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Additive CAD/CAM Process for Dental Prostheses

Nelson R.F.A. Silva, DDS, MSc, PhD,[1,2] Lukasz Witek, MS,[2] Paulo G. Coelho, DDS, PhD,[2] Van P. Thompson, DDS, PhD,[2] Elizabeth D. Rekow, DDS, PhD,[2] & Jim Smay, PhD[3]

[1] Department of Prosthodontics, New York University College of Dentistry, New York, NY
[2] Department of Biomaterials and Biomimetics, New York University College of Dentistry, New York, NY
[3] Department of Engineering, Oklahoma State University, Stillwater, OK

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Correspondence
Nelson R.F.A. Silva, Department of Prosthodontics, New York University College of Dentistry, 345 E 24th Street Room 804-S, New York, NY 10010. E-mail: nrd1@nyu.edu

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Abstract

This article describes the evolution of a computer-aided design/computer-aided manufacturing (CAD/CAM) process where ceramic paste is deposited in a layer-by-layer sequence using a computer numerical control machine to build up core and fixed partial denture (FPD) structures (robocasting). Al_2O_3 (alumina) or ZrO_2 (Y-TZP) are blended into a 0.8% aqueous solution of ammonium polyacrylate in a ratio of approximately 1:1 solid:liquid. A viscosifying agent, hydroxypropyl methylcellulose, is added to a concentration of 1% in the liquid phase, and then a counter polyelectrolyte is added to gel the slurry. There are two methods for robocasting crown structures (cores or FPD framework). One is for the core to be printed using zirconia ink without support materials, in which the stereolithography (STL) file is inverted (occlusal surface resting on a flat substrate) and built. The second method uses a fugitive material composed of carbon black codeposited with the ceramic material. During the sintering process, the carbon black is removed. There are two key challenges to successful printing of ceramic crowns by the robocasting technique. First is the development of suitable materials for printing, and second is the design of printing patterns for assembly of the complex geometry required for a dental restoration. Robocasting has room for improvement. Current development involves enhancing the automation of nozzle alignment for accurate support material deposition and better fidelity of the occlusal surface. An accompanying effort involves calculation of optimal support structures to yield the best geometric results and minimal material usage.

State-of-the-art production of all-ceramic dental prostheses has evolved to include computer-aided design/computer-aided manufacturing (CAD/CAM) of dense core materials followed by post-sintering processing to apply esthetic veneers.[1] The manufacture of the cores typically involves one of the following routes: (1) traditional ceramic forming such as casting or pressing followed by high-temperature sintering (e.g., Procera, Nobel Biocare, Yorba Linda, CA), (2) computer numerical control (CNC) milling of a bisque-fired blank into the desired shape followed by sintering (e.g., LAVA 3M ESPE, St. Paul, MN; Procera), or (3) CNC milling of a dense ceramic (e.g., Empress and e.max CAD, Ivoclar, Schann, Liechtenstein). This article describes the evolution of a CAD/CAM process where ceramic paste is deposited in a layer-by-layer sequence using a CNC machine to build up core and fixed partial denture (FPD) structures. The output of the process is a green ceramic that is then fully sintered. The process has been dubbed solid freeform fabrication in general, or robocasting when dealing with ceramic materials. Robocasting offers a diverse pallet of materials that may be printed, from bioactive ceramics such as hydroxyapatite and β-tricalcium phosphate to dental ceramics such as aluminum oxide (Al_2O_3) and zirconium dioxide (ZrO_2).

CAD/CAM

CAD/CAM production of fixed prosthetic restorations such as inlays, onlays, veneers, crowns, and FPDs is a relatively mature technology used by dental health professionals for over 20 years.[2] CAD/CAM systems have also been used for alternative restorations using different materials such as porcelain, composite resin, and metallic blocks, which could not be fabricated previously because of technical limitations.[3] Current CAD/CAM for ceramic prostheses can use fully or presintered blocks to obtain either a framework to support the veneer porcelain or anatomically correct definitive restoration. Machining of fully sintered ceramic blocks poses the challenge of avoiding surface microcracking, which may lower the long-term durability of the restorations.[4] Surface microcracking is particularly troublesome in alumina. For zirconia, machining of dense ceramic has been shown to induce tetragonal-to-monoclinic (t-m) transformation.[5] It remains unclear if the t-m transformation is detrimental to the service lifetime of zirconia (e.g., Y-TZP) restorations. Nevertheless, zirconia as a material is attractive because of good mechanical strength and toughness as well as esthetics. Consequently, clinicians have come to expect superior performance when zirconia is used as framework for dental prostheses.[6] To avoid unexpected failure from surface microcracking or t-m transformations, a presintering forming process for the ceramic has been recommended.[7]

Instead of machining the final sintered ceramic parts, Halcomb and Rey[8] and Klocke et al[9] performed green and white machining. In green machining, a powder compact is prepared by pressing ceramic powder along with a small amount of polymeric binder into a machinable stock, whereas in white machining, the stock is a partially sintered (presintered) ceramic. For either case, the ceramic must be sintered to full density after machining. For dental prosthetic components, the presintered process (white machining) starts from a die or wax pattern scanned by optical or contact scanners. The CAD/CAM system must then design an enlarged restoration to compensate for the predicted volumetric shrinkage that occurs in the sintering operation. The presintered block is milled and then fully sintered, obtaining the final framework for further veneering porcelain application. Besides the improvement in reducing microcrack formation or t-m transformation for zirconia restorations, another advantage of the presintering method is the possibility of using metal salts to color either the presintered blocks or milled frameworks.[10] This processing can create desirable esthetic effects for the definitive restoration.

Solid freeform fabrication concept: Robocasting

Robocasting is a rapid prototyping (RP) that assembles geometries in a layer-by-layer process.[11] Also known as freeform fabrication, the technique uses computer-controlled extrusion of colloidal pastes (also called slurries, gels, or inks) onto a flat substrate without the need for additional molds or tooling.[12] Rather than removing unwanted material from a stock by machining, material is strategically printed to evolve the three-dimensional (3D) structure. The instructions for how to print the layers are derived from a 3D computer model of the structure (e.g., assembled using computed tomography (CT) scans, point clouds from optical scanning, or stereolithography (STL) files). Once the 3D model is created, the software slices the model into a number of stacked layers and then designs a sequence of print operations to build the layers one atop the other. This strategy has been used to assemble a variety of structures with applications ranging from electronics to bone scaffolds[13] (Fig 1).

Recently, robocasting has been used in the orthopedic setting, primarily for bone and tissue engineering,[14] where the intricate 3D networks of porosity that can be constructed are being exploited for enhanced bone regeneration. Production of dental restorations by robocasting has recently evolved, but is not yet at the point to compete with commercial CAD/CAM systems. Nevertheless, we want to highlight its current status. The potential advantages over CAD/CAM systems include the capability to spatially grade composition and/or microstructure (e.g., porosity) to meet specific designs or needs, without requiring a previous mold.[14] Also, this fabrication technology permits internal morphology, shape, distribution, and connectivity to be controlled more precisely. Another benefit from this system is the ability to "print" with multiple materials at one time as well as create graded structures.[15]

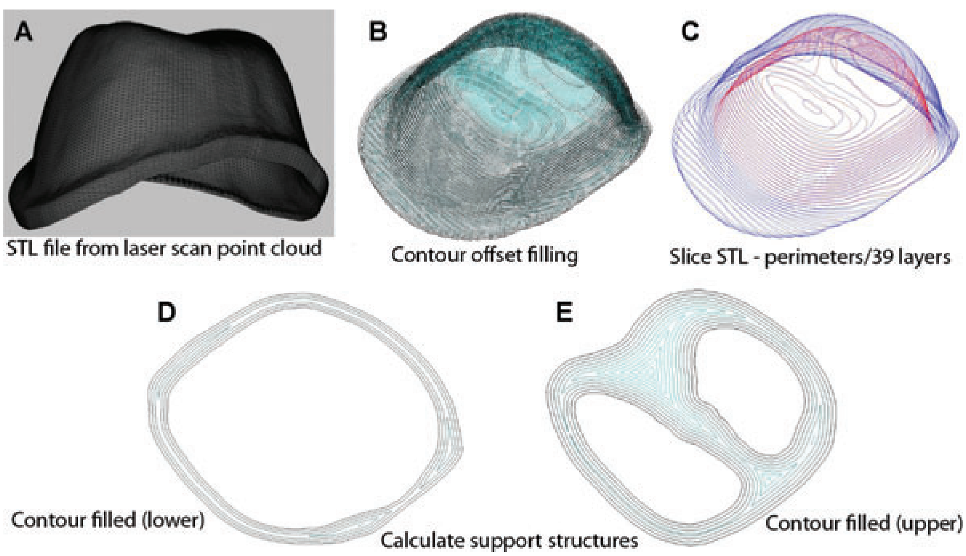

Figure 1 (1A) Shows an STL file with 60,352 triangular facets representing the core. The STL file is sliced to generate two-dimensional (2D) perimeters (1B). A tool tooth path is generated by a parallel contour offsetting of the perimeters (1C). The carbonate support structure (when used) must be properly calculated (1D and 1E) before printing process.

Current stage of robocasting for dental prostheses

Two key challenges to successful printing of ceramic crowns by the robocasting technique are the development of suitable materials for printing, and the design of printing patterns for assembly of the complex geometry required for a dental restoration. The ink for robocasting is an aqueous paste of ceramic particles (ca., 0.5 μm in diameter) housed in a standard 3 to 10 ml syringe. The paste is extruded as a continuous filament at a controlled rate through a nozzle (typically a 0.25″ long cannula with 25 to 32 needle gauge) attached to the syringe. The requirements of the ink are that it must flow through the nozzle with modest pressure, retain the desired shape after deposition, dry with minimal shape change after printing, and sinter to high density. A typical ink formulation process follows.

Disperse a commercial ceramic powder in water using a polyelectrolyte processing aid. Here, Al_2O_3 (alumina) or ZrO_2 (Y-TZP) (Refractron Technologies Corp., Newark, NY) are then blended into a 0.8% aqueous solution of ammonium polyacrylate (Darvan 821A, R.T. Vanderbilt Co., Norwalk, CT) in a ratio of approximately 1:1 solid:liquid. In this state, the slurry is highly fluid. Next, a viscosifying agent, hydroxypropyl methylcellulose (Methocel F4M, Dow Chemical Co., Midland, MI) is added to a concentration of 1% in the liquid phase. The final step is to add a counter polyelectrolyte to gel the slurry. In this case, polyethylenimine (100K MW, Aldrich Chemical Co., Milwaukee, WI) is added to a concentration of about 0.1% in solution. The final product is an aqueous paste of about 47% solid by volume and approximately 1 to 2% organic material. The paste may be extruded to form fine filaments and dries with minimal shrinkage. The shape evolution/retention by the extruded filaments has been well documented in the literature.

After the ink is made, a digital representation of the core is needed. This can be obtained by laser scanning an impression or a cast with a crown preparation and converting it to a file that describes only the surface geometry of the 3D object (Fig 1A). The image presented in Figure 1A contains 60,352 triangular facets representing the surface. Next, the STL file is sliced to generate two-dimensional (2D) perimeters (Fig 1B). A tool tooth path is then generated by a parallel contour offsetting of the perimeters (Fig 1C). Unlike commercial codes, this step allows for the composition to be varied as a function of distance away from the exterior surface. It is also important to point out the need for a fugitive support material for the eventual building of the upper layers, which would otherwise be printing material into thin air. These support structures must be properly calculated (Fig 1D and 1E). Also, the tool path is optimized based on composition and closest contour to current position rather than inside-out or outside-in filling. All this information is properly input into the program for the printing process.

Figure 2 shows two methods of robocasting crown structures (cores). One is for the core to be printed using zirconia ink without support materials, in which the STL file is inverted (occlusal surface resting on a flat substrate) and built (Fig 2A). For this particular case, the STL file was scaled up by approximately 30% to account for sintering shrinkage. The lack of a support structure in this case resulted in a flattened occlusal surface after sintering (the STL file was supplied by Noble Biocare). The sintered core can be compared to a commercial one (Fig 2B). For the core produced by robocasting, the internal structure (i.e., intaglio surface) accurately conformed to the STL file, but the external surface lacked the fidelity of the commercial core. This may be acceptable, provided veneering layers are to be built up on the core.

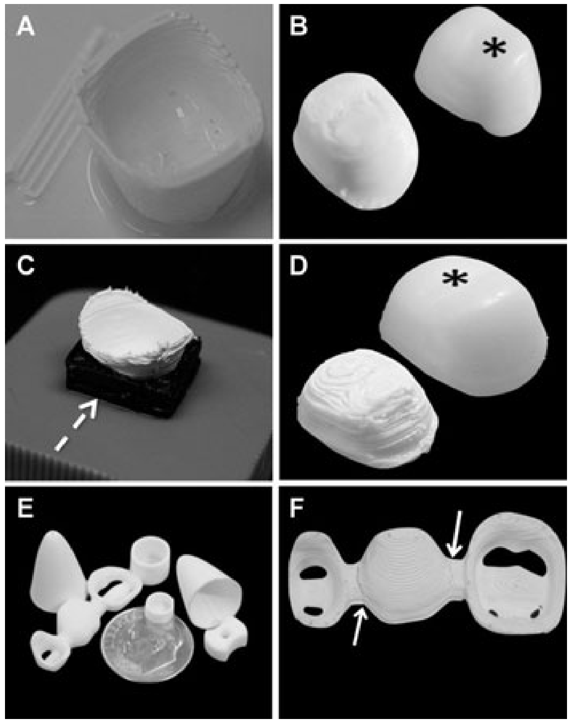

Figure 2 A series of images of methods for robocasting a zirconia core. On the first one, the core is printed using zirconia ink without support material, in which the STL file is inverted and built (A). Upon sintering (B) the top of the crown is flattened. The sintered core (B) can be compared to a commercial core (black asterisk). Note: STL file was scaled up approximately 30% to account for sintering shrinkage. (C) The use of carbon black (segmented white arrow) support material to further build a support for the crown. After sintering, the carbon black is gone, with a better shape retention on the occlusal surface (D). The STL file in this case was not scaled up to compensate shrinkage. Note (D) with commercial core as an example (black asterisk). (E) Shows various specimens with different shapes produced using robocasting. A tentative printing of a three-unit FPD zirconia framework support is shown in (F). Note crack lines (white solid arrows) as a result of sintering process.

In an attempt to produce an improved occlusal surface, a support structure was calculated, and a fugitive material composed of carbon black particles, as an aqueous paste was codeposited to assemble the geometry. The printed crown (again inverted) along with the fugitive support structure prior to sintering is shown in Figure 2C. During the sintering process, the carbon black is removed, and better shape retention on the occlusal surface of the core is obtained (Fig 2D). Here, the STL model was not enlarged to compensate for sintering shrinkage as is evident by comparison to the commercial core. The use of a support material presents a challenge in alignment of printing tips and flow behavior of both the ceramic paste and fugitive support material. In this particular case (Fig 2A and 2D), the printing tips were not perfectly aligned, causing a mixing between carbon black and zirconia ink, leading to a rough surface finish upon sintering (Fig 2D); however, with adequate automation of the tip alignment process, this roughness can be minimized. The potential utility for using robocasting in dentistry can be seen by observing the variety of shapes that can be easily created and the scale of the structures (Fig 1E). The production time for a printed structure is about 10 to 30 minutes (depending on the size of the part), and the sintering process/time is similar to other CAD/CAM systems.

To achieve its full potential as a dental restoration production process, robocasting must improve the use of support materials to produce better tolerance occlusal surfaces. In addition, the digital nature of the layer printing process leads to a "stair stepped" surface (Fig 2F) that may need to be improved for commercial acceptance. The step size is a function of the nozzle diameter used for printing. The issue of support materials/structures seems to be a tractable problem; however, the stair stepping may require some postprocessing (e.g., a dip coating process) prior to final sintering. Occasionally, drying issues, such as cracks, can occur (Fig 2F).

As with any evolution of a process for the challenging job of dental restoration production, robocasting has room for improvement. Current development involves improving the automation of nozzle alignment for accurate support material deposition and better fidelity of the occlusal surface. An accompanying effort involves calculation of optimal support structures to yield the best geometric results and minimal material usage. Strategies to create margins with tolerances $<25\ \mu$m are also being investigated, as are techniques to smooth the stair stepping.

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