Introduction

Recently, indirect bonding popularity increased due to its advantages as reduction of chair time and enhancement of patient comfort. Although the techniques of indirect bonding have improved over the years, the literature has shown different techniques of bracket placement; furthermore, different materials were specially developed for this technique.

Many researchers have tried their methods to achieve proper indirect bonding by changing their approach either during laboratory or clinical procedures. Also many studies have been performed in order to test the indirect technique efficiency. In fact, just few reports were able to evaluate the clinical reliability of the indirect bonding technique compared with the conventional bonding technique, most of these studies evaluated either the bond and shear strength or the bracket placement accuracy compared to direct bonding or the precision of the used transfer tray.

The theoretically more ideal bracket placement which is intended to be achieved in indirect bonding is of no importance to the orthodontist unless the bracket position planned in the set-up is transferred with complete accuracy to the patient's dentition. Recent methods of evaluating the accuracy of bracket position were used in this study, which opened the door for precise evaluation for all of the indirect bonding techniques available in the market either computer-aided or manual techniques.

Therefore, insights into both positional accuracy and reliability in several ways were the aim of this study. Specifically, how often the brackets "Strike-the-target" and are placed accurately within clinically acceptable

boundaries. Also, investigated several clinical assumptions about the pattern of indirect bonding errors.

Review of Literature

In this chapter, a review of literature regarding the evolution of straight wire appliance, the emerging need of indirect bonding techniques, and the recent use of digital world in orthodontics. The use of computer-aided indirect bonding and the accuracy of desktop and intraoral scanners will be highlighted. The review will thus be divided into the following subtitles for the purpose of organization and simplification:

I-Straight wire appliance

A-History

B-Ideal bracket position and their errors outcome

II-Indirect Bonding

A-Conventional indirect bonding

1-Methods and techniques

2-Accuracy and reliability

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III-Digital orthodontics

A-Digital casts and intraoral scans

B- Computer-aided treatment plan, diagnostic setup, and 3d printing

I-Straight wire appliance

A-History:

Lawrence F. Andrews developed the first "fully programmed pre-adjusted" appliance[1]. Andrews, an extraordinary orthodontist -well trained on using edgewise treatment- thoroughly understood the limitations of edgewise treatment. He started his work in developing the appliance by gathering 120 non-orthodontic normal models. These were models of subjects whom Andrews assessed as having remarkably ideal occlusions, and who had never had to go through orthodontic treatment. Then he observed many features but found 6 features or "6 keys" that were consistent in all of these models.

He published these unique observations in his classic article "The six keys to normal occlusion."[2]

These keys included the following: molar relationship, crown tip, crown torque, rotations, lack of spaces, and plane of occlusion, and nowadays they are an important factor of the American Board of Orthodontics grading system. Then he measured the in-and-out, tip, and torque values for all the teeth on these models.

Three references were used to measure these values: the long axis of the center of the clinical crowns, the center of the clinical crowns, and the thickness of the clinical crowns from a specific position on the teeth to the center of the clinical crowns. This gave him the opportunity to have consistent measurements on both small and larger teeth. After collecting these data, it was possible to determine norms and standard deviations. He then transferred this information into a "pre-adjusted" appliance with tip,

torque, and in and out specific values built into each bracket for each tooth, he called his unique appliance: the straight-wire appliance (SWA)[3].

Andrews Figured out that two important factors were needed in order to develop the SWA. First, each bracket should have a "compound contoured" base, which would allow perfect fit for each tooth occlusogingivally and mesiodistally while centered on the long axis of the clinical crown and positioned at the center of the clinical crown. Second, each slot needed to accept passively the rectangular archwire, rectangular archwire was adjusted to the shape of each model and positioned along the center of the clinical crown. These two factors were crucial to the appliance design.

In order to achieve these two goals, Andrews noticed that three points needed to be positioned on the same horizontal plane. These points were the center of each bracket base, the center of the clinical crown, and the center of the bracket slot. This would allow the desired in-and-out and torque values in the appliance which are similar to the in and out and torque values measured on the nonorthodontic normal models.

In order to allow this 3-point horizontal alignment, Andrews realized that he needed to vary the angles at the bracket bases from 90º to varying amounts of obtuse and acute angles. This unique feature is referred to as "torque in base," and was patent by Andrews. This obligated other manufacturers that did not have the patent to place both tip and torque, into the brackets face. In the SWA, tip was precisely placed into the face of rectangular brackets, also the thickness of the brackets was determined by the in-and-out measurements on normal models.

Andrews' choice was the 0.022-in slot size. He concluded that the best choice in brackets manufacturing was to cast them with stainless steel, same

material was used in the casting of crowns or inlays. The challenge with casting brackets was it had never been cast in this manner. The temperatures needed to cast stainless steel were much higher than for gold. In order to achieve this, experienced engineers who determined how to carry out this process provided great aid, and he was able to construct these brackets.

This extraordinary effort by Andrews was one of the most remarkable contributions in orthodontics history. His magnificent work created a baseline reference for all future pre-adjusted appliances in the our specialty.[4]

B-Ideal bracket position and their errors outcome

Brackets are considered as the key constituent of the fixed orthodontic appliances used for the treatment of different malocclusions. Besides the different types of orthodontic archwires that are inserted into the bracket and ligation methods used, a three‑dimensional (3D) configuration of tooth positioning is usually established.[5]

In 1988 Balut, discussed the variations in Bracket Placement in the Preadjusted Orthodontic Appliance[6].

The aim of his study was to determine angular and vertical bracket position utilizing a preadjusted orthodontic appliance. Discrepancies in brackets position were measured from a horizontal reference line, deviations were evaluated with respect to the specific tooth type, classification of malocclusion, and intra/inter operator differences.

He concluded that: In order to obtain excellent treatment results, accurate placement of an appliance is required. However, the correct placement is probably of high importance in the preadjusted appliance.

Errors in tooth - position created by attachment misplacement for built-in tip have the ability to be much more significant. Limited space between adjacent roots allows a small error margin for root placement. One main objective of orthodontic treatment is to ensure a regular bone thickness preserving roots parallelism. Attachment misplacement that creates deviation in the designed tip will affect this objective.

In 1990 Fowler PV. evaluated the differences in the perception of ideal bracket position and its implications for the pre-adjusted edgewise appliance[7], variations between both different clinicians and also the same clinician was measured, in this trail, seventy one clinicians with different levels of experience participated and concluded that:

1. The variability in the perception of the ideal bracket position not only by the same clinician but also between different clinicians was greatest for the long axis of clinical crown (LACC) angulation, less for long axis (LA) point height, and least for long axis point MD position.

2. The learning curve of recent training and experience affected significantly the amount of inter- and intra-clinician variability in the perception of the LACC angulation. There was a minimal reduction in the intra-clinician variability in the long axis point height, with no differences in inter-clinician variability. The capability to perceive the LA point MD position was the same in all three groups and was consistent.

3. For the majority of clinicians, the clinical implications for differences in the perception of the LACC and LA point position appear to be limited to only minor changes in root apex position and crown inclination. However, extreme variations in LACC angulation observed in this study could well result in poor root apex positioning.

II-Indirect Bonding

A-Conventional indirect bonding

1-Methods and techniques

Indirect bonding has been a remarkable advancement in orthodontics over the last years. Due to its great benefit to the clinician as it improves patient comfort, improves the accuracy of bracket placement, and reduces chair time. It has been widely recognized that accurate bracket positioning is of crucial importance in the proper biomechanics application and in expressing the full potential of a preadjusted edgewise appliance. There are so many applications and steps in indirect bonding, so all these are opened for modification.

Silverman et al in 1972[8] were the first to describe indirect bonding in detail. In a discussion, the researchers were asked about their opinion in indirect bonding:

Thomas confirmed that indirect bonding takes much less clinical time (chair time) and accurate bracket positioning could be obtained with the success rate up to 98%. And *Zachrisson* stated that it is much better to position brackets on models.[9]

-Examples of conventional indirect bonding methods in literature:

Silverman et al in 1975[10], improved indirect bonding technique using ultraviolet (UV) cured BisGMA resin and a perforated mesh base.

Swartz in 1974[11] proposed Sugar Daddy technique, caramel candy was used as an adherent for placing brackets to models. After completing the final trays, the caramel candy -water soluble material- was easily removed

from the back of bracket base then mesh pads were exposed for bonding in the clinic. The clean base method combined with a single silicone delivery IBT is the original technique used in indirect bonding.

Moin and Dogon [12]invented a technique in which they used a drop of sticky wax and it was placed on teeth surfaces of the cast. Then brackets were warmed over a flame followed by setting on the cast. Polyether material was used for impressions and tray separated from the cast but brackets remained in situ. Brackets are then removed from a cast, warmed again to eliminate residual wax then placed into the impression. Enamel surface applied with a mixture of both universal and catalyst sealant, bracket base was covered with the adhesive and tray was seated. There was enough time for adjustments until optimal bracket alignment was achieved.

Read and O'Brien and Read and Pearson [13] used transparent material for the transfer trays construction which allowed the use of light cured adhesive resins instead of the self-cured adhesive resins.

In 1990, Reichheld et al [14]used unique bracket placement jigs. Brackets with preformed height gauges were used and reinforced each height gauge with a little amount of sticky wax. A small piece of soft rope wax was placed over the cusp tips. The occlusal rests of the height gauges in the wax were embedded until they contact the incisal surfaces of the teeth while the bracket bases contact the labial surfaces of the teeth. As the wax remains soft, there was no time limit for brackets positioning. All brackets were placed in the same manner then rope wax was removed. Then a cold-cure acrylic splint was made and used for transferring the brackets from the model to the mouth. The splint was then removed from the model with gentle force. The acrylic splint could be transferred to the mouth using the

preferred indirect bonding system. This technique generally needs only 15 to 20 minutes.

Sondhi [15] presented effective and efficient indirect bonding method using APC brackets. Using these brackets, contamination was eliminated and laboratory time was cut to a minimum as individual brackets did not need resin to be applied to the base before being placed on a model. A fine particle fumed silica filler (approximately 5%) was used to increase the viscosity of the resin, so that the filled resin could overcome any small imperfections in the custom base crafted from the light-cured. Transfer trays were made by using Biostar unit to vacu-form a one mm thick layer of Bioplast, over layered with a one mm thick layer of Biocryl. On the other hand, a silicon putty could be used as a transfer material. Trans bond moisture insensitive primer (MIP) applied to enamel surfaces. Resin A was used onto the tooth surface and resin B was painted on the resin pads in the indirect bonding tray.

White [16] used Tacky Glue to precisely place brackets on the cast which was simple, inexpensive, water-soluble adhesive. The glue was removed during the tray transfer stage. He also used a hot-glue gun to form the matrix of the transfer tray construction.

In 2008, Vashi and Vashi [17] recommended the use of thermoplastic glue as earlier tried by White in 1999. But the trays were not rigid enough during full arch indirect bonding. So, thermoplastic impression compound was used in combination with thermoplastic glue in order to increase the rigidity of transfer trays. The technique had the advantages of being an economical and quick method for indirect bonding.

Also in 2008, B.Wendle[18] investigated an new transfer method using the Aptus Bonding Device (ABD) and concluded that it provides an accurate transfer method for indirect bonding of the brackets.

In 2012, a new technique called "Gum and Gun"[19] was described by *Aileni et al.* using Erkogum as an adhesive and glue gun for making transfer tray.

"Prescription-based precision full arch indirect bonding" is used by some researchers as they draw vertical long axis lines on the models indicating the long axes of the teeth. Then, they draw horizontal lines on the bicuspids and molars connecting the distal and mesial marginal ridges. They measure 2 mm between the tips of the divider, and transfer this measurement to the models by making a mark on the vertical lines (0.5 mm decrease for second molar). This mark is used to draw second line parallel to the marginal ridge line. The 2 mm slot line is arbitrary, so a clinician can choose 2.5 mm for larger teeth if suitable. After measuring the distance from the slot line to the cusp tip on the first bicuspid (it is usually 4.5 mm), the same measurement is transferred to the upper central incisors slot lines. The measurement is decreased by 0.5 mm for the lateral incisors and increased by 0.5 mm for the upper canines. For the posterior part of the lower arch, the same methods are used including marginal ridge lines, long axis lines, and slot lines. The measurement for the distance from the cusp tip on the first bicuspid to the slot line is obtained and is transferred to the mandibular centrals and laterals.[20,21]

Besides these, many attempts have been performed by the researchers in order to accomplish accurate indirect bonding by changing their ways either during laboratory or clinical procedures.

-Indirect bonding in lingual orthodontics [22]

In lingual orthodontics, indirect bonding is preferred because:

• Variations in lingual tooth structure which complicates the fabrication of a standard bracket.

• The persistent difficulty to achieve an ideal view for bonding.

• The difficulty of wire bending which could be needed in case of improper bracket placement.

• Lingual tooth morphologies are not familiar to the clinicians.

There are multiple indirect bonding techniques for lingual orthodontics. Orapix®[23] (Orapix, Seoul, Korea) system showed improved results. Another system, Incognito® (TOP Service, Bad Essen, Germany) System provides better results and reduces bond failure rate.

2-Accuracy and reliability

Many studies have been performed to evaluate accuracy and reliability in indirect bonding techniques, most of these studies assess either the bracket placement accuracy or the bond and shear strength compared to direct bonding or the precision of the used transfer tray.

i. In vitro studies evaluating shear-bond strength:

The strength of the brackets bonded using the indirect bonding technique was investigated in multiple studies. Unfortunately, rapid advancement of resin technology made it hard to compare these studies.

There are two SBS studies performed by *Hocevar and Vincent* [24]and *Milne et al* [25] in 1988 and in 1989, respectively, with similar results. In these studies, they used a chemically-cured resin (Concise) for direct and indirect

bonding groups. Then they investigated SBS of the groups and no differences was found in SBS between both groups.

Klocke et al[26] performed a study in 2003 comparing SBS values of different custom base resins in the indirect bonding groups with the direct bonding group[26]. Thermally-cured (Therma Cure), Chemically-cured (Maximum Cure), and light-cured (Transbond XT) resins were used for indirect groups, and there was no significant difference between the direct and indirect groups.

Polat et al [27]compared SBS values of three different groups; first group performed direct bonding using light-cured resin (Transbond XT),second group performed indirect bonding using chemically-cured resin (Custom IQ), and the third group performed indirect bonding using chemically-cured resin (Sondhi Rapid Set). There was no difference between the first and second groups, but the lowest bond strength was noticed for the third group.

Linn et al [28]compared the SBS values of the indirect and direct bonding groups in 2006. Sixty teeth were divided into three groups; one group used light-cured resin (Transbond XT) for direct bonding; another group used chemically-cured resin (Sondhi Rapid Set) for indirect bonding; and the last group used light-cured resin (Enlight LV) for indirect bonding. No differences were found among the groups.

In 2012 Shimizu et al[29] evaluated shear bond strength of brackets bonded by indirect and direct techniques, thirty healthy human maxillary premolar teeth were used. The teeth were divided into three groups,10 teeth each: the first group – indirect bonding with Sondhi™ Rapid-Set system (3M/Unitek), the second group – indirect bonding with Transbond™ XT adhesive system (3M/Unitek) and the third group – direct bonding with

Trans- bond™ XT adhesive system (3M/Unitek),they concluded that direct bonding group had higher Newton (N) and megapascal (MPa) values but the results found in the three groups were within the range of mean values found in the literature and within clinically accepted limits, therefore can be safely used in clinical orthodontic practice, and there's no need to use special primer for indirect bonding.

ii. In vitro studies of bracket position accuracy in indirect bonding:

Aguirre et al [30]evaluated bracket position accuracy in the indirect and direct bonding techniques. For both techniques, although they achieved the desired results, indirect bonding revealed favorable results for upper canines and direct bonding for second premolars.

In 1999, *Koo et al* [31] models of the same patient were 19 times, the first model was ideally bonded by one orthodontist, in the second group, nine models were bonded to a simulator and nine different orthodontists bonded brackets directly to these models using a light-cured adhesive (Transbond XT), in the third group, nine models were bonded to the simulator and the same nine orthodontists bonded brackets indirectly with a thermally-cured adhesive (Thermacure). Standardized photos of the model were taken, and measurements were obtained from the photos. They concluded that no differences were found in either mesio-distal or angular position of the brackets with both techniques, but the brackets, which were indirectly bonded showed more proper position in the vertical dimension.

In 2004, *Hodge et al* [32] evaluated the accuracy of indirect versus direct bracket placement, after using standardized photographic technique, they concluded that mean bracket placement errors were similar with both techniques.

Nichols et al[33] assessed bracket position repeatability in the indirect bonding technique in 2013. Five experienced orthodontists bonded 10 models at three different times. ICAT scanner was used for models scanning and superimpositions of the models were performed with a computer. As a result, every clinician's bracket position was consistent in them, the maximum bracket position deviation was 1.25 mm between the groups, and they concluded that orthodontists are consistent in determining bracket positions for an indirect bonding setup at different time periods.

Recently in 2018 *Kalra et al* [34] compared the accuracy of bracket placement by indirect and direct bonding techniques using digital processing, they found that the difference in accuracy in bracket placement between direct and indirect bonding was statistically insignificant, though indirect bonding yielded more accurate results on selected teeth. Neither technique yielded ideal bracket placement. Overall, Indirect bonding was better in terms of accuracy more often (60% for horizontal & 70% for vertical positioning), but the difference was statistically insignificant indicating high variability. Hence, the advantage wasn't consistent.

iii- In vivo evaluation of bond failures of indirectly bonded brackets

Polat et al[27] used two different types of chemically-cured resins (Custom IQ vs. Sondhi Rapid Set) using indirect bonding technique with a split-mouth for study design. Fifteen patients were enrolled in this study and were followed up for 9 months. Molar teeth were excluded in the study. A total number of 295 teeth were bonded indirectly, thirteen teeth (4%) were debonded, and there was no significant difference between the groups.

In 2006**,** *Thiyagarajah et al* [35] used light-cured resin (Transbond XT) for both indirect and direct bonding. Thirty-three patients were enrolled in this