

Article

Clinical Evaluation of Torque Protocols on the Stability of 3D-Printed Anatomical Healing Abutments

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Abstract

(1) Background: Customized 3D-printed anatomical healing abutments (AHAs) are increasingly incorporated into digital implant workflows to optimize emergence profile development. However, the influence of tightening torque on their mechanical stability remains poorly understood. This prospective pilot clinical study evaluated the effect of different torque protocols on the stability of 3D-printed AHA placed on intermediate abutments. (2) Materials and Methods: Forty-two patients (52.4 ± 12.3 years) receiving 60 Paltop implants (Paltop Advanced Dental Solutions Ltd., Ashkelon, Israel) were included. Following implant uncovering, all implants received titanium intermediate abutments fabricated from a photopolymerized acrylate-based resin (MAZIC D TEMP; Vericom Co., Ltd., Chuncheon, Republic of Korea), torqued to 35 Ncm, and were allocated to four AHA tightening protocols. Clinical mobility, torque maintenance, and mechanical complications were evaluated at 4, 8, and 12 weeks. Group comparisons were performed using Fisher's exact test. (3) Results: At 12 weeks, mobility occurred in 5/15 AHA (33.3%) in the hand-tightened group and 1/15 AHA (6.7%) in the 20 Ncm group, whereas no mobility was observed in 15/15 AHA (100%) in both the 25 Ncm and 30 Ncm groups. Mechanical complications differed significantly among groups (Fisher's exact test, $p = 0.047$). (4) Conclusions: Tightening torques ≥ 25 Ncm provided superior early mechanical stability of 3D-printed AHA.

Keywords: digital implant workflow; 3D-printed healing abutment; implant–abutment stability; torque protocol; emergence profile



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1. Introduction

Dental implant therapy is a highly predictable treatment modality for replacing missing teeth, with long-term success dependent not only on osseointegration but also on the development and maintenance of stable peri-implant soft tissues [1]. Stable soft tissue architecture is essential for preserving the peri-implant mucosal seal, minimizing bacterial infiltration, maintaining marginal bone levels, and supporting long-term peri-implant tissue health [1]. In contemporary implant dentistry, particularly following ridge preservation or ridge augmentation procedures, preservation of the peri-implant transmucosal architecture

is critical for achieving predictable biologic and prosthetic outcomes. Healing abutments play an important role in shaping peri-implant soft tissue contours and establishing the emergence profile prior to definitive prosthetic rehabilitation. However, conventional stock healing abutments often demonstrate limited anatomical conformity and may inadequately support individualized peri-implant contours, potentially compromising esthetic outcomes and necessitating additional soft tissue modification procedures [2].

Recent advances in digital dentistry and additive manufacturing have facilitated the incorporation of customized healing abutments into digital implant workflows. Customized healing abutments fabricated using computer-aided design/computer-aided manufacturing (CAD/CAM) technologies and three-dimensional (3D) printing may improve peri-implant tissue development by more accurately replicating patient-specific emergence profiles and transmucosal contours [3–5]. Clinical studies have demonstrated that customized healing abutments can reduce peri-implant soft tissue variation, improve esthetic outcomes, and enhance patient comfort compared with prefabricated healing abutments in immediate implant sites [3,6,7].

Customized healing abutments have been proposed to improve several clinical and biological parameters compared with conventional stock components. By preserving the peri-implant transmucosal architecture and minimizing repeated abutment disconnection, they may facilitate emergence profile development, support peri-implant soft tissue maturation, and simplify restorative procedures [8–11]. Furthermore, customized transmucosal contours have been associated with improved volumetric stability of peri-implant ridge dimensions, particularly following immediate implant placement in extraction sites, as well as enhanced esthetic outcomes and patient satisfaction [5,12,13].

The ability to digitally customize the emergence profile may be particularly advantageous following implant placement in regenerated or augmented ridges, where preservation of peri-implant tissue architecture is essential for long-term stability and esthetic integration [14–17].

Despite increasing interest in customized healing abutments and digital implant workflows, the mechanical behavior of additively manufactured anatomical healing abutments (AHAs) under different torque conditions remains insufficiently investigated. Torque application during abutment placement generates preload within the abutment screw, directly influencing the mechanical stability of the implant–abutment interface [18]. Adequate preload is essential for minimizing micromotion and maintaining joint stability, whereas inadequate torque application may result in screw loosening, and mechanical complications [19–21]. Additionally, torque and preload influence microgap formation at the implant–abutment interface, which may contribute to bacterial microleakage, peri-implant inflammation, and marginal bone loss [22–25]. Previous investigations have also demonstrated that implant–abutment connection geometry and cyclic loading conditions affect maintenance of applied torque and interface stability [26–28]. Although much of the existing evidence originates from *in vitro* studies involving definitive abutments, these biomechanical principles are directly relevant to digitally fabricated healing abutments used during early peri-implant tissue maturation.

Mechanical stability during the healing phase may be particularly important for maintaining a stable peri-implant mucosal seal and supporting predictable soft tissue adaptation. Repeated abutment micromotion or loosening may compromise the integrity of the peri-implant soft tissue interface and disrupt transmucosal healing dynamics [29]. In digitally driven implant therapy, where customized transmucosal contouring is increasingly incorporated into regenerative and restorative workflows, understanding the influence of torque application on AHA stability becomes clinically relevant.

Therefore, the purpose of this prospective pilot clinical study was to evaluate the influence of different tightening torque protocols on the early mechanical stability of 3D-printed AHA placed on intermediate abutments within a digital implant workflow. The study aimed to investigate how torque variation may affect abutment stability, torque maintenance, and short-term mechanical behavior during the peri-implant healing phase. Within the limitations of a pilot clinical design, these findings may provide preliminary insights into the biomechanical and clinical behavior of customized healing abutments used in contemporary digital implant dentistry.

2. Materials and Methods

The study protocol was reviewed and approved by the Ethical Committee for Research of the Dodecanese Dental Association, Greece (Approval No. 223/6-4-2024). All participants received detailed information regarding the study procedures and provided written informed consent prior to enrollment. The study was conducted between January and December of 2025, and in accordance with the principles of the Declaration of Helsinki [30] and followed Good Clinical Practice guidelines (ICH E6[R2]) [31].

2.1. Study Design and Patient Selection

This prospective clinical study included 42 consecutive patients (23 males and 19 females; age range: 22–75 years) who had previously received one or two dental implants (Paltop Advanced Dental Solutions Ltd., Ashkelon, Israel) placed using a two-stage surgical protocol. All implants were inserted with an insertion torque exceeding 30 Ncm at the time of implant placement. Patients were recruited from a single private clinical center, and all surgical and prosthetic procedures were performed by the same experienced board-certified periodontist and implant surgeon (I.V.).

At the time of second-stage surgery, all implants were deemed clinically and radiographically osseointegrated, based on the absence of clinical mobility, pain, or suppuration, together with radiographic assessment demonstrating stable peri-implant bone levels and no radiolucency at the implant–bone interface. Only implants meeting these criteria were included in the study.

2.2. Group Allocation and Torque Protocols

Following implant uncovering, patients were randomly assigned to one of four anatomical healing abutment tightening protocols using a computer-generated randomization sequence with equal allocation among groups. Because different torque values had to be applied clinically, operator blinding was not feasible. Patients were unaware of the assigned torque protocol.

A total of 60 implants were randomly allocated into four experimental groups according to the torque applied during AHA (iCervico, VP Innovato Holdings Ltd., Larnaca, Cyprus) placement, with 15 implants in each group. Group A included 11 patients (15 implants) in whom the AHA were secured by hand tightening only (<15 Ncm). Group B comprised 10 patients (15 implants) with AHA tightened to 20 Ncm. Group C consisted of 10 patients (15 implants) with AHA tightened to 25 Ncm, and Group D included 11 patients (15 implants) with AHA tightened to 30 Ncm. Overall, 42 patients and 60 implants were included in the analysis, and all implants featured a 2.9 mm prosthetic platform with an 11° conical connection.

All AHA were placed by the same clinician (I.V.) using a single manufacturer-specific calibrated mechanical torque ratchet. In accordance with established implant screw mechanics principles and to compensate for the settling (embedment relaxation) effect, implant screws in Groups B, C, and D were retightened to the assigned torque value 10 min after the initial torque application, following the protocol described by Winkler et al. [32]. Mechanical torque instrumentation was used instead of hand drivers to ensure consistent and reproducible torque delivery at the manufacturer-recommended values.

Prior to study initiation, the accuracy of the prosthetic torque ratchet (Paltop Advanced Dental Solutions Ltd., Ashkelon, Israel) was verified using a calibrated digital torque gauge (Series TT03; Mark-10 Corporation, Copiague, NY, USA), confirming that applied torque values corresponded within ± 1 Ncm of the device setting. Verification was repeated at regular intervals throughout the study to ensure consistent performance and reproducibility of torque application.

2.3. Surgical and Prosthetic Protocol

At the second-stage surgery (implant uncovering), each implant received a titanium intermediate abutment (iBase, VP Innovato Holdings Ltd., Larnaca, Cyprus/Paltop Advanced Dental Solutions Ltd., Ashkelon, Israel) with a transmucosal height of either 1.5 mm or 2.5 mm, selected according to the peri-implant vertical soft tissue thickness at each site (Figure 1). Implant diameters ranged from 3.75 to 5.0 mm and implant lengths from 8 to 13 mm. Intermediate abutments were secured using the manufacturer-recommended prosthetic torque of 35 Ncm with a calibrated prosthetic torque ratchet (Paltop Advanced Dental Solutions Ltd., Ashkelon, Israel), (Figure 1).

Following placement of the intermediate abutments, each implant received a custom 3D-printed AHA. The AHA were fabricated from MAZIC D TEMP (Vericom Co., Ltd., Chuncheon, Republic of Korea), a photopolymerized acrylate-based resin indicated for the fabrication of temporary crowns and bridges. According to the manufacturer, the material exhibits a flexural strength ≥ 50 MPa, flexural modulus ≥ 1500 MPa, Shore hardness D80–90, water sorption < 40 $\mu\text{g}/\text{mm}^3$, and water solubility < 7.5 $\mu\text{g}/\text{mm}^3$, supporting its use in provisional restorative applications. As the AHA were commercially available prefabricated end products and were not manufactured by the authors, detailed information regarding specific manufacturing parameters, including printing orientation, post-processing protocols, and certain material properties, was beyond the scope of the information provided with the components (Figure 2).

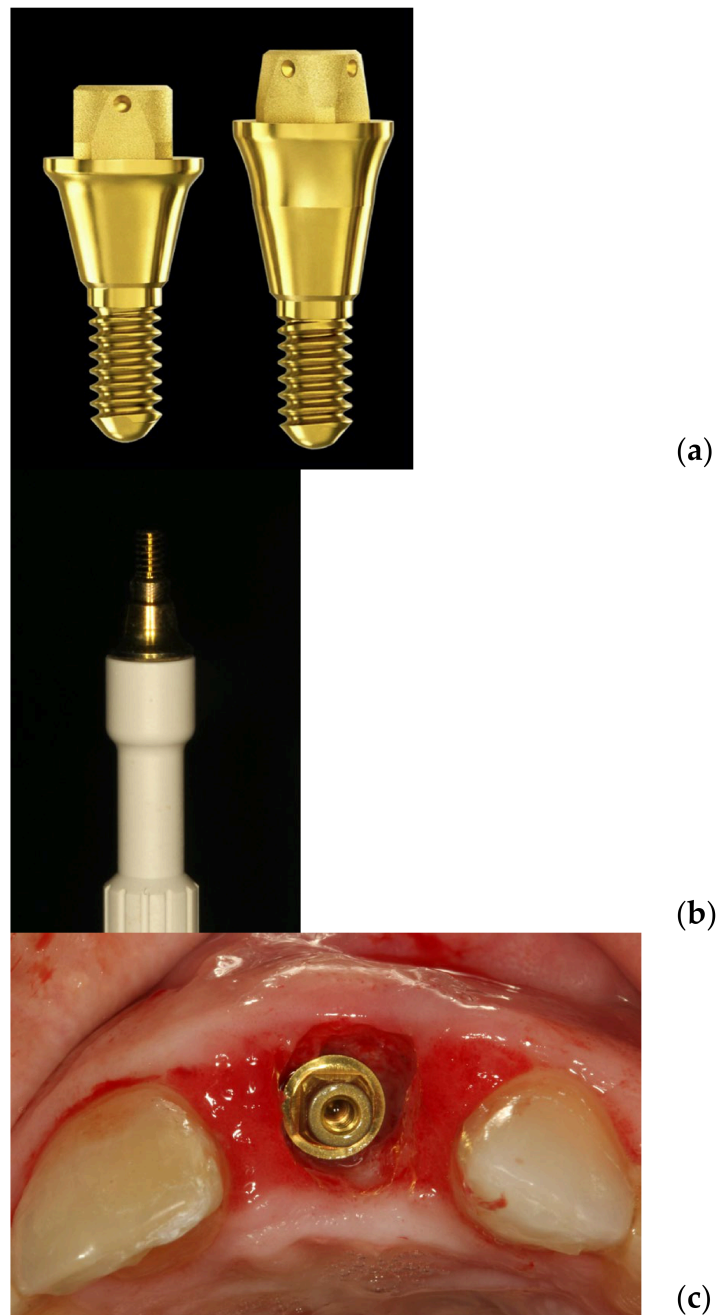


Figure 1. (a) Intermediate abutments with transmucosal heights of 1.5 mm and 2.5 mm, respectively. (b) The screwdriver used for the placement of the intermediate abutments. (c) Clinical view of implant site #9 at second-stage surgery showing an intermediate abutment (2.5 mm transmucosal height) placed based on peri-implant vertical soft tissue thickness to optimize transmucosal adaptation.

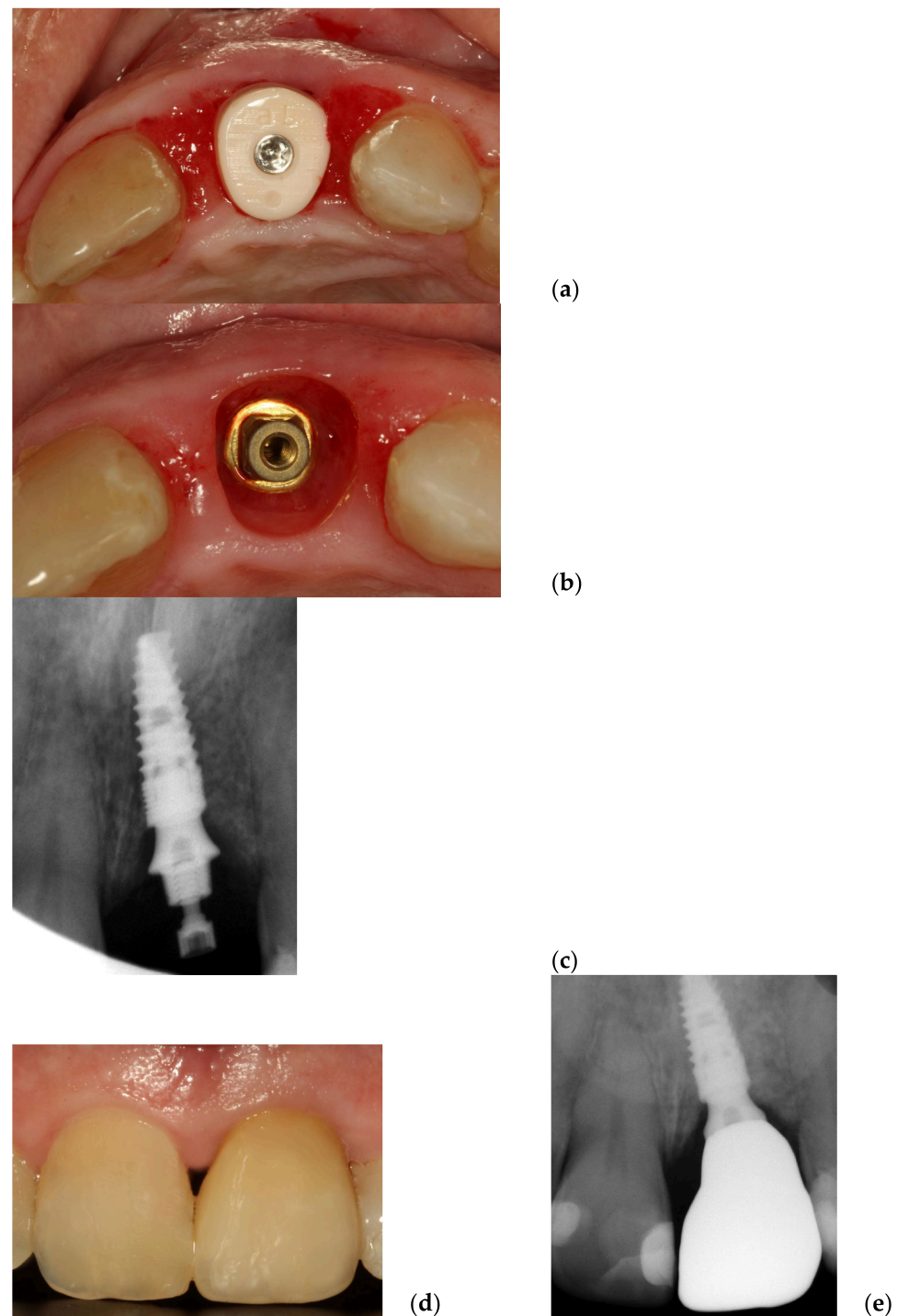


Figure 2. (a) Clinical view of site #9 following placement of a custom 3D-printed AHA seated onto the titanium intermediate abutment to establish the site-specific transmucosal contour and emergence profile. (b) Clinical view of site #9, three months following placement of the custom 3D-printed AHA, demonstrating a well-defined and stable peri-implant emergence profile after removal of the AHA. (c) Periapical radiograph of implant site #9 at six-month follow-up following placement of the 2.5 mm titanium intermediate abutment and custom 3D-printed AHA, confirming complete seating of the components and maintenance of peri-implant marginal bone levels. (d) Clinical intraoperative view of the definitive restoration at implant site #9 six months postoperatively, demonstrating harmonious adaptation of the definitive crown with the adjacent natural tooth #8 and well-contoured, healthy gingival architecture. (e) Six-month postoperative periapical radiograph of implant site #9 following placement of the definitive restoration, illustrating stable marginal bone levels and absence of radiographic complications.

The AHA were available in three anatomical configurations (anterior, premolar, and molar) and three size categories (small, medium, and large) to approximate the clinical emergence profile corresponding to each implant site (Figures 3 and 4).

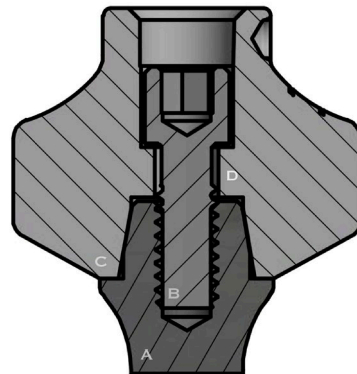


Figure 3. Cross-sectional illustration of the intermediate abutment (A), abutment screw (B), and 3D-printed AHA (C). The resin thickness beneath the screw head within the AHA measures 1.3 mm (D), providing sufficient structural integrity to withstand the vertical forces generated during screw tightening onto the intermediate abutment.

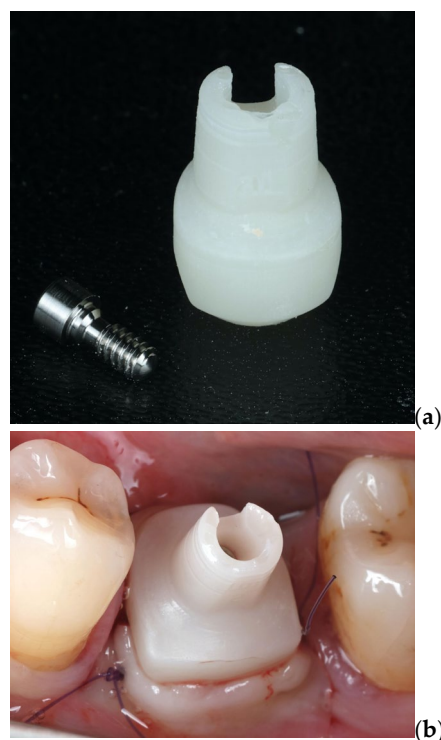


Figure 4. Cont.

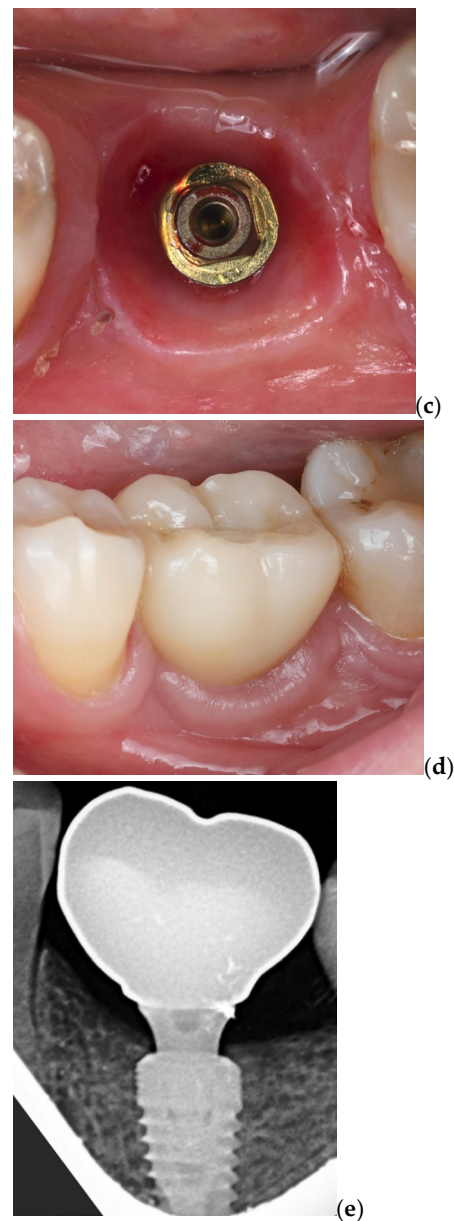


Figure 4. (a) View of a 3D-printed AHA and its corresponding abutment screw, illustrating the customizable transmucosal contour designed to replicate the site-specific emergence profile. Note the resin thickness beneath the screw head within the AHA. (b) Clinical view of site #19 demonstrating placement of the custom 3D-printed AHA and stabilization of the peri-implant soft tissues with 5-0 Vicryl simple interrupted sutures. (c) Clinical appearance of site #20 following removal of the AHA, revealing mature peri-implant soft tissue architecture and a well-contoured emergence profile. (d) Definitive restoration in place at site #19, demonstrating approximately 3 mm of keratinized tissue and healthy, coral-pink peri-implant mucosa with stable marginal tissue levels. (e) Periapical radiograph of site #20 taken six months after placement of the definitive restoration, showing stable peri-implant marginal bone levels around the 5.0 mm implant, a well-defined mesial triangular peak of bone, and absence of radiographic complications.

The anatomical healing abutments used in the present study represented commercially available prefabricated designs and were not fully customized for each patient. The anatomical configuration was selected according to the tooth group corresponding to the edentulous site, with anterior abutments exhibiting a triangular contour, premolar abutments exhibiting an ovoid contour, and molar abutments exhibiting a broader rectangular contour. Size selection was based on implant position and edentulous ridge dimensions.

The largest healing abutment that could be accommodated mesiodistally while maintaining the transmucosal contour within the buccolingual envelope of the ridge was selected. Care was taken to avoid over contouring beyond the soft tissue envelope, which could potentially increase the risk of soft tissue recession. Adjacent size categories differed by approximately 1 mm in maximum diameter. Although the material permitted chairside modification, no additional customization was performed in the present study.

2.4. Clinical Evaluation and Follow-Up

Patients were recalled for clinical evaluation at 4, 8, and 12 weeks following AHA placement. At each follow-up visit, AHA were assessed for mobility and mechanical complications by the same experienced periodontist (I.V.) using manual finger pressure and gentle buccolingual probing with two instrument handles. Mobility was defined as any clinically perceptible displacement of the healing abutment relative to the underlying intermediate abutment. To ensure consistency, all evaluations were performed by the same examiner throughout the study. Because the primary objective was to identify clinically detectable mobility requiring intervention, no formal calibration or quantitative validation of the assessment method was performed. In addition, a standardized lateral force was applied using a dental explorer along the abutment margin to detect any micromotion at the implant–abutment interface, providing a supplementary assessment of early mechanical stability. For Groups B, C, and D, torque maintenance was further evaluated by reapplying the same torque value used at initial placement (20, 25, or 30 Ncm, respectively) using the same calibrated torque ratchet. Immediate activation of the torque ratchet without additional screw rotation was interpreted as maintenance of the originally applied tightening torque and absence of clinically detectable screw loosening. Direct measurements of reverse torque values or clamping force were not performed. Any AHA demonstrating clinical mobility was removed, steam sterilized and reinstalled using the same torque protocol as at the initial appointment. The presence or absence of mobility, torque maintenance, and other mechanical complications was recorded for all implant sites at each follow-up interval. Composite mechanical complications were defined as the occurrence of any mechanical event during the follow-up period, including clinically detectable healing abutment mobility, loss of torque maintenance requiring retightening, or fracture of the anatomical healing abutment.

2.5. Statistical Analyses

Descriptive statistics were used to summarize healing abutment mobility, torque failure, and overall mechanical complications at 4, 8, and 12 weeks. Healing abutments were grouped according to tightening torque (hand tightening, 20 Ncm, 25 Ncm, and 30 Ncm). Outcomes were recorded as binary variables (presence or absence of mobility, torque failure, or mechanical complications) and are presented as frequencies and percentages. Baseline implant characteristics, including implant diameter, implant length, implant site distribution, and intermediate abutment (iBase) height, were compared among torque groups to assess group comparability. Continuous baseline variables were compared using one-way analysis of variance (ANOVA) [33], whereas categorical variables were compared using Fisher's exact test [34]. Comparisons of healing abutment mobility, torque failure, and composite mechanical complications among torque groups at each follow-up interval were also performed using Fisher's exact test because of the relatively small sample size and low event frequency. Statistical significance was established at $p < 0.05$. All analyses were performed using a statistics software [IBM SPSS Statistics (version 27; IBM Corp., Armonk, NY, USA)].

Given the exploratory nature of this pilot investigation, no adjustment for multiple comparisons was performed. Furthermore, no formal a priori sample size calculation was performed because the study was designed as a pilot clinical investigation intended to generate preliminary clinical data. A post hoc power analysis based on the observed 12-week healing abutment mobility rates among the four torque groups demonstrated a large effect size (Cohen's $w = 0.46$). With 60 implants included, the estimated statistical power was approximately 86% at $\alpha = 0.05$. Therefore, the findings should be interpreted as exploratory and hypothesis-generating rather than definitive. Because some patients received more than one implant, the implant was considered the unit of analysis. The potential lack of complete independence among observations has been acknowledged as a limitation and is discussed in the Section 4. No longitudinal modeling or adjustment for within-patient clustering was performed because of the pilot nature of the study and the limited number of events. Future studies with larger sample sizes should employ statistical approaches that account for repeated measurements and within-patient correlation. The primary analyses were performed using Fisher's exact tests. Because some patients contributed more than one implant and outcomes were measured repeatedly over time, generalized estimating equations (GEEs) were also performed as a sensitivity analysis for repeated binary outcomes using patient identification as the clustering variable, a binomial distribution, logit link, and exchangeable working correlation structure [35].

3. Results

Forty-two patients (mean age, 52.4 ± 12.3 years) receiving 60 implants were included. Baseline implant characteristics are summarized in Table 1. The implants were evenly distributed among the four torque groups (15 implants per group). All implants demonstrated insertion torque values exceeding 30 Ncm at placement, and all intermediate abutments were torqued to 35 Ncm. Baseline implant diameter, implant length, implant site distribution, and iBase height did not differ significantly among groups (all $p > 0.05$), indicating comparable baseline characteristics. One anatomical healing abutment in the 30 Ncm group fractured during the follow-up period and was replaced without affecting the underlying implant or intermediate abutment. Therefore, although 60 implants and implant sites were included throughout the study, a total of 61 anatomical healing abutments were evaluated during the 12-week observation period.

Table 1. Baseline implant characteristics according to anatomical healing abutment tightening protocol. A total of 60 implants were included. Data are presented as mean $\pm$ standard deviation (SD) for continuous variables and frequency (%) for categorical variables. Percentages for implant site and intermediate abutment (iBase) height are based on the number of implants ($n = 15$ per group). Baseline comparisons among groups demonstrated no statistically significant differences in implant diameter, implant length, implant site distribution, or iBase height (all $p > 0.05$). Comparisons were performed using one-way analysis of variance (ANOVA) for continuous variables and Fisher's exact test for categorical variables.

Variable Mean Patient Age; 52.4 ± 12.3 Years	Hand Tightening ($n = 15$)	20 Ncm ($n = 15$)	25 Ncm ($n = 15$)	30 Ncm ($n = 15$)	p -Value
Implant diameter (mm), mean $\pm$ SD	4.26 ± 0.57	4.47 ± 0.57	4.45 ± 0.62	4.40 ± 0.63	0.768
Implant length (mm), mean $\pm$ SD	10.37 ± 1.13	9.70 ± 0.96	9.93 ± 1.10	9.62 ± 0.81	0.180
Implant site, n (%)					0.644

Table 1. Cont.

Variable Mean Patient Age; 52.4 ± 12.3 Years	Hand Tightening (n = 15)	20 Ncm (n = 15)	25 Ncm (n = 15)	30 Ncm (n = 15)	p-Value
Anterior	4 (26.7)	1 (6.7)	2 (13.3)	1 (6.7)	0.158
Premolar	6 (40.0)	6 (40.0)	5 (33.3)	7 (46.7)	
Molar	5 (33.3)	8 (53.3)	8 (53.3)	7 (46.7)	
iBase height, n (%)					
1.5 mm	10 (66.7)	11 (73.3)	6 (40.0)	11 (73.3)	
2.5 mm	5 (33.3)	4 (26.7)	9 (60.0)	4 (26.7)	

3.1. Healing Abutment Mobility

In Group A (hand tightening), AHA mobility was observed in 26.7% (4/15) of implants at 4 weeks, 13.3% (2/15) at 8 weeks, and 33.3% (5/15) at 12 weeks. Recurrent mobility was noted, as 80% (4/5) of later events corresponded to the same implant sites. In Group B (20 Ncm), AHA mobility was detected in 6.7% (1/15) of implants at 12 weeks, with no mobility observed at 4 or 8 weeks. In Groups C (25 Ncm) and D (30 Ncm), all AHA remained clinically stable throughout the 12-week observation period.

The between-group difference in mobility at 4 weeks was statistically significant (Fisher's exact test, $p = 0.004$), reflecting the increased frequency of early mobility in the hand-tightened group. Although mobility remained more frequent in the hand-tightened group at 8 weeks, the overall group comparison did not reach statistical significance ($p = 0.096$). At the 12-week evaluation, mobility rates remained highest in the hand-tightened group and differed significantly among groups ($p = 0.021$).

3.2. Torque Maintenance and Mechanical Stability

Torque maintenance was not assessed in Group A because no calibrated torque value was applied during healing abutment placement. In Group B (20 Ncm), torque stability was preserved in 100% (15/15) of implants at 4 weeks, decreasing to 86.7% (13/15) at 8 weeks and 80.0% (12/15) at 12 weeks. Loss of torque stability coincided with the single site demonstrating clinical mobility. In Groups C (25 Ncm) and D (30 Ncm), torque maintenance remained stable throughout the observation period.

Torque failure was not observed in any group at the 4-week evaluation. At 8 weeks, torque failure occurred exclusively in the 20 Ncm group (2/15; 13.3%), although the overall comparison among groups was not statistically significant ($p = 0.096$). At 12 weeks, torque failure was observed in 3/15 implants (20.0%) in the 20 Ncm group and in 1/16 healing abutments (6.3%) in the 30 Ncm group, the latter corresponding to a fracture event. No torque failures were recorded in the hand-tightened or 25 Ncm groups ($p = 0.088$).

3.3. Mechanical Complications

One AHA fracture occurred in the 30 Ncm group prior to the 12-week follow-up and was replaced to maintain group balance; therefore, 16 AHA were evaluated for torque failure analysis in this group. Composite mechanical complications, defined as the occurrence of healing abutment mobility, loss of torque maintenance requiring retightening, or fracture of the anatomical healing abutment, differed significantly among groups at 12 weeks ($p = 0.047$). Composite mechanical complication rates at 12 weeks were 5/15 (33.3%) in the hand-tightened group, 3/15 (20.0%) in the 20 Ncm group, 0/15 (0%) in the 25 Ncm group, and 1/15 (6.7%) in the 30 Ncm group. The single event in the 30 Ncm group corresponded to fracture of one anatomical healing abutment. No additional mechanical

failures or biological complications involving the intermediate abutments or implants were observed during the study period.

Among the evaluated torque protocols, 25 Ncm was the only tightening value associated with complete absence of mobility, torque failure, and fracture during the 12-week observation period. The GEE analysis demonstrated that increasing tightening torque was significantly associated with reduced healing abutment mobility ($p = 0.0002$) and fewer composite mechanical complications ($p < 0.001$), supporting the findings obtained with Fisher's exact tests.

4. Discussion

This prospective pilot study evaluated the early mechanical behavior of 3D-printed AHA placed on intermediate abutments under four different torque protocols. The principal finding was that torque application ≥ 25 Ncm resulted in complete mechanical stability throughout the 12-week observation period, whereas hand tightening and lower torque levels were associated with increased rates of clinical mobility and progressive loss of torque maintenance. These findings align with the established biomechanical principles, demonstrating that adequate screw preload is essential for minimizing micromotion at the implant-abutment interface and maintaining joint stability [18,19,26–28,32]. Screw loosening due to embedment relaxation and cyclic micro-movements is a well-documented phenomenon, particularly during the early healing phase, when functional and biological conditions are evolving [32,36]. In this context, insufficient torque may fail to compensate for early settling effects, resulting in increased micromotion and mechanical instability [18,19,29,36]. The present results extend these principles to digitally fabricated anatomical healing abutments and suggest that torque values ≥ 25 Ncm may provide improved mechanical stability during the early healing period.

From a clinical perspective, the observed differences in mobility and torque maintenance are relevant because mechanical instability during healing may necessitate additional clinical intervention and component management. Previous experimental and clinical studies have demonstrated that cyclic loading can exacerbate screw loosening and interface instability, particularly in systems with insufficient initial torque [32,36]. Koutouzis further emphasized that abutment micromotion and repeated component manipulation may influence peri-implant tissue behavior [37]. However, biological outcomes, including bacterial microleakage, peri-implant inflammation, and marginal bone remodeling, were not evaluated in the present study and therefore remain as hypotheses requiring future investigation. Within this framework, the present findings suggest that mechanical stability during early healing is not merely a technical consideration but a biologically relevant factor influencing peri-implant tissue behavior. Although soft tissue outcomes were not quantitatively assessed, the absence of mobility in the ≥ 25 Ncm groups may indirectly support more favorable conditions for soft tissue maturation and maintenance of the emergence profile [3–5,14–17].

The comparative performance of the four torque protocols further supports this interpretation. The hand-tightened group exhibited the highest incidence of mobility, particularly at 12 weeks, highlighting the inherent variability and inadequacy of manual torque application [19,20,36,38]. Although the 20 Ncm group demonstrated improved early stability, it exhibited progressive torque loss and late mobility, suggesting that this torque level may lie near the lower threshold required to compensate for screw loosening. In contrast, the 25 and 30 Ncm groups demonstrated complete mechanical stability, indicating that torque ≥ 25 Ncm reliably maintains preload without increasing the risk of clinically significant mechanical complications. The single fracture observed in the 30 Ncm group

did not affect implant or abutment integrity, suggesting that higher torque levels remain within the mechanical tolerance of the tested system.

The AHA investigated in the present study were selected because they represent commercially available prefabricated components specifically designed for use with scannable intermediate abutments within a digital workflow. Although the manufacturer recommends a tightening torque of 30 Ncm, no clinical studies were available to validate or challenge this recommendation. Consequently, the present pilot investigation was undertaken to evaluate the influence of different tightening torque protocols on the early mechanical stability of these components and to provide preliminary evidence to guide clinical torque selection during the healing phase.

The present study also provides insights specific to 3D-printed AHA, which are increasingly incorporated into digital implant workflows. These components allow customization of emergence profiles and may improve esthetic and soft tissue outcomes compared with conventional stock abutments [3–5,14–17]. However, their mechanical performance remains a subject of concern, particularly with respect to material properties, printing orientation, and structural integrity. Previous finite element and mechanical investigations have suggested that improved implant-abutment stability and favorable strain distribution may contribute to the mechanical reliability of implant-supported components, findings that are particularly relevant for additively manufactured structures [39,40]. The absence of torque-related complications in the ≥ 25 Ncm groups supports the notion that contemporary medical-grade 3D-printing technologies can achieve sufficient mechanical strength for clinical application when appropriate torque protocols are followed.

These findings also address concerns raised in recent prosthodontic literature. Talmazov and Michaud highlighted potential limitations of 3D-printed healing abutments, including risks related to material polymerization, component orientation, and mechanical instability in non-engaging designs [41]. In the present study, the AHA relied solely on the retention screw for stability, without an anti-rotational engaging mechanism. The retention screw design provides primarily vertical clamping force, making adequate preload even more critical for maintaining stability. The observed performance of the ≥ 25 Ncm groups suggests that appropriate torque application can mitigate some of the mechanical limitations inherent to non-engaging, digitally fabricated components.

The findings of the present study have broader implications for the evolution of digital implant workflows. As digital planning, intraoral scanning, and additive manufacturing technologies continue to advance, customized transmucosal components are expected to play an increasingly important role in implant therapy [8,42,43]. Although the anatomical healing abutments evaluated in the present study represented commercially available prefabricated designs, future workflows may incorporate fully patient-specific healing abutments fabricated directly from digital scans and virtual wax-ups. Such approaches could facilitate more precise emergence profile management, reduce the need for soft tissue modification during restorative treatment, and improve communication between clinicians and dental laboratories [8,42,43]. Furthermore, integration of digital design, guided surgery, and customized transmucosal components may simplify restorative procedures and contribute to more efficient and predictable clinical workflows [8,43]. While the present investigation focused exclusively on mechanical behavior, future studies should evaluate how these digital protocols influence peri-implant tissue stability, esthetic outcomes, and long-term prosthetic success.

Several limitations should be considered when interpreting the findings of the present study. First, this was a single-center pilot investigation with a relatively limited sample size and short follow-up period of 12 weeks. Although a post hoc power analysis demonstrated adequate power to detect large effects, the findings should be regarded as exploratory

and hypothesis-generating. Second, the study evaluated implants during the unloaded healing phase, and therefore the results cannot be directly extrapolated to fully restored implants subjected to functional occlusal loading. Third, healing abutment mobility was assessed clinically rather than by objective quantitative methods, and direct measurements of reverse torque values or clamping force were not performed. Consequently, the present investigation evaluated clinically detectable screw loosening and torque maintenance rather than true preload preservation. Future studies incorporating reverse torque measurements, digital micromovement analysis, and quantitative assessment of clamping force are warranted to better characterize the biomechanical behavior of 3D-printed anatomical healing abutments.

In addition, only intermediate abutment heights of 1.5 mm and 2.5 mm were evaluated, which may not fully represent clinical scenarios with greater peri-implant soft tissue thickness. Furthermore, the anatomical healing abutments used in this study were predesigned rather than fully patient-specific components, potentially limiting their adaptability to more complex peri-implant soft tissue configurations. The study was also restricted to a two-stage surgical protocol, and the findings may not necessarily apply to one-stage treatment approaches. Although implant location and intermediate abutment height were recorded, other potentially relevant variables, including opposing dentition, occlusal scheme, and detailed soft tissue dimensions, were not systematically analyzed. However, because all implants were evaluated during the unloaded healing phase, the influence of functional occlusal forces was minimized. Future studies should investigate the effects of these variables under loaded conditions.

Because a small number of patients contributed more than one implant and each implant was evaluated repeatedly over time, complete statistical independence among observations could not be assumed. To address this issue, generalized estimating equations were performed as a sensitivity analysis, demonstrating findings consistent with the primary analyses. Nevertheless, larger longitudinal studies employing clustering-adjusted statistical models are needed to confirm these results.

Despite these limitations, the study benefited from standardized surgical and prosthetic protocols, consistent torque application, and controlled follow-up conditions, which helped standardize treatment procedures and minimize variability. The consistency of findings across multiple outcomes, including healing abutment mobility, torque maintenance, and composite mechanical complications, further supports the reliability of the observed associations.

Future research should focus on larger multicenter randomized clinical trials with extended follow-up periods, incorporation of functional loading, and quantitative assessment of peri-implant soft tissue dimensions and marginal bone levels. Additionally, the integration of digital measurement techniques capable of directly assessing reverse torque values, clamping force, and micromotion would further enhance understanding of implant–abutment biomechanics within contemporary digital workflows.

In conclusion, within the limitations of this prospective pilot clinical study, tightening torques of ≥ 25 Ncm were associated with improved early mechanical stability and maintenance of 3D-printed AHA during the 12-week healing period. These findings suggest that tightening torques of at least 25 Ncm may provide a more reliable mechanical protocol than lower torque values for minimizing clinically detectable loosening during early healing. Further multicenter clinical studies with larger sample sizes, longer follow-up periods, and functional loading are required to confirm these preliminary findings and establish evidence-based recommendations for digital implant workflows.

5. Conclusions

Within the limitations of this prospective pilot clinical study, tightening torques of ≥ 25 Ncm were associated with improved early mechanical stability of 3D-printed anatomical healing abutments compared with hand tightening and 20 Ncm.

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