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ORIGINAL RESEARCH

Modeling and Printing of Successive Misaligned Teeth Stages

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ABSTRACT

Introduction: Patients suffering from problems related to teeth crowding and misalignment require braces for realignment and restoring of perfect teeth. This process of realignment is a long-term treatment varying from 6 to 12 months including many stages during which teeth alignments are achieved in small steps. Patients are always eager to view their futuristic teeth alignment condition at the beginning of their treatment. This requires a predictive methodology on the part of the dentist, which is achievable using software tools and finally reproducing these software-designed stages using rapid prototyping.

Materials and methods: Dental molds, 3D Scanner, 3D Printer, and 3D computer-aided design software, such as 3-Matic, Maestro ortho studio, 3D Orchestrate, or 3Shape ortho studio for manipulations.

Results: According to the quantitative analysis, average variation between the preprint and postprint is 0.32. Three-dimensional (3D) printed models of these stages are within the units of 0.01 mm; hence, the rapid prototyping method supplements automation of the complete procedure of teeth alignment. Whereas, qualitative analysis of the scans after printing shows little-distorted boundaries due to which clarity has been slightly decreased but, according to the experts, this is clinically acceptable.

Conclusion: In this study, we provide an insight into generating different aligned stages or steps using available 3D software and further 3D printing of these stages using polylactic acid models.

Clinical significance: These models are expected to provide very important and tangible information related to the treatment purpose to both patients and dentists. These 3D models further provide platform for the manufacturing of customized transparent teeth aligners which are specific to the patient, better in esthetics, easy to wear, and is inexpensive than traditional teeth braces.

Keywords: 3D printing, 3D scanning, Braces, Computer-aided design, Dental molds, Teeth.

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INTRODUCTION

Teeth are a group of hard organs situated in the oral cavity which helps masticate food into small pieces. It has major role in the shape of face and mouth along with the production of speech.[1,2] Before going into the detail, some of the terms associated with study of teeth are mentioned below.

Human dentition: It is the collection of both upper and lower jaws wherein maxilla is the upper jaw and maxillary teeth are the one situated in the maxilla region. On the other side, mandible is the lower jaw and mandibular teeth are the one situated in the mandible region. In humans, two types of teeth are present during its lifespan. Primary dentitions are the initial set of teeth also known as baby teeth. They are 20 in numbers whereas permanent dentition is the second set of teeth also known as adult teeth and they are 32 in number. The tooth is made up of two major parts known as root and crown. Crown is the part of tooth visible to the naked eye whereas, the root is a part which is not visible and is anchored beneath the bone.[3] Primarily, each tooth is comprised of four tissues: Enamel, dentin, pulp, and cementum. Enamel is the outer protective surface of crown. Dentin is the inner of tooth which is normally seen with the X-ray. The pulp is the region inside the tooth which holds blood vessels and nerves of tooth. It is present in center and occupies both crown and roots whereas, cementum forms the exterior surface of the tooth root which is softer than enamel. Both mandible and maxilla comprise similar structure of teeth. Teeth are basically of four types: incisors, canine, molars, and premolars. Each of them has its own functionality in process of mastication. Incisors are the first four front teeth present in both mandible and maxilla. The teeth in the center are central incisors and those on either side are lateral incisors. They are like scissors which help in cutting of food. Canine are teeth located next to the incisors. There are two canines in the maxilla region and two in the mandible region which help in tearing the food while chewing. Premolars are teeth located next to the canine and there are four premolars in the maxilla as well as in the mandible region respectively, which help in crushing of food while chewing. They are not present in primary dentition. Molars are the teeth located on the corners of maxilla and mandible and are available as six in number in both regions respectively, which aids to grinding of food. These are classified into first, second, and third molars, but third molars are not developed in every person.[4]

There are many dental anomalies which are operated by the orthodontics. Some of them are underbite, spacing, protrusion, crowding, crossbite, overbite, open bite, and midlines.[5] Underbite is the condition in which the front teeth of lower jaw extend outward in such a way that it causes lower front teeth to sit in front of upper front teeth. Spacing is the condition in which there is gap between teeth due to missing teeth, small teeth, or large dental arches. Protrusion is the condition in which upper front teeth are extending forward in such a way that it causes upper front teeth to sit in front of lower front teeth. Crowding is the condition in which all teeth do not get enough space to fit in the jaw. Crossbite is the condition in which upper teeth sit inside the lower teeth which may result in altered growth of jaw leading to connective surgery in future. Overbite is the condition in which there is a vertical overlap of upper front teeth over the lower front teeth leading to biting of roof in the mouth. Open bite is the condition in which upper and lower front teeth do not overlap leading to improper chewing and tongue thrusting. Midlines not matched are the conditions in which middle teeth in front do not lie up between lower and upper arches.[5] Among the above-mentioned problems, some of them can be corrected by the use of braces.

The designing of braces is a challenging task for orthodontics in which improvement in the structure of teeth is provided by removing various anomalies and taking person's safety into consideration. Braces must be designed in such a way that they accurately fit on the teeth of a person and do not infect the person's mouth. Braces are devices that straighten and align the teeth in their original position. Some of the commonly available braces till date are: metal braces, ceramic braces, lingual braces, and invisible braces. Metal braces are the least expensive stainless steel braces used till date. They are thin wire placed with rubbers to build pressure on teeth to move in the desired position with the drawback of being visible. They may also irritate cheeks and gums initially. It is generally suggested by orthodontics to avoid eating hard foods when braces are placed on teeth.[4] Ceramic braces are more expensive than metal braces as they are blended in such a way that they are less visible as compared to metal braces and use white elastic ties to hold braces in their position. Ties are replaced each time braces are adjusted in span of months and are more sensitive to get damaged. Their time of maintenance and installation is more than metal braces which result in increased cost.[6] Lingual braces are customized to bind and hide behind the teeth to remain out of sight. They are more costly than ceramic braces due to complicated process and hence, require orthodontics to install them. For small teeth, lingual braces are not favorable as they touch the tongue resulting in speech problems and injuries. Invisible braces or clear aligners, such as Invisalign are more costly than other types as they are totally invisible and require less number of visits to the doctor.[7] The aim of this study is to model various alignment stages during the dental treatment and their fabrication to design aligners. It starts with the scanning of dental molds and ends on printing of customized and transparent aligners along with providing all intermediate stages.

MATERIALS AND METHODS

In this section, a detailed procedure for the designing of aligner has been presented which used a series of steps, starting from the use of plaster model to 3D printing of the model, using thermoforming to generate an invisible clear aligner.

Step 1: Using Plaster Models

In this step, plaster models were developed by taking negative impressions of hard and soft tissues of oral-maxillofacial region using alginate powder and dental impression trays.[8,9] These elastic impressions were then converted into hard, stable dentition cast models designed in such a way that it included both teeth with normal cases and crowding problems (Fig 1).

Step 2: Scanning of Dental Casts to generate Its Optical Scan

In this step, tooth models were scanned to get its 3D image which was manipulated using step 3. This scan was in stereolithography (STL) format. Figure 2 shows the view of optical scanned dental molds for a patient with misaligned teeth. This scan was used to generate different stages by altering various teeth positions along different axis.

Fig. 1: Plaster models

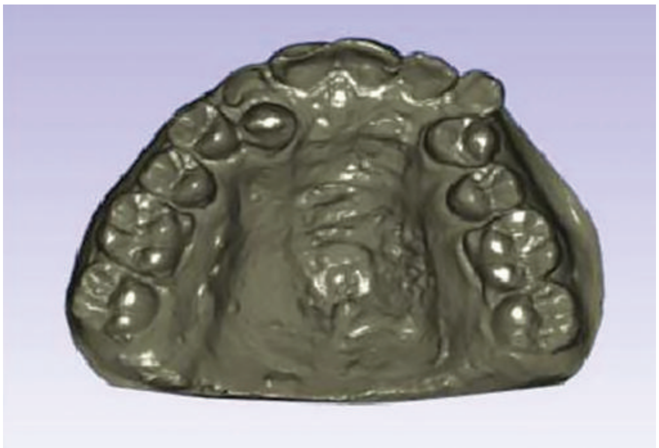


Fig. 2: Scanned dental mold

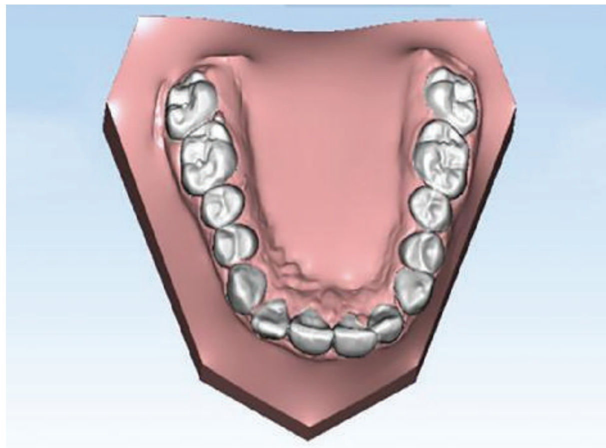


Fig. 3: Stage of Invisible aligner

Step 3: Editing of Optical Scans to generate Stages of Aligners

In this step, manipulations were performed on STL file generated using above step to design stages of clear aligner on 3D computer-aided design (CAD) systems, such as 3-matic, maestro, 3D orchestrate, or 3shapes.[10-13] This output was in STL format which was used directly for 3D printing. Figure 3 shows the stage of clear aligner designed after manipulations on crowded teeth model.

Step 4: Thermoforming

In this step, a standalone plastic sheet was transformed to develop clear aligner by reshaping it on the above-generated stage models. It is a process of reshaping the plastic sheet to the shape of object by heating at certain temperature and applying the pressure on it to form the shape of an object on which it is kept. Later, it was removed from the object firmly by removing extra parts to get the final precise shape of object.[14,15] For this process, a special thermoplastic material polylactic acid was used which incorporated itself into the shape of model. The mould scans, after manipulation of the teeth positions, was used to generate negative image of the mold called aligner (Fig. 4).

GENERATION OF STAGES IN 3D CAD SOFTWARE

For the purpose of creating aligner using step 3 discussed above, we used 3D CAD software, such as Mimics, Maestro, Orchestrate, or 3Shape [10-13] which follow basic steps as given below to create the stages of aligners.

- *Step 1*: Load STL file
  In this step, the desired pair of scanned files was loaded in the 3D CAD software from its database to visualize the position of each tooth for abnormality.

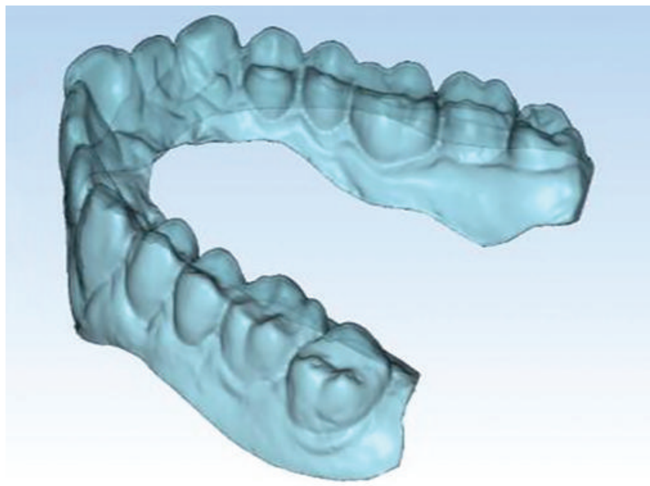
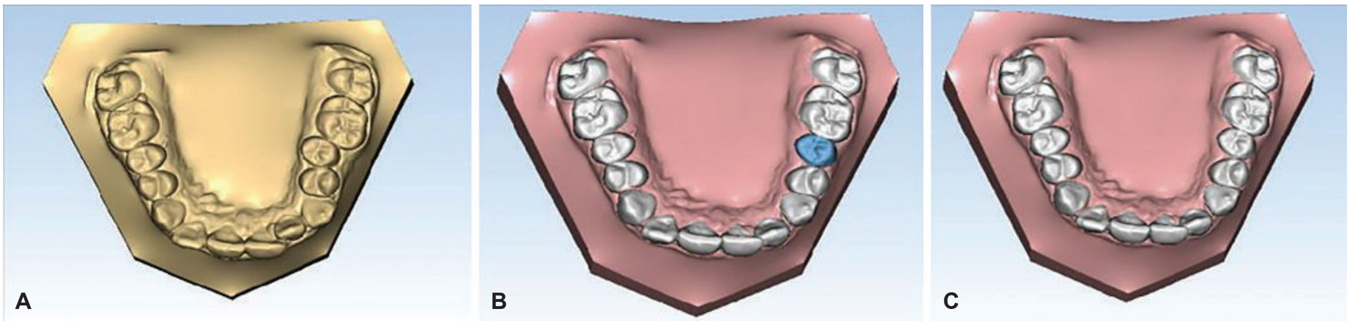


Fig. 4: Clear aligner created using 3D computer-aided design software

- *Step 2*: Perform manipulation
  This step was used to measure the length of each tooth to separate the gingival and tooth regions from each other in a model for easy visualization of abnormality. It was carried out from analysis and measure functionality in 3D CAD software. Furthermore, segmentation was performed and measure of each tooth was used to create contour around each tooth to separate it from gingival regions totally. Thereafter, single defective tooth was selected and manipulated accordingly to create stages using operations, such as displacement and rotation from virtual setup tab in 3D CAD software.
- *Step 3*: Save tooth model
  Manipulated tooth model was then saved to create its sublayer and modeled for further analysis using virtual tab. In the last step, the aligner was exported in STL format for printing and designing the invisible aligners which can be used by patients.

Figure 5 shows the steps performed for generation of stages of clear aligner.



Figs 5A to C: Steps for creating stage of invisible aligner using computer-aided design software: (A) Initial stage; (B) manipulation of selected tooth; and (C) final stage with corrected teeth

Distortions were carried out on upper jaw using the manipulations, such as:

- Rotation

A rotation is a circular movement of an object around a center. It is measured in unit of degrees. It is of two types:

1. Negative (counterclockwise)
2. Positive (clockwise)

- Buccallingual

It is forward and backward movement of tooth from its original position. It is measured in millimeters (mm). It is of two types:

1. Negative (forward)
2. Positive (backward)

- Mesial-distal

It is sideways movement of the tooth to generate space for tooth or to remove the overlapping of two teeth. It is measured in millimeters (mm). It is of two types:

1. Negative (left)
2. Positive (right)

- Torque

It is the description of movement that more accurately describes the rotational components of a force system and appliance design. It is of two types:

1. Inward torque
2. Outward torque

- TIP

A tooth movement in which the angulations of the long axis of the tooth is altered.

- Extrusion/intrusion

It is inward and outward movement of tooth. It is of two types:

1. Negative (inward)
2. Positive (outward)

These manipulations were performed on upper jaw and five stages were created using measures as given in Table 1.

Thereafter, the manipulated molds generated from 3D CAD software were printed and further manipulated to analyze the accuracies of scanner and printer.

Table 1: Manipulations performed on upper jaw

Stage 1						
Teeth	TI	R	TO	B-L	E-I	M-D
18	0	0	0	0	0	0
17	0	0	0	0	0	0
16	0	0	0	0.5	0	0.5
15	0	0	0	0.5	0	0
14	0	0	0	−0.5	−0.4	0.4
13	0	−1	0	−0.28	0.41	0.12
12	0	0	0	−0.49	−0.47	0.44
11	0	0	0	−0.5	0	0.5
21	0	0	0	−0.5	0	−0.2
22	0	0	0	−0.5	0	−0.5
23	0	0	0	0	0	−0.3
24	0	0	0	0	0	−0.5
25	0	0	0	0	0	−0.4
26	0	0	0	−0.5	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
Stage 2						
Teeth	TI	R	TO	B-L	E-I	M-D
18	0	0	0	−0.2	0	0
17	0	0	0	−0.5	0	0
16	0	0	0	1	0	0.5
15	0	0	0	0.5	0	0
14	0	0	0	−1	−0.4	0.4
13	0	−2	0	−0.27	0.41	−0.18
12	0	0	0	−0.99	−0.47	0.94
11	0	0	0	−0.9	0	0.5
21	0	0	0	−1	0	−0.2
22	0	0	0	−0.5	0	−0.5
23	0	0	0	0	0	−0.3
24	0	0	0	0	0	−0.5
25	0	0	0	0	0	−0.4
26	0	0	0	−0.5	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
Stage 3						
Teeth	TI	R	TO	B-L	E-I	M-D
18	0	0	0	−0.2	0	0
17	0	0	0	−0.5	0.6	0
16	0	0	0	1.5	0	0.5
15	0	0	0	0.6	0	0
14	0	0	0	−1.5	−0.4	0.4
13	0	−6	0	−0.29	0.41	0.095
12	0	0	0	−1.4	−0.47	1
11	0	0	0	−1.3	0	0.7
21	0	0	0	−1.4	0	−0.3

(Cont'd…)

(Cont'd…)

Teeth	TI	R	TO	B-L	E-I	M-D
22	0	0	0	−0.5	0	−0.5
23	0	0	0	0	0	−0.3
24	0	0	0	0	0	−0.5
25	0	0	0	0	0	−0.4
26	0	0	0	−0.5	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
Stage 4						
Teeth	TI	R	TO	B-L	E-I	M-D
18	0	0	0	−0.2	0	0
17	0	0	0	−0.5	0.6	−0.5
16	0	0	0	2	0	0.3
15	0	0	0	0.6	0	−0.2
14	0	0	0	−1.9	−0.4	0.3
13	0	−4	0	−0.29	0.41	0.11
12	0	0	0	−1.4	−0.47	1
11	0	0	0	−1.3	0	0.7
21	0	−1	0	−1.9	0	−0.33
22	0	0	0	−0.5	0	−0.5
23	0	0	0	0	0	−0.3
24	0	0	0	0	0	−0.5
25	0	0	0	0	0	−0.4
26	0	0	0	−0.5	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
Stage 5						
Teeth	TI	R	TO	B-L	E-I	M-D
18	0	0	0	−0.2	0.5	0
17	0	0	0	−0.5	0.6	−0.5
16	0	0	0	2.5	0	0
15	0	0	0	0.6	0	−0.2
14	0	0	0	−1.9	−0.5	0.3
13	0	−4	0	−0.29	0.41	0.11
12	0	0	0	−1.4	−0.16	1.1
11	0	0	0	−1.3	−0.3	0.7
21	0	−2	0	−1.9	−0.3	−0.37
22	0	0	0	−0.5	−0.2	−0.5
23	0	0	0	0	0	−0.3
24	0	0	0	0	0	−0.5
25	0	0	0	0	0.2	−0.4
26	0	0	0	−0.5	0.2	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0

TI: TIP; R: Rotation; TO: Torque, BL: Buccallingual; EI: Extrusion intrusion; MD: Mesial-destal

Steps used for evaluating accuracy of printed samples are as follows:

- Take an initial model with misaligned teeth.
- Perform some manipulations on it to generate an intermediate stage.
- Now print the model of intermediate stage to analyze the accuracy of printer.
- Input it again to 3D CAD software for performing manipulation.
- Check the measurements of manipulated files before printing and after printing.
- Compare the differences between two files.

Based on the above steps, measurements before and after prints were analyzed to calculate the accuracy of scanner and printer. For comparison of accuracy, manipulations were performed on same set of upper jaw scans before and after printing (Fig. 6).

RESULTS AND DISCUSSIONS

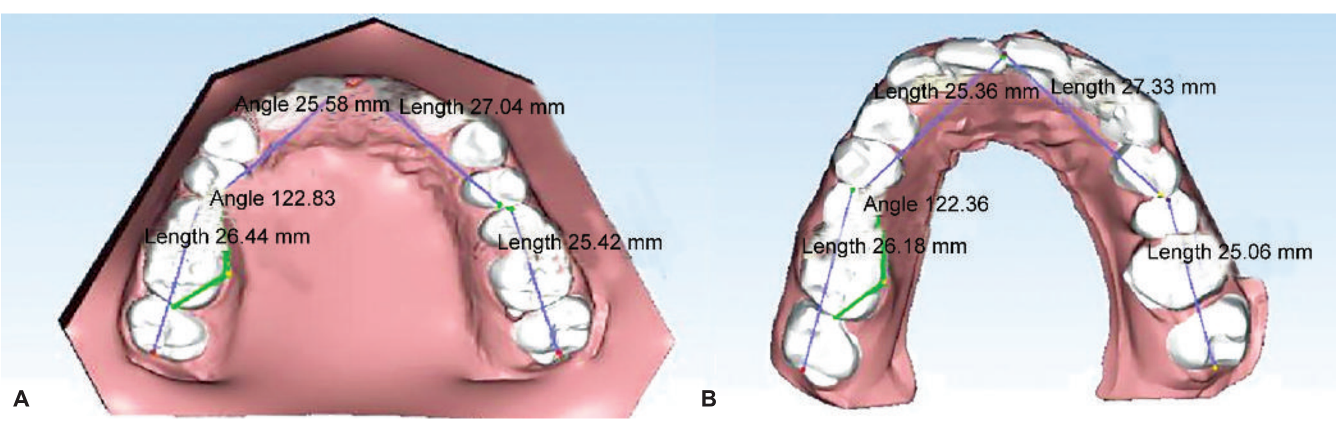
Numerical values displayed in Figure 6 shows that the printing has slightly deviated the measurements in scanned files of preprinting and postprinting. For the analysis, five measurements have been carried out as listed in Table 2.

From the above measures, it can be analyzed that average variation between the preprint and postprint is 0.32 which can also be visualized with the help of images shown above for the scans of preprint and postprint images. According to the quantitative and qualitative analysis, scans after printing has distorted the boundaries

Table 2: Comparison of preprint and postprint

Preprint (mm)	*Postprint (mm)*	*Variations*
26.44	26.18	0.26
122.83	122.36	0.47
25.58	25.36	0.22
27.04	27.33	0.29
25.42	25.06	0.36

Average = 0.32



Figs 6A and B: Analysis of the scans: (A) Before printing; and (B) after printing a little due to which clarity has been slightly decreased, but this is clinically acceptable.

CONCLUSION

This study has presented an approach to design different stages of patient's misaligned teeth. It also discusses the method to design aligner from the images of their misaligned teeth. Various stages have been successfully 3D printed which can be used by dentist for better understanding of patient's treatment. These models can be used to fabricate accurate diagnosis using thermoforming. Using Scanner and software methods, lot of inaccuracies get eliminated which are common in traditional wax method of taking impression. Three-dimensional printed models of these stages are within units of 0.01 mm; hence, the rapid prototyping method supplements automation of the complete procedure of teeth alignment.

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