Custom-Made Root Analog Immediate Dental Implants: A Prospective Clinical Study with 1-Year Follow-up

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Purpose: To compare three different types of custom-made root-analog immediate (RAI) dental implants. ***Materials and Methods:*** Patients with fractured and/or nonrestorable teeth with uncompromised periodontal ligaments were included in the study. The exclusion criteria were as follows: any uncontrolled systemic disease, bruxism, poor oral hygiene, active periodontal disease, and/or chronic marginal periodontitis. CBCT scans of the teeth were taken, and the datasets were used to reconstruct 3D models that were transferred to 3D modeling software to design the RAIs. Group 1 (GR1) consisted of zirconia RAIs manufactured using a computer numerical control (CNC) machine, group 2 (GR2) consisted of titanium RAIs formed by using a CNC machine, and group 3 (GR3) consisted of titanium RAIs manufactured by using direct laser metal sintering (DLMS) technology, all of which were placed immediately after tooth extraction. Primary stability was measured by using Periotest M. Metal-ceramic single crowns were cemented 3 months later. All implants were evaluated clinically and radiologically 1 year after implant placement. ***Results:*** A total of 51 patients (18 men, 33 women) aged between 18 and 66 years (average 34.2 years) were included in the study. In 4 patients, RAIs could not be placed due to the lack of primary stability, and they were excluded. In the remaining 47 patients, the custom-made RAIs (GR1: n = 21, GR2: n = 17, GR3: n = 18, total: n = 56) were placed into fresh extraction sockets immediately after tooth extraction for each patient. Primary stability was achieved. Periotest values (PTV) were between –1.4 and –6.2 (mean –3.3). The mean initial PTV (PTV0) was –2.3 ± 1.8 for the failed implants and –4.5 ± 0.8 for the surviving implants. PTV0 was an independent risk factor (HR 3.61, 95% CI: 1.56–8.35, $P = .004$) for survival rate, which was 33.3%, 70.6%, and 44.4% for GR1, GR2, and GR3, respectively. The overall survival rate was 48.2%. There was no significant difference between the groups regarding the probability of survival ($P = .051$). The survival rate was significantly lower for anterior RAIs ($P < .001$). Clinically healthy gingival margins were observed without any signs of periodontitis or implant mobility, and the mean PTV was –4.0 ± 1.9 in surviving implants, whereas the mean marginal bone loss was 1.3 ± 0.6 mm (median, 0.8; 95% CI: 0.1–3.4) at the 1-year follow-up. ***Conclusion:*** This study was the first attempt to compare different RAI manufacturing techniques and biomaterials in the literature. Although the probability of survival was not statistically significant between the groups, the survival rate in GR2 was higher than in the other two groups. Nevertheless, the overall survival rate was significantly lower (48.2%) than in the previous reports. Primary stability was an independent risk factor for failure. Further studies with the minimized variables between groups should be designed for precise results. *Int J Oral Maxillofac Implants 2022;37:1223–1231. doi: 10.11607/jomi.7198*

Keywords: anatomical, custom-made, dental implant, immediate, root analog, titanium, zirconia

Dental implants are widely used for prosthetic rehabilitation of edentulous patients, with long-term high success rates.[1] In the past few decades, immediate implant placement has been developed to shorten the treatment time. Although it has many advantages, difficulties such as incongruence with the extraction socket, which leads to lack of primary stability and the need for guided tissue regeneration to prevent soft tissue migration to the space between the tooth and implant, may complicate the procedure.[2] The custom-made root analog dental implant (RAI) concept was introduced to avoid such problems.[3] RAIs are identical copies of the extracted teeth, manufactured from biocompatible materials such as titanium and zirconia.[4] Researchers have recently taken more interest in the RAI concept due to the advancements in CAD/CAM technologies.[5–8]

The RAI concept was first introduced in a study by Hodosh et al[3] in 1969, which placed the autopolymerizing and heat-processed polymethacrylate implants

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into the extraction sockets of baboons. However, they reported that the implants were encapsulated with connective tissue instead of osseointegration and failed. Along with that, Lundgren et al[4] used a pure titanium material in their experimental study in beagle dogs. They reported that 88% of the implants were osseointegrated when placed into extraction sockets in an early stage of healing and denoted that a close fit between the implant and the socket was the primary factor for implant success. Therefore, Kohal et al[9] enlarged the coronal part of the RAIs to compensate for the width of the lost periodontium for better congruence, but fracture of the buccal alveolar bone occurred while placing the implants. Nevertheless, direct bone-to-implant contact was observed in all evaluated implants.

Recently, several clinical studies have demonstrated the success of RAIs.[6,8,10–14] Various CAD/CAM techniques were administered for design and manufacture. The manufacturing techniques are mainly classified as additive manufacturing and subtractive manufacturing. The American Society for Testing and Materials (ASTM) defines additive manufacturing as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[15] This technique enables operators to build complex-shaped objects with high accuracy.[16–18] Direct metal laser sintering (DLMS), an additive manufacturing technology, was used to manufacture RAIs, and high success rates were reported.[5,6,10] The subtractive manufacturing of zirconia RAIs with dental computer numerical control (CNC) machines were also presented.[11–14,19,20] Recently, a commercially available RAI system was evaluated in a pilot study. A titanium milled RAI and a ceramic milled abutment portion were fused together to create a one-piece implant.[8]

Although different RAI techniques and modifications have been presented in many experimental and clinical studies, there are no comparative studies of RAIs manufactured using different techniques and different biomaterials. Therefore, the aim of the present prospective clinical and radiographic study was to compare three different types of RAIs.

MATERIALS AND METHODS

Study Design and Patient Selection

This prospective study was designed as a nonrandomized parallel-group clinical trial. The study followed the Declaration of Helsinki on Medical Protocol and Ethics and was approved by the Local Ethics Committee of Erciyes University (2014/193). Between July 2015 and December 2016, all patients referred to the Erciyes University Faculty of Dentistry, Department of Oral and Maxillofacial Surgery were considered for inclusion in this study.

The patients in whom teeth extractions were required due to root caries, vertical/horizontal root fracture, endodontic lesions, and unsuccessful root canal treatment were examined clinically and radiographically. The fractured and/or nonrestorable teeth with uncompromised periodontal ligaments were included in the study. The exclusion criteria were any uncontrolled systemic disease, bruxism, poor oral hygiene, active periodontal disease, and chronic marginal periodontitis. Chronic apical periodontitis and fenestration/dehiscence defects were not exclusion criteria. Chronic apical periodontitis was treated by removing the infection area, and the defects were restored with alloplastic bone grafts after RAIs were placed. The study protocol was explained to each patient, and signed informed consent was obtained. Three study groups were planned as group 1 (GR1), zirconia CNC-machined RAIs; group 2 (GR2), titanium CNC-machined RAIs; and group 3 (GR3), titanium DLMS RAIs. The patients who had incisor or canine teeth extractions were included in the zirconia RAI group (GR1) because of esthetic reasons. All other patients were randomly assigned to one of the three study groups.

CBCT Scan and Implant Design

The implant design protocol was the same for the three study groups. The CBCT datasets of the teeth were acquired using a CBCT scanner (NewTom 5G, QR). The CBCT datasets with a voxel size of $0.25 \times 0.25 \times 0.25$ mm were transferred in the DICOM format to 3D reconstruction software (Mimics, Materialise), and virtual 3D models of the teeth, surrounding bone, and opposing arches were constructed for each patient. The 3D teeth models were smoothed to obtain a regular surface. The virtual models were exported as stereolithographic (STL) files, transferred to 3-matic Modeling Software (Materialise), and the RAIs were designed. The macroretentions on interdental surfaces of the root were added. The reduction on the buccal and lingual surfaces of roots (0.1 to 0.2 mm) was done to avoid fractures on thin alveolar bone walls. The abutments in the shape of a prepared tooth with a taper of 5 degrees and chamfer margins were designed. Finally, all designed parts were merged to create an RAI (Fig 1). RAIs were smoothed and exported as STL files with three different sizes (original [oRAI], 5% magnified [mRAI], and 5% downsized [dRAI]) to avoid potential distortions or errors related to the 3D projection steps.

Implant Manufacturing

GR1. The RAIs were milled from yttria-stabilized tetragonal zirconia polycrystal blanks (Alliance, Kuraray Noritake Dental) by using a five-axis CNC machine (Yenadent DC40 CAM, Yenadent). The surface of the

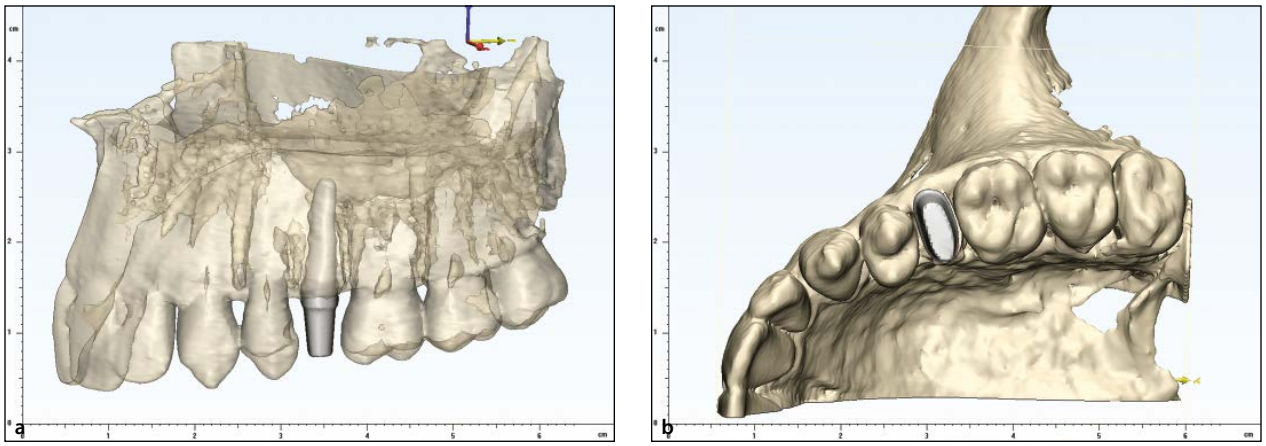


Fig 1 STL file of an RAI *(a)* with surrounding bone and neighboring teeth and *(b)* occlusal view.

implant was roughened by sandblasting with alumina and sintered for 8 hours. Then, RAIs were cleaned in an ultrasonic bath containing 96% ethanol for 10 minutes.

GR2. The RAIs were milled from Ti-6Al-4V alloy blanks (Copra Ti-5 Titanblank, Whitepeaks Dental Solutions) by using a five-axis CNC machine (Yenadent DC40 CAM). The extraosseous parts of each implant were polished. The intraosseous parts of the implants were roughened by sandblasting with alumina and acid-etching with a mixture of orthophosphoric acid and nitric acid (15% to 20% diluted with distilled water) at 65°C. Then, RAIs were washed for 10 minutes in distilled water at 45°C in an ultrasonic bath.

GR3. The DLMS technology was used to fabricate the RAIs in this group. The implants were made of Ti–6Al–4V alloy powder, with a particle size of 25 to 45 µm. The process was carried out in an argon atmosphere using a powerful ytterbium (Yb) fiber laser system (M2 Cusing, Concept Laser) with the capacity to build a volume up to 250 × 250 × 215 mm using a wavelength of 1,054 nm with a continuous power of 200 W, at a scanning rate of 7 m per second. The size of the laser spot was 0.1 mm. The extraosseous part of each RAI was polished. To remove residual particles from the manufacturing process, the RAIs were sonicated for 5 minutes in distilled water at 25°C, immersed in sodium hydroxide (20 g/L) and hydrogen peroxide (20 g/L) at 80°C for 30 minutes, and then further sonicated for 5 minutes in distilled water. Acid etching was carried out by immersing the samples in 50% hydrofluoric acid at 80°C for 3 minutes, followed by washing for 5 minutes in distilled water in a sonic bath.

Three RAIs (oRAI, mRAI, and dRAI) were fabricated for each extraction socket in all groups. The average surface roughness (Ra) was measured by a profilometer (Surftest SJ-301, Mitutoyo). The surface topography of RAIs was also evaluated by scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDX) analysis to ensure an ideal surface. Finally, the implants were packaged and sterilized in a steam sterilizer (Getinge HS44, Getinge Infection Control) at 134ºC for 45 minutes.

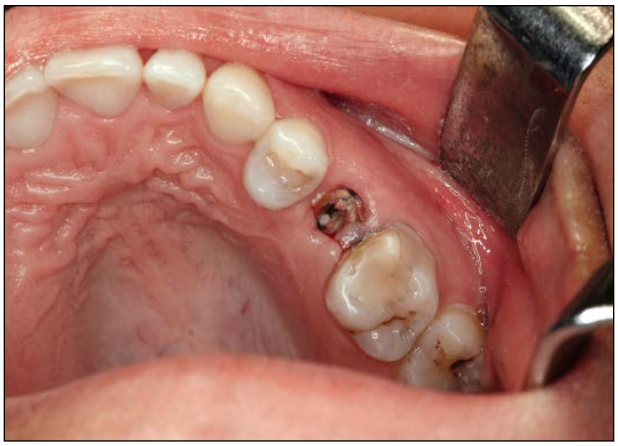


Fig 2 Clinical view before tooth extraction.

Surgical Procedure

All patients received nonsurgical periodontal therapy and oral hygiene education before implant placement (Fig 2). Chlorhexidine (0.12%) gluconate mouthwash (Klorhex, Drogsan) was administered 30 minutes before surgery to reduce the risk of postoperative infection. Under local anesthesia—infiltrating articaine 4% containing 1:100,000 adrenaline (Ultracain DS forte, Sanofi Aventis)—an intrasulcular incision was made. A minimally invasive flap was released to expose the marginal bone level and ensure the implants were in the right position. The larger flaps were raised only in patients with bone defects repaired with the bone grafts and the membranes. The teeth were carefully extracted by applying predominantly vertical forces avoiding any damage to the socket and soft tissue (Fig 3). The roots of the molar teeth were separated before extraction (Fig 4).

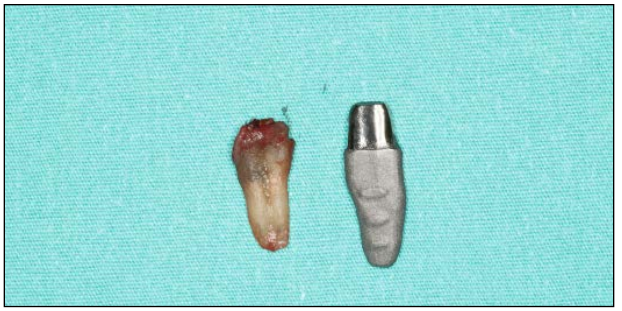


Fig 3 The extracted tooth and an RAI from GR2 before placement.

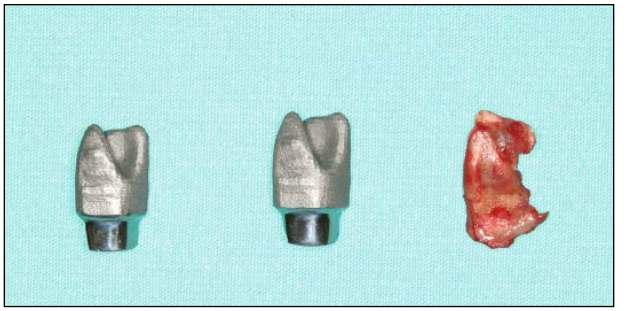


Fig 4 An RAI from GR3. Roots of molar teeth were separated before extraction.

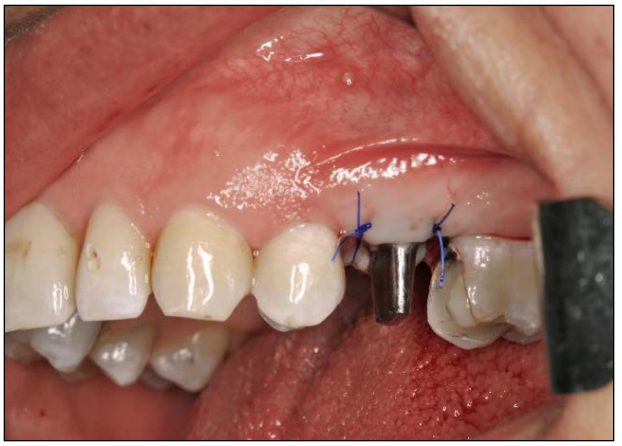


Fig 5 RAI was placed in the socket and interrupted sutures were positioned.

Then, the extraction sockets were carefully debrided and irrigated with saline solution. In case of chronic apical periodontitis, the area of infection was removed. RAIs were placed in the sockets under finger pressure and gently tapped into the sockets with a hammer and a mallet (Fig 5). The primary stability was checked by percussion and palpation. At the end of the surgical procedure, interrupted sutures (Propilen, Doğsan) were positioned, and primary stability was measured using Periotest M (Medizinteknik Gulden). A mucoperiosteal flap was released slightly to expose the defect area in case of fenestration/dehiscence defects or minimum alveolar bone trauma. The defects were reconstructed with the particulate bone grafts (Tutobone, RTI Biologics, Tutogen) and the collagen membranes (Tutopatch, RTI Biologics, Tutogen) with the same protocol. The patients who had alveolar bone damage, lack of primary stability, or incongruence of RAIs with the extraction sockets during the RAI placement were excluded from the study. The conventional screw-type implants were placed after bone healing.

The patients received postoperative analgesics (Arveles, Menarini) on demand and antibiotic therapy (Augmentin BID 1 g, GalaxoSmithKline, Beecham) for 5 days. The mouthrinses with 0.12% chlorhexidine gluconate were administered for 7 days. Detailed instructions about oral hygiene were given. The patients were instructed to chew predominantly on the contralateral side and avoid hard foods.

Postoperative Evaluation

Immediately after implant placement, periapical radiographs were taken to confirm the correct position of the RAIs in the extraction sockets and to measure the distance between the implant apex and the first visible bone contact in millimeters for later measurement of marginal bone loss. The parallel cone technique and film holders were used for reproducible radiographs. The measurements were compared with the real implant length to avoid inaccuracies from possible dimensional distortions. The sutures were removed on the seventh day after the surgery (Fig 6). The patients were seen weekly during the first month, then monthly until prosthetic rehabilitation. Three months later, metal-ceramic single crowns were cemented (Fig 7a). In patients with multiple RAIs, adjacent implants were not splinted with crowns; single-crown restorations were used. Each implant was evaluated individually. The patients were seen at 6 and 12 months.

After 1 year of functional loading, the RAIs were evaluated clinically and radiographically. The presence of bleeding on probing, pocket depth, suppuration, pain, and mobility was investigated. The stability of RAIs was measured with Periotest M. Periotest values (PTV) < 0 were accepted as an indication of good osseointegration. Peri-implant radiolucency and excessive bone loss were evaluated on periapical radiographs (Fig 7b). The marginal bone level was measured, and the changes in the first year were recorded.

The RAIs that were still functional after 1 year of loading were defined as surviving. The RAIs presenting pain on function, suppuration, or clinical mobility were removed and defined as failed. The following clinical and radiographic success criteria had to be fulfilled to achieve implant success: PTV < 0, absence of pain on function, suppuration or exudation, clinically detectable implant mobility, continuous peri-implant radiolucency, and prosthetic complications.

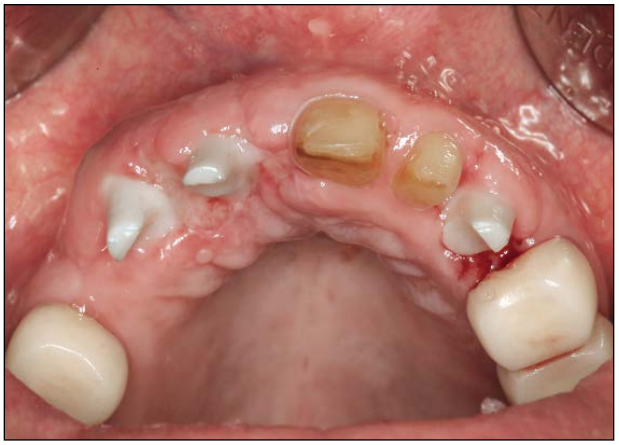
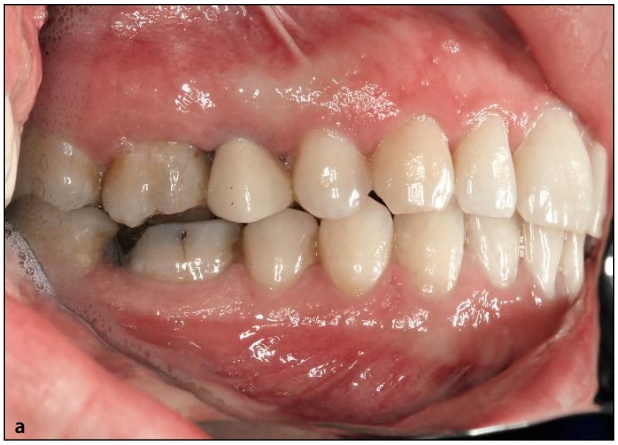


Fig 6 RAIs from GR1. One week after implant placement, the sutures were removed.



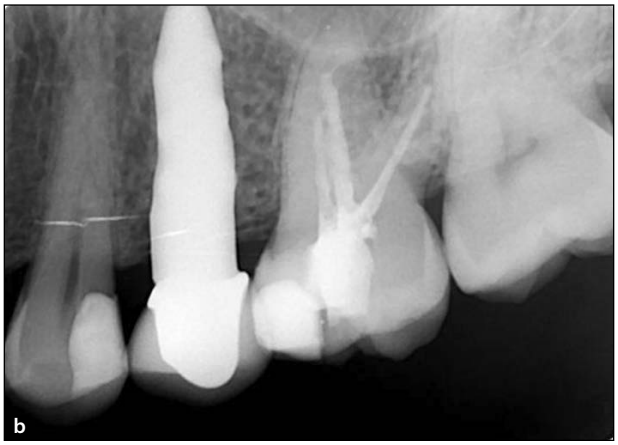


Fig 7 (a) The crown restoration 1 year after RAI placement, (b) periapical radiograph at 1-year follow-up.

Statistical Analysis

Statistical analyses were performed using SPSS Statistics 17.0 (SPSS). An implant survival curve with 95% CI was constructed using the Kaplan-Meier method. The differences in survival between groups were assessed by log-rank test. Univariate and multivariate Cox regression model was developed to evaluate the possible correlation between variables and to identify the variables associated with implant failure. All factors with a *P* value of < .25 were considered in the multiple models using a backward elimination strategy. The significance was set at $P < .05$.

RESULTS

A total of 51 patients (18 men, 33 women) aged between 18 and 66 years (average 34.2 years) were included in the study. In 4 patients, the RAIs could not be placed, and they were excluded. In two of the excluded patients, buccal alveolar bone loss (one in GR1 and one in GR2) led to the lack of primary stability, and in the other two patients (one in GR1 and one in GR3), the RAIs were too large for the extraction sockets (even the 5% downsized ones). Therefore, RAIs were not placed. In the remaining 47 patients, the custom-made RAIs (GR1: n = 21, GR2: n = 17, GR3: n = 18, total: n = 56) were placed in the extraction sockets immediately, and primary stability was achieved. Six patients had more than one RAI (patient no. 1: 4 RAIs; patient no. 2: 3 RAIs; patient no. 13: 2 RAIs; patient no. 34: 2 RAIs; patient no. 37: 2 RAIs; patient no. 45: 2 RAIs). The initial PTVs (PTV0) were between –1.4 and –6.2. The mean PTV0 was –2.3 ± 1.8 for failed RAIs and –4.5 ± 0.8 for surviving RAIs. PTV0 was significantly lower in surviving implants than failed implants ($P = .001$) and was an independent risk factor for survival (HR 3.61, 95% CI: 1.56–8.35, $P = .004$). The PTVs measured at the 1-year follow-up (PTV1) were all < 0 (mean: –4.0 ± 1.9). There were no statistically significant differences between PTV0 and PTV1 (Table 3).

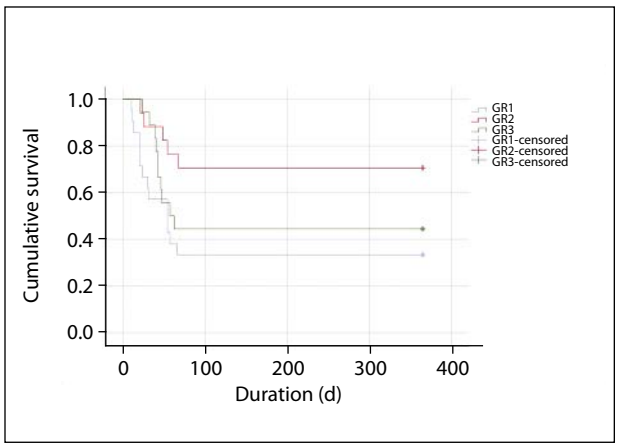


Fig 8 Survival curves for groups (GR1, GR2, GR3).

At the first-week control visit, no complications were observed, such as swelling, inflammation, bleeding, and pain. All implant loss was seen during the first 3 months after implant placement (Fig 8). None of the implants failed after functional loading. Out of 56 RAIs,

Table 1 Summary of Patient Information and Clinical Results of Implant Placement

Variables	GR1	GR2	GR3	Total
Sex				
Female	14	12	13	39
Male	7	5	5	17
Mean age (y)	40.2	30.9	34.8	34.2
Implant placement site				
Anterior (maxilla)	12	0	0	12
Premolar	8	15	6	29
Mandibular	2	4	1	7
Maxillary	6	11	5	22
Molar	1	2	12	15
Mandibular	1	2	7	10
Maxillary	0	0	5	5
Graft usage				
Used	3	5	10	18
Not used	18	12	8	38
Implant status				
Survived	7	12	8	27
Failed	14	5	10	29
Total implants	21	17	18	56

Data reported as n.

Table 2 Median Marginal Bone Loss (First Quartile / Third Quartile) at 12 Months After Implant Placement

	GR1	GR2	GR3	Overall	*P*
Marginal bone loss (mm)	1.26 (1.0/1.5)	1.1 (0.1/3.1)	1.8 (0.7/3.2)	1.3 (0.5/2.9)	.623

Table 3 Median PTVs (First Quartile/Third Quartile) at the Day of Surgery (PTV0) and 1 Year After Implant Placement (PTV1)

	PTV0	PTV1	*P*
GR1	−4.4 (−4.6/−3.6)	−3.5 (−4.7/−1.3)	.150
GR2	−4.4 (−5.0/−4.1)	−4.9 (−5.6/−3.8)	.753
GR3	−3.4 (−5.0/−1.2)	−4.4 (−5.3/−3.1)	.612
Total	−4.4 (−4.6/−3.5)	−4.3 (−5.5/−2.8)	.869
P	.772	.317	

The values were given as median (First quartile/Third quartile).

29 (51.8%) were loosened and suddenly lost without any pain, infection, noticeable bone resorption, or soft tissue inflammation within 19 to 63 days (40 ± 19, mean ± SD). After failed implants were removed, a soft tissue encapsulation surrounding the socket walls was observed. Three months later, metal-ceramic single crowns were cemented on the surviving RAIs. The patients were followed up for 13 to 21 months. No periimplant radiolucency or prosthetic complications were observed. The prosthetic restorations were stable, with good functional and esthetic results at the end of the study. The survival rates were 33.3%, 70.6%, and 44.4% for GR1, GR2, and GR3, respectively, at the end of the observation period. The overall survival rate was 48.2%. There was no significant difference between groups regarding the probability of survival ($P = .051$). The survival rate was significantly lower for anterior RAIs ($P < .001$) and higher for premolar RAIs ($P = .003$). The bone grafts were used for dehiscence or fenestration defects in 18 patients. The probability of survival by bone grafting was not statistically significant ($P = .832$). Four of 4 mRAIs (100%), 5 of 14 dRAIs (35.7%), and 20 of 38 oRAIs (52.6%) failed. The probability of survival by size was statistically significant ($P = .01$). The implant size was detected as an independent risk factor; the mRAIs had 5.25 times more risk of failure than the dRAIs (HR 0.12, 95% CI: 0.03–0.48, $P = .002$) and 2.70 times more than the oRAIs (HR 0.22, 95% CI: 0.07–0.70, $P = .011$). The 1-year mean marginal bone loss was 1.3 ± 0.6 mm (median: 0.8; 95% CI: 0.1–3.4; Table 2). No statistically significant difference in the marginal bone loss was found among groups ($P = .623$). Clinically healthy gingival margins were observed without any signs of periodontitis or implant mobility. The mean PTVs measured at 1-year follow-up (PTV1) were −4.0 ± 1.9. The PTVs for each surviving implant were < 0 at the end of the study. PTV0s were significantly lower in surviving implants ($P = .001$).

DISCUSSION

The application of digital technology in dentistry has become increasingly widespread with the introduction of CBCT scan technology and the advancements in CAD/CAM techniques.[21] The acquirement of digital 3D copies of the teeth, which is the first step of RAI design and manufacture, can be performed by two techniques: CBCT scanning and laser scanning.[5–7,13,14,19,20,22] CBCT scanning allows testing of the congruence between the implants and the alveolar sockets, as well as the neighboring/opposing teeth, before manufacture. The RAI could be manufactured prior to extraction and placed afterward, reducing the number of visits and improving the patient's comfort.[5–7,10] However, image processing software and an experienced operator are needed to create an accurate virtual 3D model, and the accuracy depends on the quality of CBCT datasets. The other method to acquire a digital copy is laser scanning the teeth after extraction. This method allows the operator to repair the fractured roots and irregularities on the root surface and helps avoid any discrepancies or CBCT scan artifacts caused by radiopaque restorative materials. However, scanning the tooth after extraction causes delayed implantation with a second surgical procedure.

Pirker and Kocher[13] modified the root surfaces before laser scanning. They designed macroretentions limited to interdental space for improving primary stability, and the buccal and lingual aspects were reduced by 0.1 to 0.2 mm to avoid fracture and pressure-induced bone loss. In the present study, these modifications were also performed on the root surfaces digitally with 3-matic Modeling Software (Materialise), providing a standardized method rather than manual preparation. In addition, abutments in the shape of a prepared tooth with a taper of 5 degrees and chamfer margins were designed using that software. This design facilitated the prosthetic treatment. Moreover, resistant and retentive restorations with esthetic results were achieved.

In this study, the incisor and canine teeth in the esthetic zone and the multiple rooted molar teeth caused a limitation in choosing the type of manufacturing procedure. The three-rooted implants could not be milled accurately in the interradicular area, which led the maxillary molars to be manufactured only by the DLMS technique. Moreover, due to esthetic reasons, anterior RAIs were manufactured from the zirconia and included in the GR1. Therefore, the randomization of the present study was affected negatively, and the evaluation of the outcomes of the study became more complicated in terms of determining the main reason for the low survival rate.

The probability of survival was not statistically significant between the groups ($P = .051$). However, the survival rate in GR2 was higher than in the other two groups. As a limitation of the present study, the sample size of the groups was inadequate for significance. Even so, the outcomes are considered valuable, giving insights for further studies.

There were many factors affecting the success of the RAIs. The low survival rate is attributed to multiple reasons. As another limitation of the study, the region of the implants was not a criterion for determining the study groups. Divergent molar roots were flattened to ease the placement of RAIs in the sockets; thus, it may have resulted in the decrease of the implant-socket congruity. Although the PTV0s of the molar RAIs were low as aimed, 11 of 15 molar RAIs failed, most likely because of the discrepancy between sockets and implants. Even though a few single molar zirconia RAI cases were reported,[14,19,20] most of the molar RAIs in the present study failed within a short time. The overall success rate (48.2%) was lower than previously reported success rates in other studies.[10,13] However, it must be considered that the other RAI studies in the literature mostly demonstrate successful premolar implants rather than molar implants. The RAIs in GR1 had the lowest survival rate (33.3%). The majority of the implants in this group were in the anterior region (57.1%). The overall success rate was 25% for the anterior region and 50% for the premolar RAIs. The reason for the low success rate in the anterior region is not clear. Higher PTV0s in this group could be responsible for the high failure rate. Possible explanations for high PTV0s in this group are the cancellous bone structure in that region and insufficiency of the macroretentions in the interdental surfaces. Further studies could be planned to evaluate zirconia RAIs in the anterior region, and larger macroretentions may be designed to improve the stability. Although simultaneous grafting was another doubtful criterion for the low success rate, the probability of survival by bone grafting was not statistically significant ($P = .832$).

In an experimental study in monkeys that evaluated titanium RAIs placed in the central and lateral teeth sockets, Kohal et al reported a low success rate. They explained the implant failure with stress-induced resorption on the thin alveolar bone surface, resulting in disturbance of stability.[9] In another study, Pirker and Kocher[13] reported that the socket remains stable without resorption after the RAI loss. In the present study, the RAIs were loosened and failed in a short time, and minimal alveolar bone resorption was observed after the implant removal. However, the conventional screw-type dental implants could be placed easily after RAI loss due to the preservation of alveolar bone width and height. Lin et al[23] reported that reducing the diameter of the maxillary central incisor root analog by up to 2 mm next to the labial cortical bone could help disperse stress in a finite element model. In the present study, the buccal and lingual aspects of the implants were reduced by 0.1 to 0.2 mm, which might be inadequate and the reason for resorption and early-phase implant loss.

Stability is crucial clinical evidence of implant survival. The stability of implants was evaluated by subjective methods, such as the percussion test, in other RAI studies. In the present study, primary and secondary stabilities were measured by using Periotest M, a quantitative test method. Periotest measures the contact time of the electronically driven and monitored probe after percussing the test surface (tooth or implant). A short contact time corresponds to a low Periotest value, while a long contact time corresponds to a high Periotest value.[24] PTV ranges between –8 (clinically rigid) and +50 (very mobile). A more negative PTV means a more stable implant. The Periotest has limited clinical use since it cannot measure the mesiodistal mobility, and the position or the angle of the probe affects the measured value. Also, it cannot detect small changes in the bone-implant surface. Another failing point of this method is that the percussing force on the implant may deteriorate the stability of implants with poor initial stability.[25] Other techniques can be used to measure the implant stability objectively, such as resonance frequency analysis (RFA), a nondestructive and noninvasive method

measuring implant stability quantitatively without any damage to the bone-implant interface in vivo at any stage of treatment.[26] Several studies have investigated and confirmed its usefulness and reliability.[27,28] However, there is no way to use the RFA to evaluate the stability of one-piece RAIs because a sensor must be directly attached to the implant body to measure the stability of the implant. Many studies have indicated the presence of correlation between PTV and ISQ, and both methods have been demonstrated to be helpful in evaluating implant stability.[29–31] Chavez et al[32] reported that the measurements ranged from −6 to −2 PTV for clinically successful, stable, functional screw-type implants. In the present study, PTV0 was higher in failed implants than in surviving implants and an independent risk factor for survival (HR 3.61, 95% CI: 1.56–8.35, $P = .004$). According to this result, the overall high failure rate in the present study can be correlated to the high PTV0. A possible reason for the lower primary stability was considered to be the implant placement site. In the mandible, where 7 of the 10 mandibular molar implants and 4 of the 7 mandibular premolar implants failed, obtaining primary stability was difficult because of the dense cortical bone structure. It was observed that the furcation of the molar implants was not manufactured with precise accuracy, so the implants were interfering with the interradicular septum. The highest survival rate was observed in GR2 (70.6%). It could be explained by the lowest mean PTV0 and the smaller number of molar teeth inclusion in this group. The low survival rate in GR3 (44.4%) can also be explained by the same reasons. The higher success rate in GR2 could also be a result of better primary stability in this group rather than the implant material and manufacturing technique. When all the limitations of this study are considered, further studies are necessary to draw a clear conclusion.

The alteration of the marginal bone level is another criterion for the evaluation of implant success. According to the previously reported implant survival and success criteria by Albrektsson et al,[33] the marginal bone loss should be < 1.5 mm in the first year. The mean bone loss of 0.2 mm per year after the first year was accepted as another criterion by Smith and Zarb.[34] In the present study, all of the surviving implants were stable and in function without any signs of peri-implantitis or implant mobility. At the end of the first year, the mean marginal bone loss was 1.3 ± 0.6 mm (median: 0.8; 95% CI: 0.1–3.4). In several other RAI studies, unchanged peri-implant marginal bone levels after 1- to 2.5-year follow-up were reported.[6,10–14,19,20]

Some conditions might limit the feasibility of the RAI technique, such as the presence of curved and divergent roots, traumatic tooth extraction, malposition, large periapical lesions, and inadequate alveolar socket height. Even if this technique has high success rates, it cannot be a widely used treatment modality due to these limitations of patient selection.

CONCLUSIONS

This study was the first attempt to compare different RAI manufacturing techniques and biomaterials in the literature.

Although the probability of survival was not statistically significant between groups because of the inadequate sample size, the survival rate in GR2 was higher than in the other two groups. Nevertheless, the overall survival rate was significantly lower (48.2%) than in previous reports. Primary stability was an independent risk factor for failure, and there were many factors that affected the PTV0s. It cannot be concluded that the success depends on the implant material and manufacturing technique with the results of this study, but it is affected by the implant placement site. Even though this study did not give adequate information about comparing three groups, it has given valuable insights into the clinical use of RAIs. Further studies with minimized variables between groups should be designed for precise results.

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