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Measurement and analysis of tooth movements during orthodontic treatment with clear aligners

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Abstract. This article aims to study, measure and verify through Reverse Engineering techniques and 3D analysis, the results obtained by an orthodontic treatment for the alignment of the teeth, using clear aligners (CA). A case study of a patient who followed orthodontic treatment using a set of 19 CA was analyzed: dental impressions by intraoral scanner were made before and after treatment; the study also analyzed the project planned by Invisalign ClinCheck® software, comparing it to the results clinically obtained, using specific software and hardware. The analysis of the obtained results shows that the measurements carried out are affected by a residual error respect to the final situation designed for the patient, caused by several factors here investigated; moreover, it is very determinant to do a correct diagnosis, to formulate an adequate treatment plan and to correct wear the chosen orthodontic appliances.

Introduction

Clear Aligners (CA) allow to perform an almost invisible orthodontic treatment that leads the teeth into the desired position through a set of clear thermo-molded plastic dental masks to be worn all day in sequence during the treatment, for a total duration that could go from few months to one or two years. The final alignment is digitally designed in the preliminary phase of the treatment: at the end, teeth will reach the pre-established positions, giving to the patient the desired aesthetic appearance and function [1] [2].

Generally, the impressions of the dental arches are acquired by an intraoral 3D scanner. The digital project defines the final shape of the arches and divides the total movements into treatment steps, distributing them over a variable number of aligners. The application of each individual aligner induces specific forces and torques to each tooth, which should cause the required movements to reach the right final position of the teeth; but this results are not always predictable in size and accuracy [2] [3]. CA are an alternative to classic metal brackets, but it is always necessary to rely on the judgment of a specialist to undertake the most suitable therapeutic path for each medical condition and for the type of coronal and root movements required [4]. Some studies have used the forces needed to obtain teeth movements with CA using Finite Elements Method for the prediction [5] [6] [7].

This work aims to measure and verify through Reverse Engineering techniques and 3D analysis, the results obtained in a case study using CA.

Materials and Methods

A case study of a patient treated with CA was analyzed. A completely digital data flow was adopted: from the dental impressions with intraoral scanner, to the planning of the treatment and definition of the pairs and sequences of aligners, to the simulation of the treatment result with Invisalign™ ClinCheck® proprietary software [8], up to the scanning of each pair of aligners (19) and comparison with the intraoral scans taken before and after treatment. The aim was to verify the real tooth movements of each affected tooth. The study also analyzed the project provided by Invisalign, complete with *.stl format files and related documentation such as the values of the single displacements from the initial situation to the final designed one.

Special attention was given to the first and last couples of aligners acquired by the initial and final intraoral scans. provided by a dentist specialist in orthodontics.

The software and hardware used in are:

- Revo Scan for the acquisition of the aligners using the Revopoint POP 2 scanner [9].
- Meshmixer [10]for cleaning the aligners and for joining the roots to the teeth.
- GOM Inspect [11] for all alignment operations and three-dimensional analysis [12].
- Matlab [13] for data analysis and drawing up graphs.

Results and discussion

Once the files in *.stl format of the intraoral scans at the end of the treatment and of the final situation designed on Invisalign have been obtained, it is possible to check at first glance whether the results actually obtained from the treatment are in line with the design initially realised.

Using the GOM Inspect software, the two models were imported and once the alignment was performed, it was possible to carry out the dimensional analysis. The software allows to measure deviations in terms of distances between the two models using various color maps such as those shown in Figure 1.

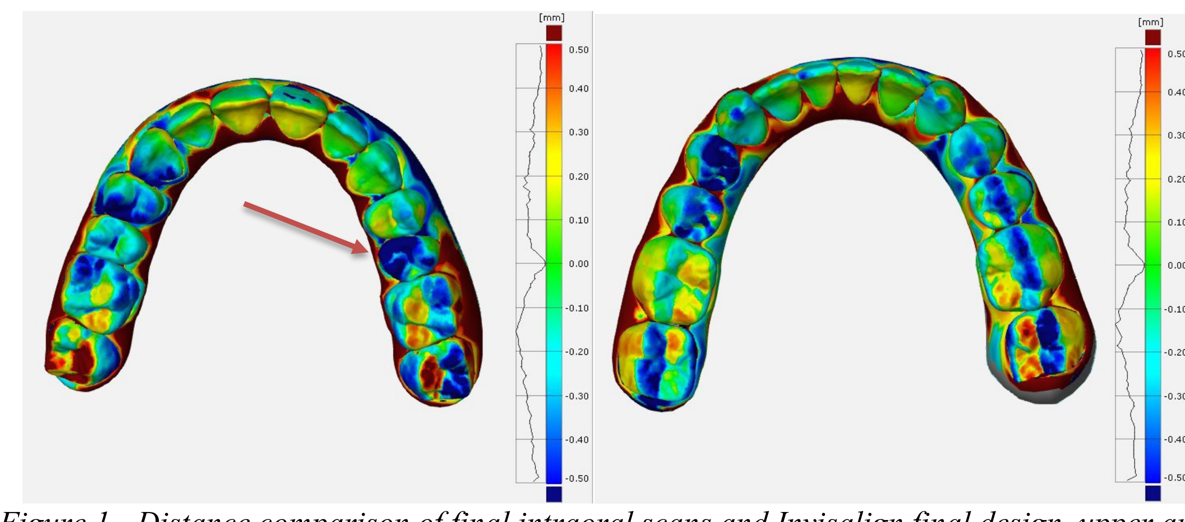

Figure 1 - Distance comparison of final intraoral scans and Invisalign final design, upper arch (left) and lower arch (right)- scale [0.5; -0.5] mm.

The intraoral scanner used was a TRIOS from 3shape, which has a long-span measurement accuracy of approximately 80 microns [14]. As can be seen from the figures, there is no perfect alignment between the two models. In fact, as the sensitivity of the scale increases to [0.5; -0.5], the alignment defects become more evident.

The teeth subject to the greatest error are the second molars and the four premolars of each arch, while the frontal and lateral incisors are the teeth whose final result is closest to the situation designed by ClinCheck®. The dental element that deviated the most from the project is 2.5

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(marked in the figure), whose correction entity is significantly lower than expected, so much so that it was necessary to proceed with a brief phase of alignment of this element.

The attachment made by the aligner supplier was not able to produce all the expected tooth movements for the most critical tooth, maybe due to a design error by the same company. In fact, post-treatment the tooth needed an additional set of 18 aligners to achieve the set objectives, for which the dentist opted for a traditional overcorrection treatment to reduce therapy times and costs.

However, it is possible to state that the error is less than a millimeter, as can be obtained from the previous maps.

Acquisition of Aligners

Parallel to the result obtained with the treatment, to better understand the movements that the teeth make inside the aligners, it is necessary to align the individual teeth inside the aligners. This operation is made possible by using the GOM software [11], which also allows you to compare the result of the alignment with the initial ClinCheck® project and with the final intraoral scans.

For this purpose, the 19 aligners were scanned using the structured light “Revopoint POP 2” scanner [9] and related software which provided the various point clouds and then the specific meshes. The transparency of the aligners made it necessary to coat them with a generic opacifying spray so that the scanner could detect the individual points (Figure 2).

According to data provided by the manufacturer of the scanner, it has a dimensional accuracy in the single frame acquired of 50 microns.

Once the aligners were acquired, a revision and cleaning operation was carried out on the Meshmixer software, by Autodesk [10]. Finally, as the last step of acquiring and cleaning the meshes, the latter were oriented automatically when some triangles had their inverted normal.

Figure 2 - Setup for acquisition of aligner Point cloud captured by Revopoint POP 2 scanner

Teeth Alignment

Analysis and Preliminary Operations

To align the teeth to the final situation, it is necessary to insert the model of each tooth inside the last tray of the treatment and using local best-fit, translate and rotate the affected tooth to have the most suitable alignment to the tray.

Before proceeding with the alignment, it is necessary to carry out some preliminary steps to obtain an appropriate starting point that allows comparisons to be made with the intraoral scans and with the situations designed by ClinCheck®:

- each dental element was segmented and renamed according to medical convention.
- to obtain a greater understanding of the overall movement of the tooth and its root, the respective 3D models of the tooth roots were added to the 3D models of the teeth crown provided by ClinCheck® [8] and this operation was performed using 3D models of roots not belonging to the patient, joined to the teeth on the Meshmixer software [10].

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Alignment of the final couple of Aligners

Before inserting the individual teeth, aligning them inside the final tray, the latter was aligned to the respective arch (lower or upper) of the pre-treatment ClinCheck® [8] project. This activity is necessary because by loading the arch and the template in the same GOM Inspect project [11], the two models are arranged in different points in space.

Therefore, it was necessary to identify which teeth by design would undergo the least displacements, since they already had good general positioning over the entire dental arch, and thus proceed to align the final tray according to the position of these teeth considered "fixed." The teeth in question are teeth 1.6, 2.6, 3.6 and 4.6, respectively, as shown in Figure 3 according to traditional nomenclature.

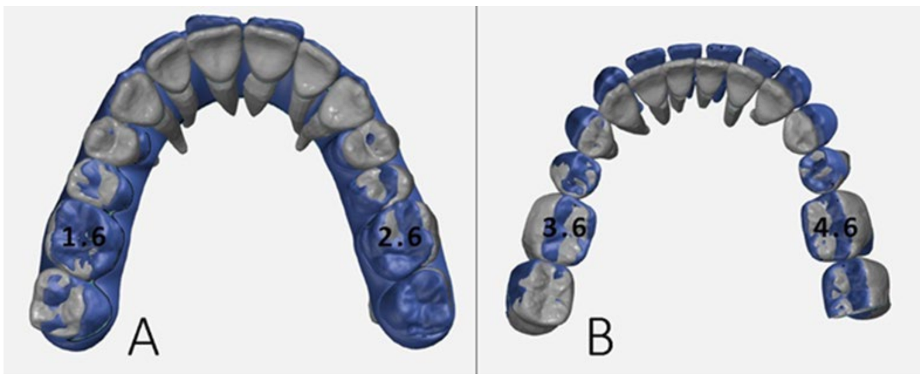

Figure 3 - A) Comparison of final aligned upper arch and initial upper ClinCheck® design; B) Comparison of final aligned lower arch and initial lower ClinCheck® design.

Using these alignments, it is already possible to deduce what the movement of the teeth will be, in particular, that of the front and lateral incisors which will have to move in the lingual direction.

The main advantage of this alignment consists in the possibility of proceeding with the direct comparison between the dental arches, without carrying out further alignment operations, once the individual teeth have been aligned as described below.

Alignment of Individual Teeth

The operator who carries out the analysis is responsible for choosing the alignment that best translates the set objective. It is useful to report the criteria pursued for the realization of the alignment:

- The colour map for alignment evaluation has the same setup for all teeth, precisely it has a tolerance range between [-0.2; 0.2] mm able to achieve maximum precision.
- The tooth must lie perfectly in its special space inside the mask and its tip must coincide with the edge of this. The local best-fit output does not always result in proper tooth placement and to overcome this problem, it is sufficient to carry out a "best-fit" on the tip of the crown and finally on the frontal part of the tooth;
- The best result was evaluated on the buccal part of the tooth for the incisors and canines, while on the entire dental crown for the molars.

Attention is drawn to the fact that the mask model does not match exactly the dental model. In fact, due to the elastic properties of the aligner material, during use, the elastic deformation of each individual aligner is able to apply the forces necessary for the required movements to the teeth. The material patented by the company is a particular polycarbonate, created specifically for medical use, multi-layer, highly elastic and transparent [4].

Once the desired alignment has been achieved, the tooth is exported in ".stl" format.

The output of the alignment between the teeth and the aligners (upper and lower aligner no. 19) is shown in Figure 4 and 5.

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The results obtained are considered by the team to be the best compromise between the above criteria. On the teeth where the attachments have been removed and the holes automatically closed, the colour map shows blue areas (-0.2 deviation between elements), these errors are therefore accepted.

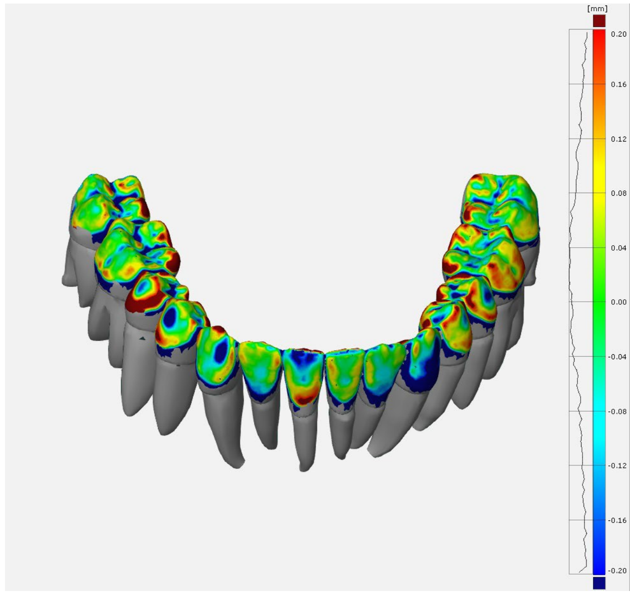

Figure 4 Lower arch: comparison between aligned teeth and aligner 19, scale [0.2; -0.2] mm

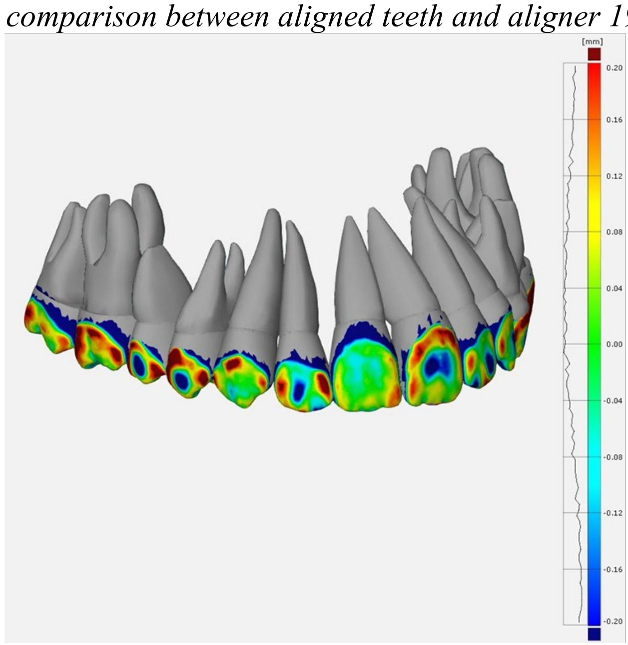

Figure 5 Upper arch: comparison between aligned teeth and aligner 19, scale [0.2; -0.2] mm

Assessment of Movements

Tooth Movements (Figure 6)

From a clinical point of view, tooth movements can be divided into [15]:

- Horizontal, when the tooth moves in a mesio-distal or buccal-lingual direction.
- Vertical, when the tooth moves in an occlusal or gingival direction.
- Circular, when the tooth moves around the long axis of the tooth.
- Torque, when the tooth changes its position within the bone structure (move the tooth buccally-lingually around its centre so that the crown and the root move in opposite ways).

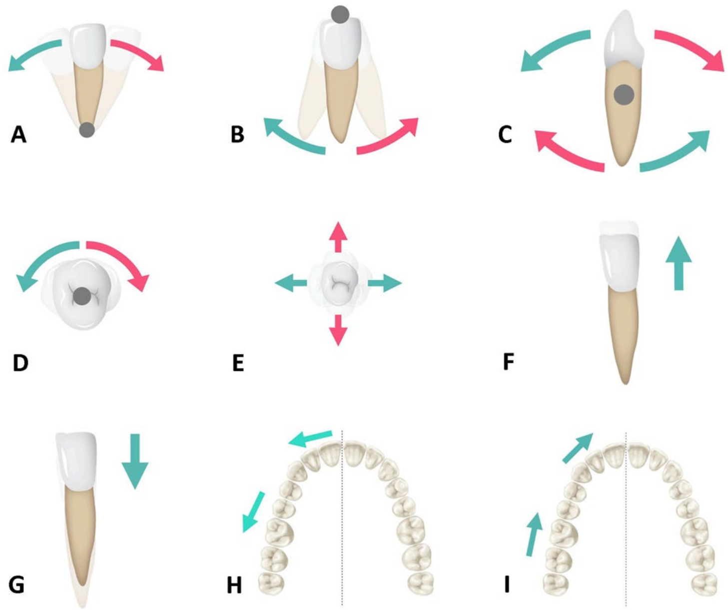

Figure 6 Main tooth movements: A) Crown tipping B) Root tipping C) Torquing D) Rotation E) Translation F) Extrusion G) Intrusion H) Distalization I) Mesialization [15] [16]

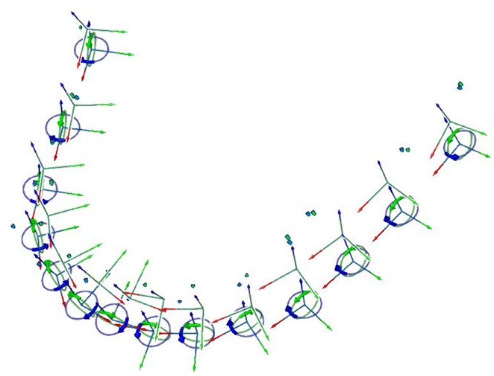

Figure 6 Reference systems on mesh and CAD models on the 'lower' arch for the evaluation of rotations

Having obtained the displacements between the initial situation (after the first phase of the treatment) and the final intraoral scans, using the Matlab software it was possible to calculate the displacement vector by performing the "norm two" of the three components of the displacement. The vector was calculated for the movements designed by ClinCheck® and those detected by measurements using GOM. The difference between the two displacements can then be calculated (Figure 7,8,9 and 10).

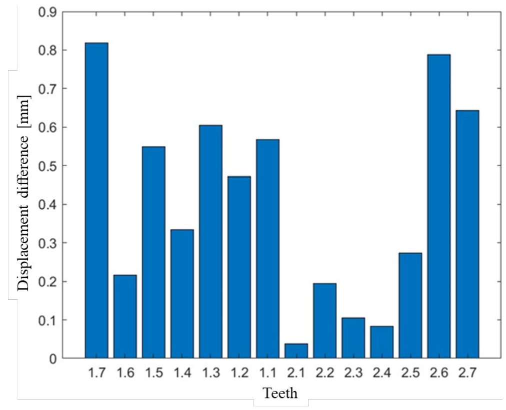

Figure 7 *- Upper arch: difference in displacements between the ClinCheck® design and teeth movements detected by GOM Inspect*

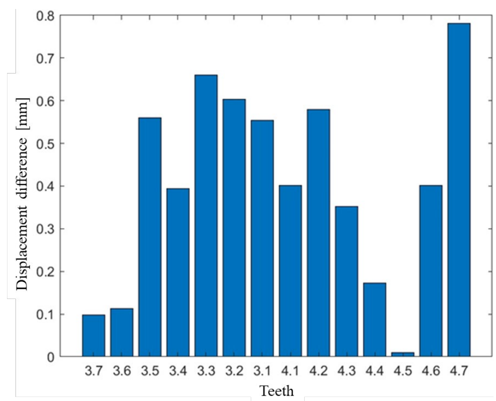

Figure 8 *- Lower arch: difference in displacements between the ClinCheck® design and teeth movements detected by GOM Inspect*

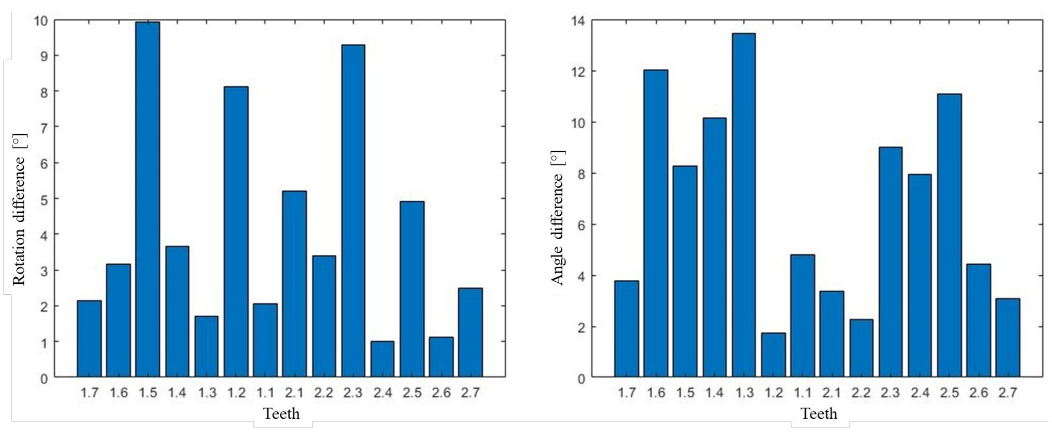

Figure 9 *- Absolute error of rotation and angulation of the teeth of the upper arch*

Error Considerations

The GOM displacement evaluation procedure is not immune to errors for the following reasons:

The reference systems considered may not coincide with the reference systems considered by the Invisalign ClinCheck® software for the evaluation of displacements and rotations, which may also be non-Cartesian (see [16]).

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The alignment procedure was carried out on elements that were not fixed in space: the so-called "fixed teeth" were actually subject to movement, especially rotation. All these factors could affect the measurement as the error is of the same order of magnitude as the variable to be measured.

By calculating the average value of the difference between the final displacements designed by ClinCheck® and those obtained from the GOM analysis, we obtain a value equal to $\Delta_{s\_sup} = 0.4061\ mm$ for the upper arch and $\Delta_{s\_inf} = 0.4058\ mm$ for the lower arch.

The values obtained are compatible with the colour maps. The average error for the rotation and angulation of the lower arch is equal to $\Delta_{rot\_inf} = 4.4°$ and $\Delta_{ang\_inf} = 4.9°$. For the upper arch instead $\Delta_{rot\_sup} = 4.2°$ and $\Delta_{ang\_sup} = 6.8°$.

Conclusions

The analysis of the results obtained shows that the measurements carried out in the project work are affected by a residual error with respect to the final situation designed for the patient. The error is caused by several factors:

- Inaccuracies maybe due to the scanner used for the acquisition of the aligners (Revopoint POP 2) not specific to the application.
- The operations carried out by the study group do not have an automatic and unambiguous procedure by the GOM Inspect software. In fact, to obtain greater precision in the work performed, it would have been advisable to use dedicated software capable of reducing the discretionarily of some operations such as the construction of the plans, the definition of the reference systems, the choice of significant points and the alignment operations. For example, the plane construction operation is based on the manual choice of points by the operator, which is why the accuracy and precision of the result do not depend on objective factors.
- The difficulty of the measurement operations is due to a degree of precision required for the case study of the order of tenths of a millimeter and to the intrinsic complexity of the tooth surfaces. In fact, the absence of standardization (dental elements that are different from each other and without significant geometric points) results in a very complex engineering situation.

A possible solution to minimize all the error components, in particular that of alignment, is to keep part of the palate present in the intraoral scan from the ClinCheck® project, in order to carry out the alignment on a fixed surface.

At the end of the following analysis work it was possible to notice how the end point of the orthodontic treatment does not coincide perfectly with the ClinCheck® project, as reported in [17], with an estimated deviation of less than one millimetre.

By minimizing the error and in the presence of data on the progressive movements of the teeth, a more in-depth analysis could be carried out by repeating the operating method illustrated for all subsequent pairs of masks.

But considering that each aligner can produce a maximum of 0.25 mm of dental movement, 2 degrees of rotation and 1 degree of torque [1], not respecting the instructions for use of a single aligner also means compromising the movements of subsequent aligners. To all this must be added the unpredictability of the movements of the teeth, which, being non-inert organs and considering the reactions of their support tissues, oppose the movements.

Therefore, explaining the reason for this difference, albeit small, it is very complex as the success of an orthodontic treatment depends on the combination of two factors:

- a correct diagnosis and consequent formulation of an adequate treatment plan.
- a correct clinical application of the chosen orthodontic technique.

The professionalism of the specialist must therefore also be accompanied by the determination of the patient, but it is essential to motivate the latter to wear the aligners correctly for 20-22 hours a day for the entire treatment period.

If from an engineering point of view the treatment has errors that are not negligible, from a clinical point of view it can be said that the patient, thanks to the Orthodontist practice, obtained a result very close to the desired one, i.e. a good balance between the dental arches and a progressive improvement of the aesthetic appearance.

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