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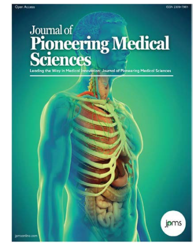

In Vitro Assessment of Immediate Implant Placement in Fresh Extraction Sockets versus Healed Sites Using a Polyurethane Mandibular Bone Model

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Abstract **Background:** Immediate implant placement in fresh extraction sockets is an established treatment option, but its initial biomechanical environment differs from that of delayed placement in healed sites. This controlled in vitro study compared stability and interface parameters between the two placement models under standardized artificial mandibular bone conditions. **Methods:** Forty polyurethane Sawbones blocks simulating type II/III mandibular bone were allocated to a fresh extraction socket model (Group A, n=20) or a healed osteotomy model (Group B, n=20). Identical SLA-surfaced titanium implants (4.0 × 10 mm) were inserted by a single operator. Primary outcomes were implant stability quotient (ISQ) and insertion torque value (ITV); secondary outcomes were removal torque value (RTV), bone-implant contact (BIC), contact area and gap volume assessed by micro-computed tomography. The artificial model evaluated mechanical stability only and did not simulate biological healing. **Results:** Healed site models demonstrated significantly higher stability than fresh socket models. Mean ISQ was 72.4±4.8 in Group B versus 64.2±5.6 in Group A ($p<0.001$). Mean ITV was 38.6±6.2 Ncm versus 28.4±5.8 Ncm ($p<0.001$) and mean RTV was 32.4±5.4 Ncm versus 24.8±4.9 Ncm ($p=0.002$). Mean BIC was 68.3±7.4% in healed sites and 52.6±8.2% in fresh socket models ($p<0.001$). Gap volume was substantially lower in healed sites (4.8±2.1 mm^3) than in fresh socket models (12.4±3.2 mm^3) ($p<0.001$). **Conclusion:** Within the limits of this in vitro polyurethane mandibular model, healed site placement showed greater primary stability and closer implant-bone adaptation than immediate placement in fresh socket models. Immediate placement may therefore require additional stabilization measures and cautious loading decisions when initial stability is borderline.

Key Words Dental Implants, Immediate Placement, Extraction Socket, Healed Site, Primary Stability, Resonance Frequency Analysis, Micro-CT

INTRODUCTION

Dental implant therapy has transformed the rehabilitation of partial and complete edentulism by providing highly predictable long-term treatment outcomes. One of the key clinical decisions in implant dentistry is the timing of implant insertion after tooth extraction, with protocols ranging from immediate placement in a fresh socket to delayed placement after complete healing of the alveolar ridge.

Immediate implant placement is attractive because it can reduce treatment time, reduce the number of surgical interventions and help preserve hard- and soft-tissue contours. However, survival rates and aesthetic success should not be interpreted as equivalent to primary mechanical stability. Immediate placement may survive clinically while still presenting a more demanding initial biomechanical environment than delayed placement.

The central mechanical challenge in immediate placement is the mismatch between implant geometry and extraction socket anatomy. Fresh sockets commonly create a residual circumferential gap or “jump distance” between the implant surface and socket wall, reducing direct initial contact. In contrast, healed ridges allow a more uniform osteotomy and broader mechanical engagement of the implant threads with cortical and cancellous bone.

Primary stability reflects the mechanical stiffness of the implant-bone interface at the time of placement and is influenced by bone quality, implant macrogeometry, site preparation and recipient site anatomy. Resonance frequency analysis (RFA) estimates interface stiffness through implant stability quotient values, whereas insertion and removal torque measurements reflect rotational resistance at the interface. These measurements are complementary rather than interchangeable and none of them alone represents biological osseointegration.

Controlled in vitro testing is useful when the research question is limited to immediate mechanical behaviour. Standardized artificial bone models remove patient-related variability and allow direct comparison of ISQ, torque values and micro-CT interface measurements in the same experimental setting. At the same time, such models do not reproduce healing, remodelling, saliva or loading and their conclusions must therefore be interpreted as mechanical rather than biological.

The present study addressed a focused gap in the literature by combining RFA, insertion torque, removal torque and micro-CT assessment of bone-implant contact and gap volume in a standardized mandibular polyurethane model. The null hypothesis was that implants placed in a simulated fresh extraction socket would not differ from those placed in a healed osteotomy model with respect to primary stability or implant-bone contact parameters.

METHODS

This controlled in vitro experimental study was performed between January and June 2024 using standardized polyurethane Sawbones blocks intended to simulate type II/III mandibular bone. Because no human participants, animal specimens or identifiable clinical records were used, the experiment represented bench-top laboratory research; institutional administrative approval for laboratory conduct was obtained and patient consent was not applicable.

Sample size was calculated with G*Power version 3.1.9.7 using a projected effect size of 0.85, alpha of 0.05 and power of 80%, yielding a minimum requirement of 18 specimens per group. To protect against specimen loss or measurement error, 20 specimens were allocated to each group.

Forty polyurethane foam blocks (40 × 40 × 30 mm) with a 2-mm cortical shell of 40 PCF over a cancellous core of 20 PCF were used. This model approximates mandibular type II/III bone quality and therefore should not be extrapolated directly to softer maxillary bone or other jaw conditions.

Specimens were randomly assigned to two groups (n=20 each). Group A represented a fresh extraction socket model. A custom socket former created a premolar-like socket 8 mm deep, with a coronal diameter of 6 mm tapering to 4 mm apically. Group B represented a healed site model, in which standard osteotomies were prepared directly in intact blocks according to the manufacturer's drilling protocol.

All implants were identical SLA-surfaced titanium implants measuring 4.0 mm in diameter and 10 mm in length, obtained from the same manufacturing lot to reduce inter-implant variability. One trained operator placed all implants to minimize technique variability; this improved standardization but also means that operator-specific technique effects cannot be excluded.

For Group A, the simulated socket was prepared first, after which the implant osteotomy was extended 3-4 mm beyond the socket apex to obtain apical engagement. For Group B, sequential drilling was performed with 2.0-, 2.8- and 3.5-mm drills at 800 rpm under copious irrigation. This design compared a fresh socket condition managed with clinically relevant apical engagement against a healed osteotomy condition rather than comparing two anatomically identical sites.

Implant stability was assessed by three complementary methods. Maximum insertion torque value was recorded at final seating with a calibrated surgical motor. RFA measurements were then obtained using an Osstell ISQ device from mesial, distal, buccal and lingual directions and the mean of the four values was used. Removal torque value was recorded as the maximum reverse torque required to initiate implant rotation.

Micro-CT scanning was performed with a SkyScan 1275 system at 100 kV, 100 µA and 15-µm voxel size. Reconstruction and quantitative analysis were completed in CTAn software. The region of interest encompassed the implant surface from the crestal level to the apical end within the prepared site. Bone-implant contact was defined as the proportion of implant surface directly contacting the surrounding bone substitute after standardized thresholding. Contact area was recorded in square millimetres and gap volume was defined as the non-contact void volume surrounding the implant inside the same region of interest. Thresholding parameters and region-of-interest selection were kept constant for all specimens.

Descriptive statistics included mean, standard deviation and 95% confidence intervals where appropriate. Shapiro-Wilk testing confirmed approximate normal distribution. Between-group comparisons were made using independent-samples t tests. Pearson correlation was used to evaluate associations among ISQ, ITV, RTV and BIC. Statistical significance was set at $p<0.05$.

RESULTS

All 40 implants were placed successfully without specimen fracture or implant damage and complete datasets were available for all specimens.

Primary Stability Measurements

Healed site models as showed in Table1, significantly higher primary stability than fresh extraction socket models. The mean ISQ was 72.4±4.8 in Group B and 64.2±5.6 in Group A (mean difference 8.2; $p<0.001$). Mean insertion torque was 38.6±6.2 Ncm in Group B and 28.4±5.8 Ncm in Group A (mean difference 10.2 Ncm; $p<0.001$). Removal torque values were 32.4±5.4 Ncm and 24.8±4.9 Ncm, respectively (mean difference 7.6 Ncm; $p=0.002$).

Table 1: Comparison of primary stability parameters between groups

Parameter	Group A (Extraction Socket)	Group B (Healed Site)	Mean Difference	p-value
ISQ Value	64.2±5.6	72.4±4.8	8.2	<0.001*
ITV (Ncm)	28.4±5.8	38.6±6.2	10.2	<0.001*
RTV (Ncm)	24.8±4.9	32.4±5.4	7.6	0.002*

Take-home message: the healed site model consistently outperformed the fresh socket model across all three mechanical stability measures.

Table 2: Bone-implant contact analysis results

Parameter	Group A (n=20)	Group B (n=20)	95% CI of Difference	p-value
BIC (%)	52.6±8.2	68.3±7.4	10.8-20.6	<0.001*
Contact Area (mm²)	48.2±7.8	62.6±6.9	9.7-19.1	<0.001*
Gap Volume (mm³)	12.4±3.2	4.8±2.1	5.8-9.4	<0.001*

Take-home message: the fresh socket model produced a markedly larger peri-implant gap, which likely contributed to lower BIC and lower primary stability.

Table 3: Pearson correlation coefficients between parameters

Parameter	ISQ	ITV	RTV	BIC
ISQ	1.000	0.847*	0.812*	0.792*
ITV	0.847*	1.000	0.884*	0.768*
RTV	0.812*	0.884*	1.000	0.724*
BIC	0.792*	0.768*	0.724*	1.000

Take-home message: stability measurements and interface contact parameters were closely related, but these correlations should be interpreted as associations rather than proof of mechanism.

Bone-Implant Contact Analysis

Micro-CT analysis also favoured healed sites. As in Table 2, mean BIC was 68.3±7.4% in Group B and 52.6±8.2% in Group A (p<0.001). Contact area was higher in healed sites, whereas gap volume was substantially lower, confirming closer initial adaptation around implants placed in intact osteotomies.

Correlation Analysis

ISQ showed strong positive correlation with ITV (r=0.847, p<0.001), RTV (r=0.812, p<0.001) and BIC (r=0.792, p<0.001). ITV was also strongly correlated with RTV (r=0.884, p<0.001) and BIC (r=0.768, p<0.001), indicating that the mechanical measurements moved in the same direction across specimens (Table 3).

DISCUSSION

The present experiment demonstrated a consistent mechanical advantage for implants placed in healed site models. Healed blocks produced higher ISQ, ITV, RTV, BIC and contact area, together with markedly lower gap volume, indicating more intimate implant-bone adaptation at placement.

The explanation is biomechanical rather than biological. In the healed site model, the implant engaged an intentionally prepared osteotomy with more circumferential support from the surrounding material. In the fresh socket model, part of the implant surface remained adjacent to a simulated socket gap rather than directly contacting the bone analogue. This reduced the effective interface stiffness measured by RFA and reduced rotational resistance during insertion and removal.

The 8.2-point difference in ISQ and the 10.2 Ncm difference in insertion torque were substantial under the present model, but these values should not be over-interpreted as direct clinical thresholds. RFA reflects interface stiffness, not osseointegration and insertion torque may vary with drilling strategy, implant macrogeometry and local bone compression. The current findings therefore support relative comparison between the two models rather than absolute clinical cut-off values.

Micro-CT findings strengthened the interpretation of the mechanical data. Healed sites showed higher BIC and contact area, whereas fresh sockets showed significantly larger gap volume. This gap finding is particularly relevant to immediate placement because it highlights the central mechanical problem of fresh sockets: reduced direct contact around part of the implant surface at the moment of placement. Although grafting and membrane-based gap management were not tested in this experiment, the data support why such strategies are commonly considered clinically.

The strong positive correlations among ISQ, ITV, RTV and BIC indicate that these methods provide related but complementary information regarding initial fixation. Correlation, however, should not be interpreted as proof of mechanism. The study did not measure surface chemistry changes, biological healing or dynamic loading behaviour and these factors remain important when translating mechanical findings into clinical recommendations.

Several practical implications emerge from this standardized model. First, clinicians should anticipate lower initial stability in fresh sockets than in healed ridges when a gap is present. Second, immediate placement may require technique modifications aimed at improving primary fixation, such as apical engagement, careful osteotomy control or the use of implant designs intended to enhance mechanical locking. Third, stability measurements can assist with loading decisions, especially when immediate or early loading is being considered.

This study also has important limitations. Artificial polyurethane blocks do not reproduce living alveolar bone, blood supply, remodelling or the secondary stability phase. The socket model was idealized and did not simulate irregular extraction sockets, periodontal ligament remnants, thin buccal plates, infection or damaged socket walls. Only one implant size, one surface type, one socket configuration and one bone density were tested and no cyclic loading or fatigue testing was performed. Accordingly, the results should be interpreted as a controlled comparison of immediate mechanical behaviour rather than as a direct prediction of in vivo osseointegration or clinical success.

CONCLUSIONS

In this standardized polyurethane mandibular model, implants placed in healed sites demonstrated higher primary stability and closer interface adaptation than implants placed in simulated fresh extraction sockets. Healed site placement yielded higher ISQ, ITV, RTV, BIC and contact area, whereas fresh socket models exhibited larger peri-implant gap volumes.

These findings suggest that immediate implant placement in fresh sockets may require additional stabilization strategies and cautious loading decisions when initial fixation is limited. However, because the model did not simulate healing, remodelling, saliva or functional loading, the present results should be interpreted as mechanical baseline data rather than direct evidence of long-term clinical superiority.

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