Contemporary plasma-sprayed hydroxyapatite (HA) coatings with high crystalline content are much more resistant to in vivo degradation than HA coatings of a decade ago but reportedly exhibit reduced wettability, which could potentially negatively affect tissue adhesion and long-term clinical outcome. The present prospective study was undertaken to determine if highly crystalline HA MP-1–coated implants could meet a minimum 5-year implant success rate standard of 85% in view of their previously reported decreased wettability. Study subjects were consecutive patients with 1 or more missing teeth in the maxillary and/or mandibular jaw who presented in 3 university dental clinics and 1 private dental practice. A total of 120 patients were treated per protocol and successfully restored with implant-supported prostheses. Four implants failed in 3 patients and were withdrawn from the study. There were no other irresolvable adverse events. Cumulative implant success at 5 years was 97% (n = 184 implants in 88 patients), which exceeded the 85% standard for implant success after 5 years of clinical function.

Key Words: hydroxyapatite, HA, implant, crystallinity, wettability
dental implants (Integral, Zimmer Dental Inc, Carlsbad, Calif) were introduced in the United States.7

Early reports8–13 in the dental literature documented the ability of HA coating to significantly increase the percentage (range, 50% to >95%), development rate, and strength of bone-to-implant contact in comparison to machined and grit-blasted titanium surfaces. Numerous short-term14–17 (<5 years) and long-term18–25 (5 years and longer) studies have reported clinical success rates ranging from 93.4% to 100% and 93.2% to 99%, respectively, with no significant adverse events attributed to implant surface. Despite these and other widely documented findings on the clinical effectiveness of HA-coated implants, several case reports26–28 during the early 1990s suggested that HA coatings were inherently unstable, susceptible to dissolution in the presence of bacterial infection, and possibly predisposed to rapid bone loss or sauceration around the cervical end of the implant. Such findings have not been substantiated by long-term clinical studies, nor do they reflect the current state of HA-coated implant technology.27,28 Nonetheless, many manufacturers added a 1-mm metal collar around the tops of their HA-coated implant designs to resist the potential plaque formation and microbial colonization that some clinicians associated with HA coating.28

Research conducted over the past decade has documented that highly crystalline HA implant coatings exhibited greater resistance to dissolution and higher percentages of bone-to-implant contact in comparison to HA coatings with lower crystallinity.29–33 Kay31 stated that the percentage of the crystalline phase in HA coatings should be maximized to contain no less than 90% crystalline HA. Burgess et al32,33 reported on a novel, pressurized, hydrothermal, post–plasma spray process, called MP-1 (Zimmer Dental Inc), that has been documented to convert the crystalline non-HA and amorphous components of plasma-sprayed HA coating back into crystalline HA. The resulting study coating was found to contain more than 90% crystalline HA.32,33 Compared with the untreated control coating, the MP-1–treated surface exhibited equivalent adhesive strength to the implant surface but significantly decreased in vitro solubility over a wide range of pH levels.32,33

Almost immediately upon placement, dental implant surfaces absorb proteins from blood, tissue fluids, and cellular activities through a complex interaction between the implant’s material composition and surface chemistry (eg, surface energy, surface charge, surface texture, etc)34,35. The proteins help to mediate tissue-implant interactions by facilitating cellular adhesion to the implant surface.34,35 One fundamental aspect of this interaction is the wettability of the implant surface, which is the degree to which these fluids are able to spread across the surface and form a pertinacious biofilm or coating. Theoretically, the greater the wettability (or spreadability of pertinacious biofluids over the implant surface), the greater the percentage of cellular attachment can occur, resulting in increased tissue attachment to the implant.

Surface wettability is determined by measuring contact angle, which is the angle formed by a liquid droplet on a solid surface (ie, the line tangent to the droplet radius from the point of contact with the solid). Mekayarajananonth and Winkler36 compared the contact angles of 8 different implant surface preparations and found that the standard, plasma-sprayed, HA-coated implant surface with 77% crystallinity32 (Calcitite, Zimmer Dental Inc) exhibited the widest contact angles/highest wettability of all surfaces tested, while the heat-treated, HA-coated surface with 95% crystallinity32,33 (HA MP-1) exhibited the lowest contact angles/least wettability of all tested surfaces.

To initially determine if the lower wettability of HA MP-1 negatively affected implant survival, a comprehensive retrospective study of 3811 HA MP-1–coated dental implants was conducted to assess their outcomes.7 The results showed a cumulative implant survival rate of 99.3% with up to 5 years of clinical follow-up.7 The authors then began a 5-year prospective study to determine if HA MP-1–coated dental implants would achieve a cumulative success rate of at least 85% at 5 years postrestoration, which has been recommended as a standard of long-term success by Albrektsson et al.37 This article reports on the results of that study.

Materials and Methods

Patient selection and evaluation

Subjects for this prospective study were consecutive patients who presented with 1 or more missing teeth in the maxillary and/or mandibular jaw in 3 university dental clinics and 1 private dental practice. All patients were subjected to a preliminary evaluation that included careful review of their medical and dental histories, detailed clinical and radiographic examinations, evaluation of oral hygiene, and the ability to commit to a long-term treatment plan. Those patients who were deemed by the clinician as acceptable candidates and who met the inclusion criteria (Table 1)
were admitted into the study after signed informed consent was obtained.

A diagnostic workup was performed for each patient to evaluate the volume and location of available bone, the esthetic and functional needs of the case, and the desires of the patient. A study cast was fabricated and mounted on a semiadjustable articulator using a facebow transfer and vertical registration to determine the jaw relationships, available occlusal dimension, proposed implant position, crown-root ratio, and potential complications. This allowed creation of a prosthetic wax up and fabrication of a surgical template to guide placement of the implants relative to the planned prosthesis.

**Implants**

Threaded implants with highly crystalline HA MP-1 coating (Spline HA MP-1, Zimmer Dental Inc) were used in this study. Selection of implant length (8 mm, 10 mm, 11.5 mm, 13 mm, 15 mm, or 18 mm) and diameter (3.75 mm or 5.0 mm) was left to the discretion of the clinician according to the prosthodontic needs and available bone of each patient.

**Success criteria**

An implant was deemed successful if it was clinically immobile, load bearing, and functional at the time of evaluation. To be considered successful, a prosthesis was required to be in function and satisfactory to the patient in terms of comfort, use, and esthetics at the time of evaluation. Success rates were determined through evaluations of individual implant survival rates and prosthetic functionality. Overall success was evaluated through assessments of periodontal health, implant integration, and radiographic analyses to determine the presence or absence of peri-implant radiolucency and any secondary marginal bone changes. Implant failure, site morbidity, other complications, and patient psychological, emotional, and esthetic satisfaction levels were also considered. Success criteria are summarized in Table 2.

**Surgical procedures**

A conventional, 2-stage surgical approach was used, and implants were placed in accordance with the manufacturer's instructions for use. All implants were placed by one of the principal investigators or by associates under direct supervision of the principal investigators. After preparation of the osteotomies, minimum residual bone was required to be at least 1 mm on the buccal and lingual plates and 2 mm below the apical end of the osteotomy. If complications arose, such as the need for bone grafting, the patient was withdrawn from the study and treated according to need. All withdrawals were duly recorded and accounted in the final analysis. Stage 2 surgery was performed 3 months (mandibles) to 6 months (maxillas) after placement. Osseointegration was conventionally confirmed by radiographic appearance and manual manipulation of the implants.

**Prosthodontic procedures**

Restorative procedures began minimum of 2 weeks after stage 2 surgery to allow for soft tissue maturation. All prosthodontic plans were developed by or with input from the principal investigator.

**Postrestoration monitoring**

Baseline periapical radiographs were taken at delivery of the definitive prosthesis and then at annual follow-up visits through year 5. High-quality, long-cone periapical radiographs of each implant were taken using high-speed film (Kodak Ektaspeed Plus Dental}

---

**TABLE 1**

**Patient selection criteria**

<table>
<thead>
<tr>
<th>Inclusion</th>
<th>Exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completely or partially edentulous in either jaw</td>
<td>History of alcoholism or other substance abuse</td>
</tr>
<tr>
<td>Adequate available bone for implant placement</td>
<td>History of mental instability</td>
</tr>
<tr>
<td>At least 18 y of age</td>
<td>Smokers who exceed 1 pack/d</td>
</tr>
<tr>
<td>Willingness to participate for study duration</td>
<td>Uncontrolled metabolic disease (eg, diabetes)</td>
</tr>
<tr>
<td>Willingness to provide informed consent</td>
<td>Uncompensated systemic disease</td>
</tr>
<tr>
<td></td>
<td>Immunocompromised status (eg, chronic steroid therapy)</td>
</tr>
<tr>
<td></td>
<td>Untreated dental disease</td>
</tr>
<tr>
<td></td>
<td>Evidence of severe parafunctional habits</td>
</tr>
<tr>
<td></td>
<td>Prior irradiation of the treatment site</td>
</tr>
</tbody>
</table>

**TABLE 2**

**Success criteria**

<table>
<thead>
<tr>
<th>Implants</th>
<th>Prostheses</th>
</tr>
</thead>
<tbody>
<tr>
<td>No radiographic peri-implant radiolucency</td>
<td>Prosthesis is fully functioning</td>
</tr>
<tr>
<td>Clinically immobile when tested manually*</td>
<td>Meets the patient’s clinical needs</td>
</tr>
<tr>
<td>Has not significantly damaged adjacent structures</td>
<td>Meets the patient's expectations for comfort, use, and esthetics</td>
</tr>
<tr>
<td>Load-bearing during function</td>
<td></td>
</tr>
<tr>
<td>The presence of periodontally healthy tissues</td>
<td></td>
</tr>
<tr>
<td>Meets the prosthodontic needs of the patient</td>
<td></td>
</tr>
<tr>
<td>Marginal bone loss limited to 1.4 mm at 3 years and 2 mm at 5 years</td>
<td></td>
</tr>
</tbody>
</table>
|                                        | *

*Testing was limited to single-tooth restorations and some removable prostheses.
Film or Kodak Ultra-Speed Intraoral Dental Film DF-58, Eastman Kodak Co, Rochester, NY) in double-film packets. Clinicians were instructed to make every effort to ensure that the radiograph source was perpendicular to the long axis of the implant. Use of an intraoral positioner was allowed. No other standardized radiographic procedures were used.

Baseline clinical examinations occurred 2 to 3 weeks after delivery of the definitive prosthesis, at 6 months postrestoration, and then at annual follow-up visits through year 5. Clinical evaluations consisted of gingival bleeding, plaque and calculus indices, and evaluation of osseointegration radiographically (ie, lack of peri-implant radiolucency) and, whenever possible, by direct manual manipulation of the implant. Implant mobility was evaluated according to Miller38 (Table 3). Single, unsplinted implants were required to be clinically immobile (Mobility Index grade 0; Table 3). If implant mobility was noted, the implant was recorded as a failure.

The Gingival Bleeding Index was used to determine the presence or absence of inflammation in the free and attached gingiva. A standard periodontal probe was applied to the internal aspect of the gingival margin with no attempt to probe the sulcus depth, and the Gingival Bleeding Index was evaluated according to Silness and Loe39 (Table 3).

Plaque and calculus indices were used to measure the supragingival and subgingival plaque or calculus accumulation around the cervical end of the implant abutment as indicators of oral hygiene compliance by the patient and overall gingival health status according to Silness and Loe39 (Table 3).

All adverse events, including peri-implant marginal bone loss, were recorded and included in the data analyses.

**Patient satisfaction surveys**

Before treatment and during annual postrestoration monitoring appointments, patients completed a self-evaluation of their functional, psychological, emotional, and esthetic satisfaction with their dental condition. Patients were also able to comment on their implant treatment procedures.

**Statistical methods**

Data analyses on the individual periodontal indices, marginal bone changes, and, whenever possible, implant mobility were performed to determine their effects on implant success. Complication rates were reported and summarized over time. Time-specific implant failure rates were statistically analyzed and reported using survival analysis techniques. Implant and prosthetic success rates were analyzed by implant location in the anterior and posterior of each arch and by type of restoration. Patient satisfaction with restored implants was analyzed and compared with preoperative satisfaction levels. Ninety-five percent (95%) confidence intervals were constructed for all point estimates. Nominal statistical significance was assessed at $\alpha = .05$.

**RESULTS**

A total of 145 patients (55 men, 90 women) ranging in age from 24 to 89 years (mean, 50–59 years) were enrolled in the study (intent-to-treat group). This
population included 13 patients who smoked 1 pack of cigarettes or fewer per day; the remaining 132 patients were nonsmokers. Patients were treated with a total of 259 implants (Table 4). Within this group, 27 patients were withdrawn for various reasons prior to restoration (Table 5); the remaining 120 patients with 245 implants were successfully restored with implant-supported prostheses (treated-per-protocol group; Table 6).

The cumulative implant success at year 5 was 97% (n = 184 implants in 88 patients). Four implants placed in 3 female nonsmokers failed after loading (Table 6): 2 implants supporting a fixed partial denture in the mandibular right first and second molar regions of a 50-year-old patient failed during year 1, a single-tooth restoration supported by 1 implant in the maxillary left first molar location of a 43-year-old patient failed during year 4, and 1 implant supporting a single-tooth restoration in the mandibular right second molar area of a 53-year-old patient failed in year 5. All failed implants were 3.7 mm in diameter; 3 were 10 mm long and 1 (single tooth restoration in the mandibular right second molar region) was 13 mm long. These patients were recorded as withdrawals because of implant mobility (Tables 5 and 8), and patients received corrective treatment outside of the study.

Results from the periodontal indices are summarized in Table 7. In year 5 of clinical follow-up, 99.45% of the patients had no bleeding on probing (grades 0 and 1) with little to no operator-induced tissue irritation, and 98.0% had little or no plaque or calculus (grades 0 and 1).

A total of 64 adverse events were reported (Table 8). Most of these events were unrelated health or medical events (n = 18). Porcelain crown fractures (n = 10) were the most common implant-related complication but were not listed as prosthetic failures because the implant-abutment assembly was not damaged and remained functional as soon as the fractured crown was replaced. The second most common adverse events were transient peri-implant infections, abscesses, or swellings (n = 7), which were clinically resolved. The 4 implant failures previously listed as withdrawals (Table 5) were the most serious adverse events, followed by minor peri-implant marginal bone loss (n = 4) that did not exceed 1.4 mm at year 5. All marginal bone loss occurred during the first 3 months of loading and then stabilized through year 5. There were 3 other infections unrelated to the implant itself and 3 reports of screw or abutment loosening. Space limitations required 1 implant to be splinted to an adjacent natural tooth, which was a protocol deviation that was listed as an adverse event. One dental implant appeared to exhibit...
slight instability when clinically manipulated; it was closely monitored, and the condition clinically resolved without intervention. Various other minor adverse events are listed (Table 8).

Patient satisfaction survey results are summarized in Table 9. An overwhelming majority of patients rated implant treatment as good to excellent and did not significantly change these assessments between year 1 and year 5 for the variables of function (year 1 = 98%, year 5 = 97.7%), esthetics (year 1 = 98%, year 5 = 98.8%), and ability to clean the prosthesis (year 1 = 94.2%, year 5 = 94.1%). In the same manner, the small number of patients who rated each clinical outcome variable as fair to poor did not significantly change between year 1 and year 5 for the variables of function (year 1 = 2.0%, year 5 = 2.3%), esthetics (year 1 = 2.0%, year 5 = 1.2%), and ability to clean the prosthesis (year 1 = 5.8%, year 5 = 5.9%).

**DISCUSSION**

Recent attempts to ameliorate the reported roughness-induced hydrophobicity of sandblasted and acid-etched implant surfaces (SLA surface, Straumann Dental, Waltham, Mass) by increasing wettability (SLActive surface, Straumann Dental) have resulted in increased bone-to-implant contact in dogs compared with the original SLA surface with lower wettability. In contrast, the reported diminished wettability of the HA MP-1 surface did not appear to negatively affect its 97% success rate after 5 years in function compared with reported historical outcomes for its predecessor HA coating with lower crystallinity.

All 4 implant failures in the present study were standard-diameter (3.75-mm) implants used to replace first and/or second molars. Three of the 4 failed implants were 10-mm long. To improve the biomechanical performance of implant-supported restorations in the molar region, the use of wide-diameter implants (>3.75 mm) or 2 standard-diameter (3.75 mm) implants to support a single replacement molar has been advocated in the dental literature. In a meta-analysis of 13 studies documenting the failure rates by implant length, Goodacre et al reported that 2754 implants 10-mm long exhibited a cumulative failure rate of 10% in comparison to 3% for 3015 implants that were longer than 10 mm. Thus, the 4 failed molar restorations were already subject to questionable long-term predictability at the time of restoration.

There were no significant or irresolvable adverse events affecting the HA MP-1 and soft tissue interface in this study. This result affirms the findings of Meffert et al, who evaluated hard and soft tissue responses...
to HA-coated implants, machined-surface implants, and grit-blasted implants in 10 mongrel dogs. Of these, 61 implants were placed level with the crest of the ridge, and the remaining 40 implants were placed with 2 mm of the implant surfaces extending above the crest of the ridge.\textsuperscript{51} Five of the 101 implants placed failed shortly after placement (1 HA, 2 machined, 2 grit blasted); the remaining 96 implants achieved osseointegration.\textsuperscript{51} After healing and restoration, pocket depth measurements ranged from 2 to 8 mm for all implants, with no differences between surfaces.\textsuperscript{51} Histological analysis showed fibrous tissue encapsulation of both machined-surface implants and grit-blasted implants, while HA-coated implants achieved bone-to-implant contact as early as 1 month after placement.\textsuperscript{51} Bone contacted 70\% of the HA-coated implant surface by 4 months and 90\% of the surface by 10 months.\textsuperscript{51} The HA-coated implants demonstrated the most normal soft tissue anatomy in terms of lack of apical migration of the junctional epithelium and lack of inflammation.\textsuperscript{51}

**CONCLUSIONS**

The 97\% success rate of HA MP-1 implants exceeded the recommended standard of 85\% for implant success after 5 years of clinical function.

**ACKNOWLEDGMENTS**

This study was funded by Zimmer Dental Inc. The authors thank Michael Collins, vice president, research and development; Angela Estepa, manager, clinical affairs; and Michael M. Warner, senior medical writer, of Zimmer Dental Inc for their contributions and assistance with this study.

**REFERENCES**