wire methods in upper and lower arches were disappeared while existed between the caliper and brass wire methods. The difference decreased to as much as 2.35/2.22 mm between the caliper and brass wire methods in upper/lower arch, and 1.56/1.38 mm between the Bonwill-Hawley and brass wire methods. To further identify the effect of crowding extent on measuring difference among the three methods, we compared the crowding discrepancies of the caliper and brass wire methods, as well as the Bonwill-Hawley and brass wire methods among various crowding classifications (Fig. 6). As a result, both the measuring differences of the caliper and Bonwill-Hawley methods were significantly decreased compared with the brass wire method with the increase of dental crowding. We attributed this finding to the highest prevalence of dental crowding in the anterior region[^29], and gradually reduced arch length available over basal bone. According to the American Board of Orthodontics Objective Grading System (ABO OGS), it appears that the smallest distinguishable distance in model analysis was 0.5 mm, which could be regard as clinical insignificant[^30]. However, the measuring difference of dental crowding between the brass wire and caliper/Bonwill-Hawley methods was at least 1.38 mm, and up to 4.19 mm, which might mislead orthodontists to choose extraction therapy[^21].

In this study, the limitation and prospect of the Bonwill-Hawley arch form in dental crowding measurement were necessary to be raised. The Bonwill-Hawley method only based on the two dimensional slice in axial plane, while the conventional brass wire and caliper methods was conducted on the digital model in three dimensions, which took the width and depth of dental arch in to consideration. As suggested by Germane, N. et.al[^31], arch length analysis should consider discrepancies not only within the sagittal plane but also within the vertical and transverse planes. Moreover, the Bonwill-Hawley method was merely used to draw the geometry arch form and evaluate the available circumference of arch according to the mesio-distal width measured on axial slice, the required space was still calculated on digital model. In addition, the Bonwill-Hawley method was more complex and inefficient to draw the mathematical arch form compared with the conventional methods. Nevertheless, this study was an initial and comparative study about the accuracy and eligibility of Bonwill-Hawley method for crowding analysis. In the future, the automated program for Bonwill-Hawley arch form could be developed and integrated into the existing CBCT software, such as the Dolphin Imaging software and Invivo Dental software, which would definitely achieve an optical efficiency than the conventional methods. Finally, combining with the digital models constructed from CBCT image, the truly personalized measurement and analysis for dental arch could be achieved using Bonwill-Hawley method, without additional dental scanning or impression making[^8].

Conclusions
1. Space analysis using the Bonwill–Hawley method basing on CBCT image was proved to be eligible and reliable in both maxillary and mandibular dental arches.

2. Compared with the brass wire method, the Bonwill–Hawley method showed a tendency to significantly underestimate the arch available length and overestimate the dental crowding.

3. The Bonwill–Hawley method gradually obtained measuring results closer to the brass wire method compared with the caliper method, which suggested to be an alternative choice.

4. With the deterioration of dental crowding, the measuring difference among the three methods gradually decreased. Although there was no absolutely accurate standard of crowding measurement, the Bonwill–Hawley method seemed to be an excellent approach.

Declarations

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent: For this type of study, formal consent is not required.

Funding: This project was supported by the Fundamental Research Funds for the Central Universities (NO: lzujbky-2021-41), and the Open Subject Foundation of Key Laboratory of Dental Maxillofacial Reconstruction and Biological Intelligence Manufacturing (20JR10RA653 - ZDKF20210401), School of Stomatology, Lanzhou University, Gansu Province, Lanzhou 730000, PR China

Author Contribution statement: Wen-yu Meng: Data curation and analysis, writing original draft preparation; Hui Xue: Reviewing and Editing; Wei-ning Wang and Yi-fei Huo: Software, visualization; Xiao-ming Wang: Methodology, conceptualization, writing—reviewing, and editing. All authors read and approved the manuscript.

References


Tables

Table I The analysis of intra-examiner reliability using different methods (n=20).
## Table II. The analysis of inter-examiner reliability using different methods (n=20).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean difference (mm±SD)</th>
<th>Wilcoxon test</th>
<th>ICC(95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max required space</td>
<td>0.03±0.41</td>
<td>0.746ns</td>
<td>0.988(0.969-0.995)</td>
</tr>
<tr>
<td>Max available space (M1)</td>
<td>0.32±1.01</td>
<td>0.173ns</td>
<td>0.919(0.808-0.967)</td>
</tr>
<tr>
<td>Max available space (M2)</td>
<td>0.19±0.69</td>
<td>0.230ns</td>
<td>0.976(0.940-0.990)</td>
</tr>
<tr>
<td>Max available space (M3)</td>
<td>0.27±0.78</td>
<td>0.146ns</td>
<td>0.975(0.937-0.990)</td>
</tr>
<tr>
<td>Dental crowding (M1)</td>
<td>0.35±1.18</td>
<td>0.202ns</td>
<td>0.473(0.051-0.752)</td>
</tr>
<tr>
<td>Dental crowding (M2)</td>
<td>0.16±0.74</td>
<td>0.345ns</td>
<td>0.932(0.837-0.973)</td>
</tr>
<tr>
<td>Dental crowding (M3)</td>
<td>0.24±0.89</td>
<td>0.865ns</td>
<td>0.906(0.777-0.962)</td>
</tr>
</tbody>
</table>

ICC intraclass correlation coefficient, CI confidence interval; n, the sample size; ^ns{p}\textgreater{}0.05; M1, brass wire method; M2, caliper method; M3, Bonwill-Hawley method; Max, maxillary dental arch.

## Table III. Kruskal-Wallis test analysis differences of measurements among the three methods (n=60)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean difference (mm±SD)</th>
<th>Wilcoxon test</th>
<th>ICC(95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max required space</td>
<td>0.07±0.33</td>
<td>0.391ns</td>
<td>0.992(0.979-0.997)</td>
</tr>
<tr>
<td>Max available space (M1)</td>
<td>0.32±1.51</td>
<td>0.361ns</td>
<td>0.810(0.581-0.920)</td>
</tr>
<tr>
<td>Max available space (M2)</td>
<td>0.24±0.93</td>
<td>0.272ns</td>
<td>0.970(0.927-0.988)</td>
</tr>
<tr>
<td>Max available space (M3)</td>
<td>0.27±0.84</td>
<td>0.166ns</td>
<td>0.986(0.966-0.995)</td>
</tr>
<tr>
<td>Dental crowding (M1)</td>
<td>0.38±1.51</td>
<td>0.274ns</td>
<td>0.261(0.194-0.623)</td>
</tr>
<tr>
<td>Dental crowding (M2)</td>
<td>0.30±1.09</td>
<td>0.233ns</td>
<td>0.861(0.694-0.945)</td>
</tr>
<tr>
<td>Dental crowding (M3)</td>
<td>0.34±0.92</td>
<td>0.121ns</td>
<td>0.892(0.748-0.956)</td>
</tr>
</tbody>
</table>

ICC intraclass correlation coefficient, CI confidence interval; n, the sample size; ^ns{p}\textgreater{}0.05; M1, brass wire method; M2, caliper method; M3, Bonwill-Hawley method; Max, maxillary dental arch.
### Table 4: Kruskal-Wallis test analysis the mean±standard deviation and differences of values of crowding among the three methods under different crowding severity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M1 VS M2</th>
<th>M1 VS M3</th>
<th>M2 VS M3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean±SD</td>
<td>Mean±SD</td>
<td>Mean±SD</td>
<td>p</td>
<td>p</td>
<td>p</td>
</tr>
<tr>
<td>Available space(Max)</td>
<td>75.93±1.32</td>
<td>72.87±1.62</td>
<td>74.08±1.40</td>
<td>0.000***</td>
<td>0.015*</td>
<td>0.163ns</td>
</tr>
<tr>
<td>Available space (Mand)</td>
<td>63.56±1.36</td>
<td>60.61±1.18</td>
<td>61.86±1.33</td>
<td>0.000***</td>
<td>0.021*</td>
<td>0.118ns</td>
</tr>
<tr>
<td>Dental crowding(Max)</td>
<td>5.92±1.33</td>
<td>8.98±1.70</td>
<td>7.78±1.61</td>
<td>0.000***</td>
<td>0.018*</td>
<td>0.181ns</td>
</tr>
<tr>
<td>Dental crowding(Mand)</td>
<td>5.73±1.41</td>
<td>8.67±1.86</td>
<td>7.42±1.19</td>
<td>0.000***</td>
<td>0.015*</td>
<td>0.099ns</td>
</tr>
</tbody>
</table>

M1, brass wire method; M2, caliper method; M3, Bonwill-Hawley method; Max, maxillary dental arch; Mand, mandibular dental arch; n, the sample size; Mean±SD, mean±standard deviation; ns p>0.05; *p < 0.05; **p < 0.01; ***p < 0.001.

### Table 5: Kruskal-Wallis test analysis the difference among the three methods in different crowding severity.

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M1 VS M2</th>
<th>M1 VS M3</th>
<th>M2 VS M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dental crowding (Mean±SD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild (n=20)</td>
<td>2.07±0.59</td>
<td>5.51±0.46</td>
<td>4.87±0.82</td>
<td>0.000***</td>
<td>0.000***</td>
<td>0.489ns</td>
</tr>
<tr>
<td>Moderate (n=20)</td>
<td>6.09±0.63</td>
<td>9.20±0.76</td>
<td>8.46±0.45</td>
<td>0.000***</td>
<td>0.000***</td>
<td>0.240ns</td>
</tr>
<tr>
<td>Severe (n=20)</td>
<td>9.16±0.65</td>
<td>11.51±0.42</td>
<td>10.72±0.81</td>
<td>0.018*</td>
<td>0.108ns</td>
<td>0.735ns</td>
</tr>
<tr>
<td>Mand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild (n=20)</td>
<td>1.99±0.40</td>
<td>6.18±0.86</td>
<td>3.97±0.50</td>
<td>0.000***</td>
<td>0.000***</td>
<td>0.000***</td>
</tr>
<tr>
<td>Moderate (n=20)</td>
<td>5.38±0.41</td>
<td>8.79±0.52</td>
<td>7.15±0.63</td>
<td>0.000***</td>
<td>0.001**</td>
<td>0.078ns</td>
</tr>
<tr>
<td>Severe (n=20)</td>
<td>9.82±0.29</td>
<td>12.04±0.79</td>
<td>11.2±0.43</td>
<td>0.002**</td>
<td>0.074ns</td>
<td>0.357ns</td>
</tr>
</tbody>
</table>

M1, brass wire method; M2, caliper method; M3, Bonwill-Hawley method; Max, maxillary dental arch; Mand, mandibular dental arch; n, the sample size; Mean±SD, mean±standard deviation; ns p>0.05; *p < 0.05; **p < 0.01; ***p < 0.001.
<table>
<thead>
<tr>
<th>Dental crowding difference (Mean±SD)</th>
<th></th>
<th></th>
<th></th>
<th>p</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>Moderate</td>
<td>Severe</td>
<td>Mild VS Moderate</td>
<td>Mild VS Severe</td>
<td>Moderate VS Severe</td>
<td></td>
</tr>
<tr>
<td>M2-M1(Max)</td>
<td>3.44±0.68</td>
<td>3.11±0.13</td>
<td>2.35±0.32</td>
<td>0.408ns</td>
<td>0.003**</td>
<td>0.084ns</td>
</tr>
<tr>
<td>M3-M1(Max)</td>
<td>2.80±0.23</td>
<td>2.37±0.46</td>
<td>1.56±0.54</td>
<td>0.208ns</td>
<td>0.003**</td>
<td>0.221ns</td>
</tr>
<tr>
<td>M2-M1(Mand)</td>
<td>4.19±0.48</td>
<td>3.41±0.30</td>
<td>2.22±0.65</td>
<td>0.064ns</td>
<td>0.000***</td>
<td>0.070ns</td>
</tr>
<tr>
<td>M3-M1(Mand)</td>
<td>1.98±0.37</td>
<td>1.77±0.51</td>
<td>1.38±0.56</td>
<td>0.838ns</td>
<td>0.043*</td>
<td>0.149ns</td>
</tr>
</tbody>
</table>

M2-M1, crowding value of caliper method minus brass wire method; M3-M1, crowding value of Bonwill-Hawley method minus brass wire method; Max, maxillary dental arch; Mand, mandibular dental arch; Mean±SD, mean±standard deviation; ns p>0.05; *p < 0.05; **p < 0.01; ***p < 0.001.

**Figures**

**Figure 1**

Example of the dental crowding measurement on a digital from the occlusal view using OrthoCAD software: (A) The required space (the sum of the mesial-distal widths of the teeth); (B) The available space (measured by brass wire method); (C) The available space (measured by caliper method).

**Figure 2**

The CBCT image of head adjusted in three dimensions. (A) Standardized orientation. (B) The orientation of axial plane (blue). (C) The orientation of coronal plane (green). (D) The orientation of sagittal plane (red).

**Figure 3**

The Bonwill-Hawley arch form drawn on the axial slice of maxillary dental arch.
Figure 4

Comparison of measurement differences of available space (A) and dental crowding (B) among the three methods in maxillary and mandibular arches. M1, brass wire method; M2, caliper method; M3, Bonwill-Hawley method; Max, maxillary dental arch; Mand, mandibular dental arch; ns \( p > 0.05 \); * \( p < 0.05 \); ** \( p < 0.01 \); *** \( p < 0.001 \).

Figure 5

Comparison of measurement differences of dental crowding among the three methods in different crowding severity, in maxillary (A) and mandibular (B) arches respectively. M2-M1, crowding value of caliper method minus brass wire method; M3-M1, crowding value of Bonwill-Hawley method minus brass wire method; Max, maxillary dental arch; Mand, mandibular dental arch; ns \( p > 0.05 \); * \( p < 0.05 \); ** \( p < 0.01 \); *** \( p < 0.001 \).
Figure 6

Comparison of crowding discrepancy between the brass wire and caliper methods, as well as the discrepancy between the brass wire and Bonwill-Hawley method in different crowding severity, in maxillary (A&B) and mandibular (C&D) arches respectively. M2-M1, crowding value of caliper method minus brass wire method; M3-M1, crowding value of Bonwill-Hawley method minus brass wire method; Max, maxillary dental arch; Mand, mandibular dental arch; ns p>0.05; *p < 0.05; **p < 0.01; ***p < 0.001.