

A new computer-assisted method for design and fabrication of occlusal splints

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In this report, we describe computer-based design and production of occlusal splints. A research effort was undertaken to develop a process to eliminate the inherent variabilities associated with current splint-fabrication methods. The digital process provides quantitative control over articulation and splint design, and produces splints with continuously smooth occlusal surfaces. Stone casts are laser scanned, and custom software is used to articulate and design flat-plane and full-coverage splints with guidance ramps. Splints are produced by milling excess acrylic placed over stone casts. Clinically, digital splints reduce the average time needed for placement because intraoral equilibration is minimized. (*Am J Orthod Dentofacial Orthop* 2008;133:S130-5)

Current laboratory methods for producing occlusal splints use various manually-based articulation and trimming methods. Each laboratory usually has a particular way to articulate unmounted casts; this causes interlaboratory differences. For example, when mounting to articulators to provide a hinge for adjusting the interocclusal distance, the casts can be visually oriented, or either the upper or the lower cast can be placed against the flat surface of a mounting jig. This forces the occlusal plane to be defined by the 3 highest points on the dentition; which can significantly tilt the orientation of the arches. Further inaccuracies arise from how the technician orients the cast on the mounting jig, since this determines the orientation of the hinge with respect to the cast as well as the axis incisal distance.

Intralaboratory variability results from the manual trimming process used to create the functional contact surface. Acrylic is typically cured between articulated casts, and a technician manually grinds down the acrylic surrounding the tooth impressions left by the contact arch. As a result, the final contact surface contains residual tooth impressions that are a result of the technician's subjective determination of smoothness. Clinically, these indexing impressions tend to lock patients in place and inhibit the free movement needed to effec-

tively deprogram muscles. Thus, the current art of splint making essentially guarantees that the same splint will never be made twice for the same patient, even by the same technician.

In comparison, digitally based manufacturing provides consistency, fine quantitative control, and speed over manual methods. When applied to medical and dental devices, flexible design software must be used to accommodate natural biologic variations. The objective of this applied research effort was to develop a digital system for designing and producing occlusal splints. The system is similar to other dental computer-aided design (CAD) and computer-aided manufacturing (CAM) systems, consisting of scanning, specialized CAD software, and digitally driven fabrication.¹

Rapid prototyping (RP) provides direct digital fabrication of plastic and metal parts. In orthodontics, plastic tooth setups are produced by RP for fabricating the sequential positioners for the Invisalign System (Align Technology, Santa Clara, Calif).² RP is also used to produce customized lingual brackets for subsequent investment.³ Surgical splints have also been produced using stereolithography as part of computer-assisted orthognathic surgery.^{4,5}

For occlusal splint CAD/CAM, specialized CAD software is used to articulate and design splints. This report describes the first computer-based design and production of flat-plane splints and splints with guidance ramps. The process is reviewed, and the main features are discussed.

MATERIAL AND METHODS

The overall approach to this development effort sought to minimize the amount of custom hardware and software. Commercially available scanning and

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Fig 1. Combination scan or 3D bite record, used to locate the maxillary arch after using the mandibular arch to locate a hinge axis (for unmounted cases).

machining equipment was used, run by customized versions of commercially available software. Custom software is used for articulation and splint design.

Stone casts, attached to standard mounting plates, are laser scanned using a Minolta VIVID 910 camera (Konica Minolta Sensing, Ramsey, NJ). Geomagic Studio software (Geomagic, Research Triangle Park, NC) is used to run the camera and work with the scan data. Six scans taken 60° apart are combined into a single object. The scanning system is calibrated to define the casts with respect to the mounting plate. For mounted cases, this allows the casts to be positioned in a computer exactly as they would be on a physical articulator.

For unmounted cases, a 3-dimensional (3D) digital bite record is created (called a combination scan) by taking a single laser scan of the maxillary and mandibular casts together with the provided centric-relation bite registration shown in Figure 1. This 3D relationship between the arches is used to locate the maxillary arch after using the mandibular arch to locate a hinge axis.

Mounted cases are articulated by modeling commercially used articulators in software. By using the mounting plate as a reference, casts are positioned in a computer exactly as they would be on the mechanical articulator. Condylar inclination angle, eminence curves, and the Bennett angle are individually controllable in the software. This allows the protrusive and lateral excursions required to design guidance ramps to be simulated.

For unmounted cases, the lower cast is used to locate a hinge axis. The standard articulation method first defines a mandibular occlusal plane and then orients the plane 15° to a horizontal. A hinge axis is located at a 100-mm axis-incisal distance and 50-mm verti-



Fig 2. Section of the articulation software used to locate a hinge axis. Either standard averages or patient-specific (custom) values are used to locate a centric axis for unmounted cases.

cal height. The mandibular occlusal plane angle, axis-incisal distance, and vertical height are independently controllable in the software. Figure 2 shows part of the articulation software used to input values. Although the software can accept patient-specific values, the only current patient-specific source of these data is cephalograms. It is planned to incorporate published data on specific population groups to provide more accurate articulation of unmounted cases. After establishing a centric axis, the maxillary arch is located by using the 3D relationship captured by the combination scan. Similar condylar control software is used as for mounted cases.

Splint design

The cast receiving the splint is designated the “splint” cast, and the opposing arch is called the “contact” cast. Splint design involves defining several parameters, including interocclusal distance, contact points, width of flat-plane shelves, anterior and canine ramps, and the perimeter or shape of the splint.

First, the opening is adjusted to the desired setting. A centric-relation bite record at the desired opening should be taken to avoid having to significantly change the opening. In general, one must be able to look through the occlusion to ensure a sufficient thickness of plastic and the absence of lateral interferences.

Contact points are defined in the software by clicking on the surface of the contact cast. Because the designer cannot precisely locate the point, software is used to optimize, or relocate, points to ideal positions. This ensures design consistency and allows the designer to concentrate on which cusps should be in contact. For cases with relatively normal curves of Spee, point optimization is based on the occlusal plane of the contact cast. This method automatically relocates the chosen position to the point on the tooth closest to the occlusal

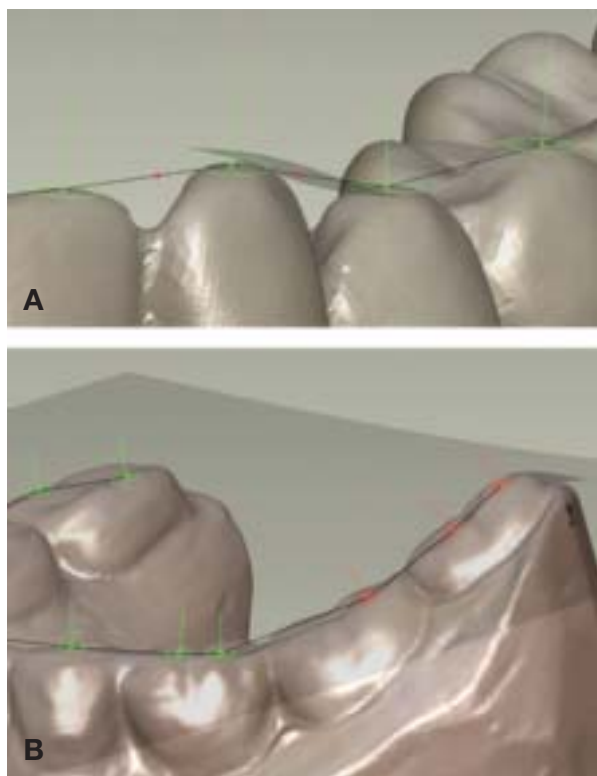


Fig 3. Mandibular arch with contact points, surface normals, and the perpendicular circular islands. **A**, Best-fit contact plane passing through the islands curves down from the canine to the premolar island. *Red guidance markers* indicate the extent of the canine ramp. **B**, Arc-optimized points in *red* and plane-optimized points in *green* in a patient with a large curve of Spee. Contact plane passes smoothly through all the contact islands.

plane. If the tooth extends above the plane, then the point on the tooth farthest from the plane is used.

After a contact point is defined, a surface normal is computed, and a perpendicular circular “island” of controlled diameter is constructed. Figure 3, *A*, shows contact points, surface normals, and perpendicular circular islands. A best-fit plane is passed through all the islands to form a contact plane. This plane is the flattest possible surface through all the contact points. A horseshoe-shaped portion of this plane, which includes the contact points and lies over the teeth of the opposing arch, becomes the functional surface of the splint.

Contact points can also be optimized based on the arc of closure. This method is best-suited for posterior teeth in patients with large curves of Spee. Then, optimization involves repositioning the initial point to the location on the tooth that is first cut by a plane rotated about the centric axis. The red contact points in Figure 3, *B*, are arc-optimized, whereas the green contacts are optimized by using the occlusal plane. The designing

technician can also turn off the optimization and define a contact anywhere desired.

Splints with guidance ramps (anterior and canine) are designed to provide posterior disclusion when the patient protrudes or moves the jaw laterally. The lateral extent of the ramps is defined by placing 4 markers (*red squares* in Fig 3*A*) on the line drawn between contact points. The anterior ramp lies between the 2 mesial markers and the canine ramps between the 2 sets of distal markers. The length and angle of each ramp is also controlled by the software. As a standard, the ramp angle required to provide zero disclusion is first computed. Ramps are then angled 5° past this theoretical angle to provide a gentle rate of disclusion.

The width of horizontal shelves associated with ramps can be directly specified in millimeters. For example, a maxillary Dawson design specifies a 1-mm shelf lingual to the ramp. When designing flat-plane splints, the width of the surface anterior and posterior to the contacts is specified. This is important for cases with large horizontal overlaps to ensure a shelf of sufficient length for protrusion. As a final step, the perimeter or the shape of the splint is defined by clicking a series of points on the splint cast.

Figure 4 shows a designed maxillary flat plane splint. The contact points from the mandibular arch are shown by visualizing the islands from the contact cast. Figure 4, *B*, shows the anterior and canine guidance ramps, and Figure 4, *C*, is a close-up lingual view.

Splint fabrication

Splints are produced by machining down acrylic placed over the splint cast. The designed splint is saved as a 3D surface file that is directly imported into PowerMILL CAM software (Delcam PLC, Birmingham, United Kingdom). The splint cast is covered with acrylic and mounted in a high-speed Haas (Haas Automation, Inc, Oxnard, Calif) vertical machine center. Carbide ball end mills of varying diameter are used. The largest possible diameter tools are always used to ensure the smoothest surface.

The underlying tooth anatomy of the splint does not have to be machined, because this surface is accurately captured by the acrylic. This significantly reduces the size of the files and greatly simplifies the machining operation. The general similarity of splint shapes allows similar cutting strategies to be used for most cases.

Regions of the contact surface that have contact points must be machined completely down to the designed surface. For these areas, smaller tools are used to exactly follow the contour of the surface. Figure 5 is an image of the PowerMILL CAM software showing contact point regions selected for finer machining

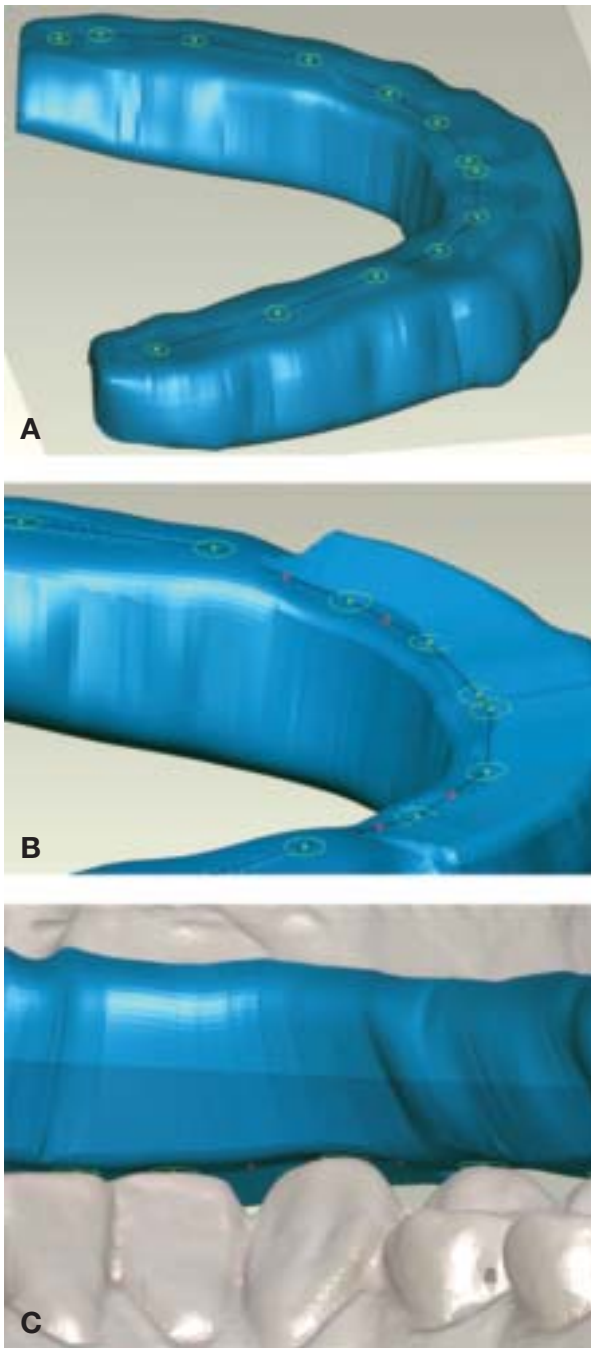


Fig 4. Flat-plane maxillary arch splint. **A**, Contact points from mandibular arch; **B**, with anterior and canine guidance ramps. The splint has a 2-mm shelf extending lingually from the anterior contact points. The canine and anterior ramps blend smoothly into each other. **C**, Lingual view shows contact points and canine and anterior ramps.

(patches outlined in white). The raster-type tool paths used inside each patch are visible. The surface of the splint is rendered as a set of 4-sided patches, with each

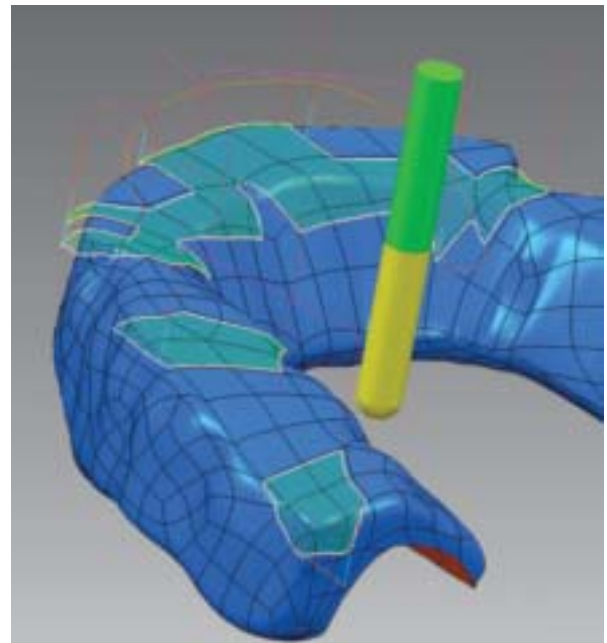


Fig 5. Screen shot of CAM software. Three sets of non-uniform rational B-spline patches on the contact surface have been selected for finer machining. The complete machining tool paths for a 1/8-in diameter tool are shown.

patch defined as a set of intersecting nonuniform rational B-splines. This provides a continuously curved surface for machining, rather than a faceted polygon surface.

The mountings must be sufficiently strong to withstand the machining forces. Mounting stone must be used instead of plaster, which is relatively weak. The milling process can accommodate standard wire clasping inside appliances by adjusting tool paths with the CAM software. The contact surface is reproducibly machined to an accuracy of less than 10 μm and does not require further finishing.

DISCUSSION

An important feature of digital splints is the smoothness of the contact surface. Conventionally produced splints have residual indexing impressions left by the contact cast. Digitally produced splints are free of divots and provide free movement of the teeth over the splint surface. Figure 6 shows equal magnification (20 times) scanning electron micrographs of a manually produced laboratory splint and a digitally produced splint. As a result of the smooth surface, clinical contacts are visualized as fine markings or points, not as the larger marks produced when the articulating paper is drawn into tooth impressions by the opposing arch. This simplifies the equilibration process, because any required adjustments are made at the precise contact points, minimizing the removal of unnecessary material.

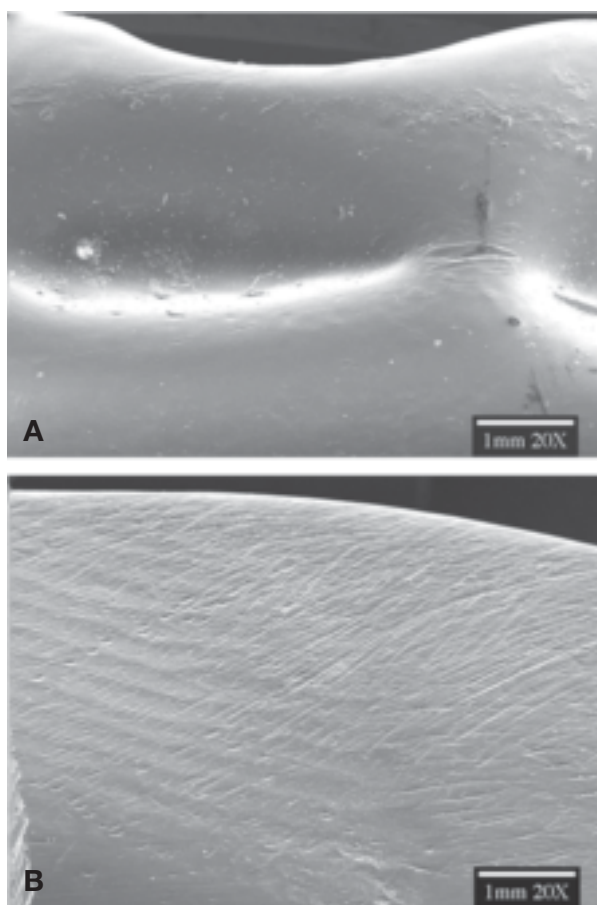


Fig 6. Equal magnification scanning electron micrographs of splint surfaces. **A**, Manually produced splint shows 2 typical tooth impressions; **B**, digital splint shows a smooth surface that also has 2 contact points.

All materials commonly used to make splints are readily machined, including cold-cure acrylic, hard thermoformable materials, hard/soft materials, heat-softening acrylics, and light-cure materials. Digital splints can also be produced using ethylene vinyl acetate over a wide a range of durometers generally reserved for mouth-guard applications.

When selecting contacts, the design technician can select points that give the flattest overall surface, especially for points on molars. As contact points are added or eliminated, the designer can see the effect on the shape of the contact plane. This allows the flattest surface to be obtained, consistent with the required contact points.

Another feature of the process is the ability, for unmounted cases, to input patient-specific articulation parameters for custom designs. These data can be obtained from either direct clinical measurement or published statistical variations based on race, age, or sex.

The character of the occlusal plane influences the location of contacts on the splint. A flat curve of Spee

allows the occlusal plane to be used to optimize contact points. It became apparent during beta testing that, as the curve of Spee increased, the occlusal plane no longer provided a legitimate means for optimizing contact points. This led to the ability to optimize points based on the arc of closure.

Another parameter that can be significant is the ramp angle. Software uses a standard 20° condylar inclination angle and average eminence curves found in fully adjustable articulators. For patients who have had a significant change in condylar angle or joint remodeling (eg, delta bruxers), the clinician should give more design information to the laboratory for construction of a proper ramp to minimize the disclusion angle.

Another clinically important consideration is the fit of the appliance over the teeth. The splint must readily seat over the teeth before beginning equilibration procedures. The design of the splint should consider the dental anatomy to ensure good seating. For example, flared anterior teeth dictate that the splint should seat passively over them and rely on the posterior teeth for retention. These factors became apparent during the beta evaluation. Two designs were evaluated during the beta testing. The first design incorporated complete overlap of the buccal and facial surfaces and palatal coverage. The second design incorporated the occlusal third of the buccal and palatal surfaces of the teeth with 2 to 4 ball clasps for retention; this ultimately was the best for ease of placement. Some warpage was observed with the first design, probably from manually grinding acrylic to achieve a more passive fit. The anterior teeth were not in contact with the splint where the overlap was adjusted to allow the splint to seat. When the splints were adjusted for ease of placement, ball-clasp retention proved to be better than friction fit.

The arc of closure influences the location of initial contacts in an anteroposterior direction. If the splint is designed with an axis-incisal distance that is too short, the initial contacts occur anteriorly on the splint. When the distance is too long, initial contacts occur posteriorly. However, most cases sent to the laboratory today are not mounted, have no facebow recording, and have an interocclusal record of varying thickness and type. This created a manufacturing challenge that is accommodated in the software by articulating to a standard axis-incisal distance of 100 mm. Although a true hinge axis recording with an accurate centric-relation record produces the most accurate representation of the arc of closure, this is not a common practice in dental offices. Most cases mounted in the dental office use an arbitrary facebow recording with a centric record. Cases mounted with an arbitrary facebow recording can produce a fairly accurate representation of the arc of closure as long as the interocclusal record is no greater than 3 mm in thickness.^{6,7}

During the beta evaluation, 2 methods were used for recording the interocclusal distance: bimanual manipulation and the Power-Bite method⁸ with a Lucia jig and silicone impression material. An advantage of the Lucia jig that one can readily control the posterior interocclusal distance and create a stable bite position for injecting silicone bite material. This has the additional advantage of not having to significantly change the bite opening when designing the splint, and it is particularly important for unmounted cases, since rotation occurs on an arbitrary hinge and can introduce error. When taking wax bites, it is more difficult to control the posterior interocclusal space.

During the beta testing, a form was enclosed with 150 cases requesting feedback on the required occlusal adjustments. Of the 78 responses, 23 indicated only minor or slight adjustments. Nine required no adjustment, and 5 questioned the quality their own records. Most of the remaining comments were “goods and “averages.” Ongoing feedback received through the Customer Service Department is consistent with these findings.

Current work includes developing methods to clinically obtain an arc of closure (for unmounted cases) to improve accuracy without mounting the case with a facebow. Toward this end, the axis-incisal distance is being measured on patients and used in place of the 100-mm standard value. Stereolithography has also been used to produce experimental splints. The main limitation of this method is the poor water compatibility of current clear RP materials. Although digitally produced splints afford distinct advantages over conventional splints, accurate bite registration recordings from the clinician remain paramount for a clinically successful prosthesis.

CONCLUSIONS

A new digital process for producing occlusal splints has been developed. The process mirrors conventional CAD/CAM systems, consisting of scanning, CAD design, and machining. The method provides precise and consistent digital control over articulation, appliance design, and production. More than 3000 cases were produced during the beta testing. Digital splints have been commercially available from Great Lakes Orthodontics since the spring of 2007. It is planned to extend the basic technology into other areas of appliance fabrication and surgical planning.

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