

# Applications

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## Something to Smile About: 3D Graphics are Revolutionizing Oral Health Care

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Most people would agree that eating is more than a necessity—it's also a major social function. In light of this, it's remarkable that we often overlook oral hygiene, a critical area of personal health. Having strong, well-aligned teeth and proper bone structure of the face and jaw are essential ingredients for maintaining proper physical health. Not only do they provide the framework for chewing and consuming a varied diet, but they also impart confidence in the social aspects that come with enjoying a meal or beverage with others.

Most of us would also agree that a trip to the dentist, oral surgeon, or orthodontist isn't our favorite way to spend time. Often, the procedures are expensive and painful with less than optimal results. On top of that, treatments are often time intensive and, in the case of orthodontics, unattractive until the treatment ends. Oral health care professionals struggle with trial-and-error methods that can cause patient anxiety and prolong already time-consuming treatments. Fortunately, computer graphics and all the computer-aided drawing and manufacturing (CAD/CAM), scanning, and imaging technology is changing dentistry. Simplicity, efficiency, and quality are factors any consumer and practitioner can appreciate.

1 The Invisalign aligner is made of clear, medical-grade plastic.



### Metal mouth

Enter any middle or junior high school and you'll find kids with braces on their teeth. They sport the metal or clear plastic brackets with wires and colorful bands to decorate their mouths with a flourish. They don't seem to mind that their pearly whites aren't the most attractive component of their smiles. It's considered normal among that age group. Besides, the payoff in just a couple of years is a smile that they can be proud of.

On the other hand, it isn't common to find adults wearing orthodontic appliances to correct misaligned teeth. The main reason is that adults don't want to have the "metal mouth" look of adolescence. They think it compromises professionalism or looks out of place. Time is also a factor. Patients must schedule regular office visits, which can involve time off from work or otherwise be inconvenient.

### Grown-up orthodontics

Recently, a company called Align Technology (<http://www.aligntech.com/home.html>) received approval from the US Food and Drug Administration for Invisalign, a technology that straightens adult teeth using a series of clear, plastic, nearly invisible *aligners*, without all the metal and wire. Figure 1 shows what a modeled aligner looks like. Through proprietary CAD/CAM software that does 3D modeling, the company creates the fixtures for orthodontists who are certified to use the system—nearly half the orthodontists in the US.

Jon Fjeld, vice president of engineering at Align, pointed out that Invisalign isn't a new idea. The system first appeared in orthodontic literature in the 1940s. However, Invisalign wasn't realistic before 3D software. Align Technology exploits state-of-the-art computer technology to make this approach to orthodontic therapy practical for the first time. According to Fjeld, "It's only possible because we have the ability to model in software, treat in software, and then manufacture the appliances."

### How it's done

After Align receives impressions of the patient's teeth from the orthodontist, the company's technicians pour and trim a plaster mold, which they then scan using a technique called destructive scanning. Destructive scanning requires a machine to cut the plaster cast into layers

for scanning, ultimately destroying the cast. The technique generates a series of digital photographs and results in a volumetric model of each arch based on a standard set of algorithms. The resolution of the polygonal files is about 100,000 triangles. Align then uses its proprietary software to generate a 3D movie that shows the series of the necessary movements of the patient's teeth from the current to the desired position. The procedure's accuracy is within 50 microns. To do all this, Align uses Windows NT 4.0 workstations with Pentium III processors at 700 MHz with 512 Mbytes of RAM, a 9-Gbyte hard drive, and an ASUS AGP-V7700 graphics card.

After the orthodontist approves the series, Align Technology produces the aligners. Using 3D Systems' (<http://www.3dsystems.com/>) stereo lithography equipment, the technicians create an exact representation of the physical model of each stage of aligners. They create the molds and then form the aligners over the molds. The aligners are made of clear, strong, medical-grade plastic. Patients wear each aligner stage for approximately two weeks before switching to the next stage. The result is a slow tooth movement until patients wear the final set of aligners. Figure 2 shows a series of computer models of the teeth before and after straightening with Invisalign.

### The treatment

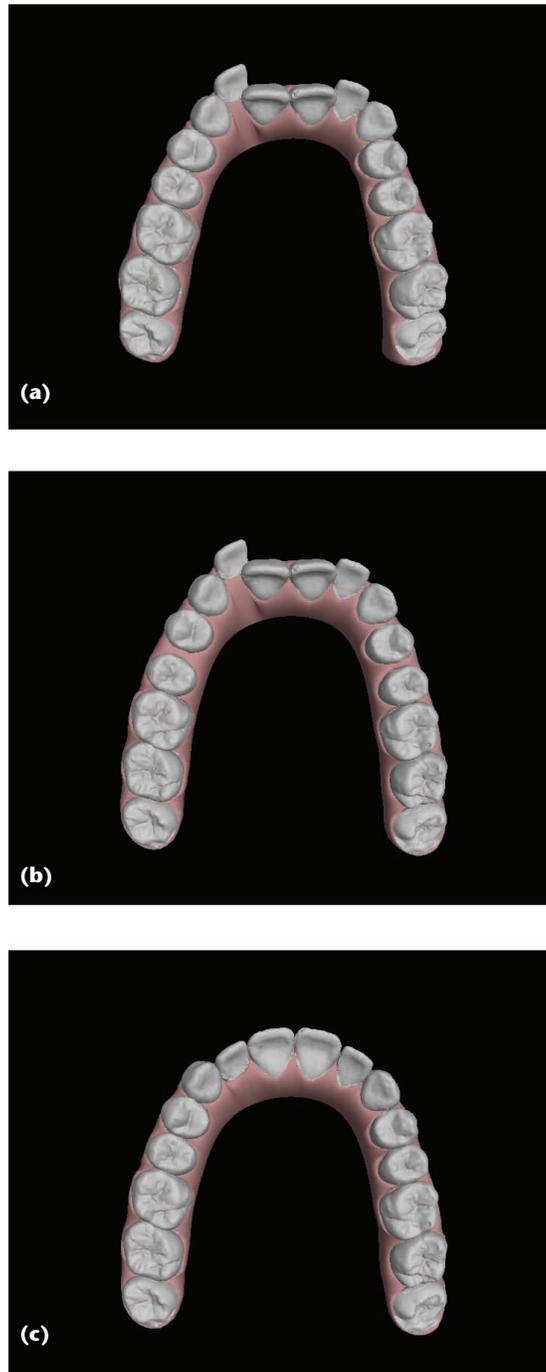
The total treatment time resembles traditional braces, ranging from 6 to 24 months, depending on a case's complexity. The time saved for the patient and practitioner is "chairside." Because no adjustments are required, patients don't need the frequent office visits required by traditional braces. However, the greatest advantages for patients are that these "braces" are nearly invisible, removable, and more comfortable than metal.

The cost of Invisalign depends on the complexity of a patient's case. The technology hasn't brought the price of adult orthodontics down; it's generally more expensive than traditional braces. Severe cases can't be treated, but generally, 50 percent of adults can use Invisalign to straighten their teeth. The biggest drawback is that children can't use the aligners because it's difficult to model the changes in the jawbone of kids. As a result, Invisalign is targeted to adults who want straight teeth.

Barton Tayer, an orthodontist in the Boston area, supports that view. Tayer has a large adult practice, and he asserts that patients really like having the option of using invisible braces, but he can't treat kids with it. The biggest attraction for him is that Align Technologies has effective marketing, "They do a very good job promoting [Invisalign]. That has encouraged people to ask about it." However, it's more costly—often thousands of dollars more than the standard \$4,500 to \$6,000—and it's designed for modest misalignments. It's not for everyone, but it is an option for adults with moderate crowding and spacing who wouldn't wear traditional braces.

### Looking ahead

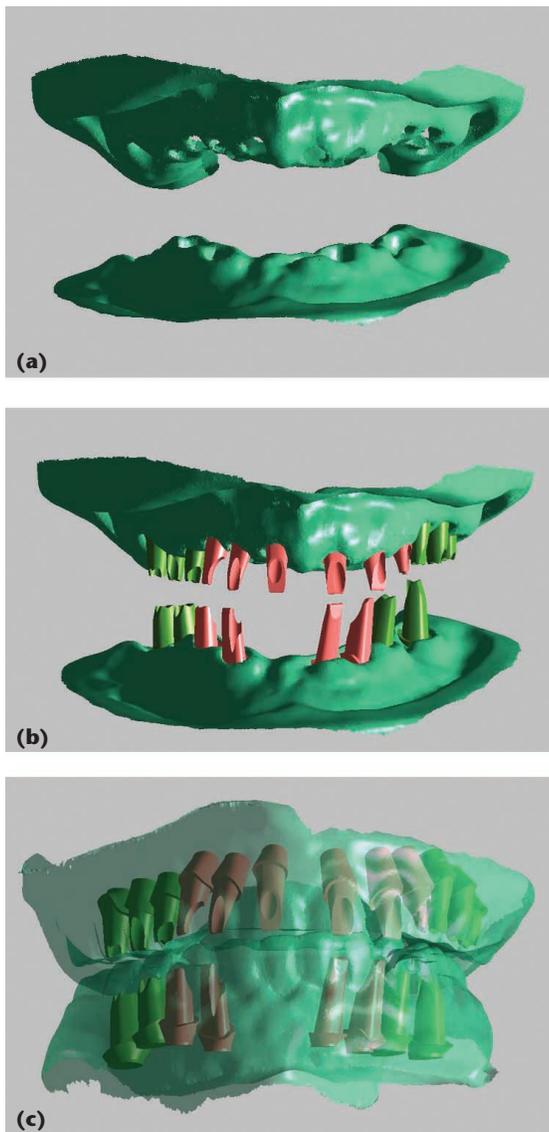
The people at Align have set their eyes on the future. "We're building the foundation for a whole set of breakthroughs in orthodontics and dental health care. We



**2** Computer-generated models of a patient's teeth before, during, and after treatment with Invisalign. (a) The original model of the teeth, (b) the projected model of the teeth halfway through the treatment, and (c) the projected model of the teeth after treatment.

didn't just improve what was already out there. We created something completely new for orthodontics," Fjeld stated. Among the projects underway, Align is using 3D software technology from Raindrop Geomagic (<http://www.geomagic.com/>) to improve the process of creating the aligners. They'll implement white-light-scanning technology so that they won't have to destroy the molds when acquiring the necessary data for the digital photographs with the destructive scanning method. Align expects the white-light-scanning technology to save time and money, reducing the cost to produce the aligners. By saving the molds, Align is creating a repository of dental impressions that researchers can

**3** A series of 3D computer images representing various phases of the modeling for one patient. (a) A surface representation of the dental study casts in a case where the patient had no teeth. (b) Modified Atlantis abutment models showing what was designed to complete the restoration for this patient. (c) A representation of the restoration plan partially translucent overlaid on the patient's study casts. This gives a good picture of what the final restoration will look like—complete with crowns.



use for future studies of orthodontics. Fjeld predicts that the white-light-scanning technology will be in place by summer 2001.

People at Align are also working on a way to treat kids with Invisalign. Treating adults creates the least number of variables to work with because adults aren't growing anymore. Now that they have been successful with that phase, they're working with the changing structures of a child's mouth to create a system suitable for treating kids with Invisalign.

### Dental implants

Dental implants have been around for decades, offering an alternative to dentures and bridges and providing replacement teeth that look more natural. Implants may be used to replace a single missing tooth or a complete functional set for individuals who have lost many or all of their teeth. Despite the advances in prosthetic teeth, the procedure for implantation is still wrought with difficulties. The process is complicated and can leave a patient feeling frustrated with less-than-ideal results.

### The basics of implants

A traditional dental implant has three main parts:

- the implant, which prosthodontists surgically place and anchor to the jawbone;
- the crown, which replaces the lost tooth; and
- the abutment, which screws into the implant and holds the crown in place.

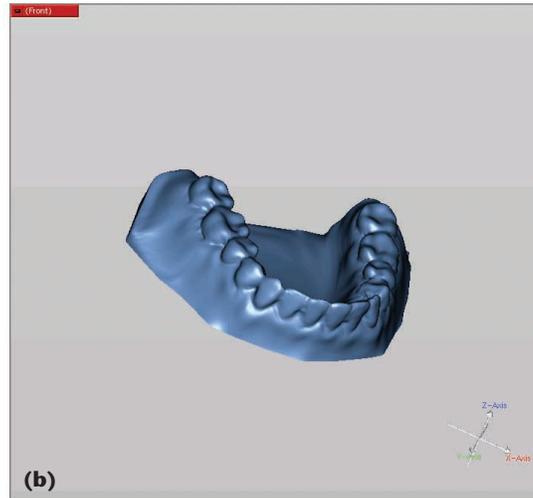
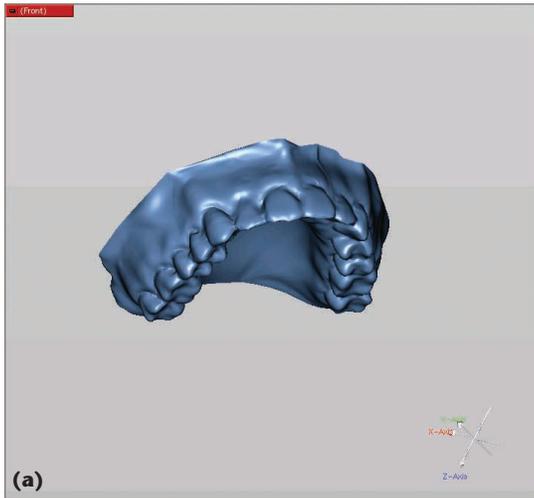
The abutment corrects for offsets and angles that deteriorated bone causes. Often, fitting the abutment can be the most difficult aspect of dental implants. Besides deteriorated bone, standard parts contribute to ill-fitting abutments because they're difficult to perfect for each individual case. Additionally, a technician makes the adjustments by hand—a somewhat imprecise method. As a result, an abundance of radiographs and anesthetic may be required while verifying the abutment placement. This may also necessitate several office visits for the patient, which translates into higher costs and inconvenience, not to mention discomfort.

The existing technology for dental implants wasn't designed with the restorative dentist or prosthodontist in mind. According to Julian Osorio, a practicing prosthodontist and founder of Atlantis Components, a custom dental products company (<http://www.atlantis-comp.com>), "The emphasis was on the surgical phase of the implant procedure, and the needs of the restorative dentist were an afterthought and were essentially ignored. The results exhibited this fact in the unacceptable aesthetics of the final crown." As a result, Osorio decided to create a more efficient way to implant teeth using computer graphics.

### Easy precision

Atlantis' technique uses software that Raindrop Geomagic customized for Atlantis. Figure 3 shows images that represent various modeling phases in a case in which the patient had no teeth. Dentists or prosthodontists make a study cast of the area where the abutment will be placed. They then scan the cast into the computer using a 3D optical scanner, creating a 3D point cloud (the digitized study cast consists of somewhere between 50,000 and 200,000 points). Technicians at Atlantis use Raindrop Geomagic's Studio software to create a polygonal surface from the point cloud. Atlantis uses proprietary software to virtually assemble the digital teeth data with an unmodified (or template) version of their product. This template is a 3D model of an ideally shaped dental abutment. Technicians virtually modify this template so that it fits within the gap created by the missing teeth. The system directly uses the digital data to fabricate the dental abutment used to restore missing teeth.

The computer generates the tool path—the instructions the milling machine uses to create the final product from the 3D model—and sends it to the milling machines that create the titanium abutment. Figure 4 shows the final models of upper and lower teeth that Geomagic Studio 3.0 generated. Bethany Grant, an engineer at Atlantis Components explained, "Now we're doing everything virtually that was hand done by the



4 The final computer models generated in Geomagic Studio 3.0. (a) Upper teeth. (b) Lower teeth.

technicians before.” The result is a more precise abutment and a better fit the first time around.

Grant said Atlantis chose Geomagic Studio because it’s quick and automatically pulls up the surface forms. Another benefit is that Raindrop Geomagic worked with them to customize the off-the-shelf software package for what they needed. The people at Atlantis use standard PCs from major manufacturers with speeds ranging from 300 to 800 MHz and traditional hardware and software. They use high-end 3D graphics cards to provide sufficient performance for viewing the images in real time. The resolution of the polygonal files corresponds to the point data, ranging from 20,000 to 100,000 triangles.

Grant asserted that any computer made within the last couple of years that has a 3D graphics card can do the job. Atlantis uses archiving systems to keep enough memory available for working with the images. The computer technicians’ experience varies—some have dental experience and some don’t. Others are computer savvy, while a few aren’t. According to Grant, the software takes about a week to learn. “Our system is very simple,” she stated, “Anyone can do it.”

### **The payoff**

The major savings are in fewer patient visits. According to Osorio, the amount of time it takes to place a dental implant has been reduced drastically. “Instead of seeing the patient for six to eight appointments, I do the cases in around two to four,” he stated. An additional benefit is that prosthodontists don’t need to make modifications at chairside. This translates into short appointments without the need for anesthesia.

In Osorio’s Boston-based practice, the cost to the consumer, on average, is around \$2,800 per tooth. The technology hasn’t lowered the price yet. However, insurance companies are starting to cover the procedure, and they usually have an effect on prices because of their volume. Also, as many practitioners begin using it to market and grow their implant practices, the price will most likely come down.

### **Maxillofacial surgery**

An unfortunate circumstance for some people, however, is that they don’t even have the basic bone structure to support dental implants or orthodontic appliances. Maxillofacial surgery repairs physical malformations resulting from disease, injury, burns, birth defects, or aging. In these cases, a maxillofacial surgeon must make changes that often include removing bone and replacing it with modeled implants. The surgical implants, made of chromium-cobalt alloy, are traditionally standardized parts that surgeons must adjust during the surgery to make a correct fit. This is a difficult and imprecise method, according to Cesar Oleskowitz, a practicing oral and maxillofacial surgeon in Brazil.

### **A single solution to several problems**

Before using computer graphics to plan his surgeries and design the implants, Oleskowitz had to overcome significant obstacles. First, no case was exactly the same; for some patients, standardized parts didn’t provide what was needed for a precise implant procedure and an aesthetic outcome. Second, the surgical field, or area, was messy and sometimes obscured things that needed to be seen. Finally, Oleskowitz couldn’t make changes to implants during the surgery, sometimes requiring the patient to undergo a second surgery to complete the treatment.

Oleskowitz turned to computer graphics to solve these problems in his practice. He uses a PC with a 700-MHz Pentium III processor, 256 Mbytes of RAM, and 32 Mbytes of video RAM in combination with the latest medical CAD programs and 3D graphics software to understand the extent of the patient’s problems.

To start, Oleskowitz takes measurements from computed tomography (CT) scan images of the patient and enters them into the computer. He uses sliceOmatic from TomoVision, a Canadian software firm, to transform the 2D cuts into precision 3D images. Using Geomagic Studio, he gets an idealized image of the structures under the skin—something that he can’t see clearly during the actual surgery. With such powerful tools, he can create

## It's All in the Software

It appears that the graphics that have revolutionized oral health care require nothing more than a relatively up-to-date computer and a little training on some innovative software. The value of automation in health care is clear and several companies are creating software for CAD/CAM purposes. The two described here stand out in the oral health care field as groundbreakers, and they're raising the bar that defines state of the art.

### Geomagic

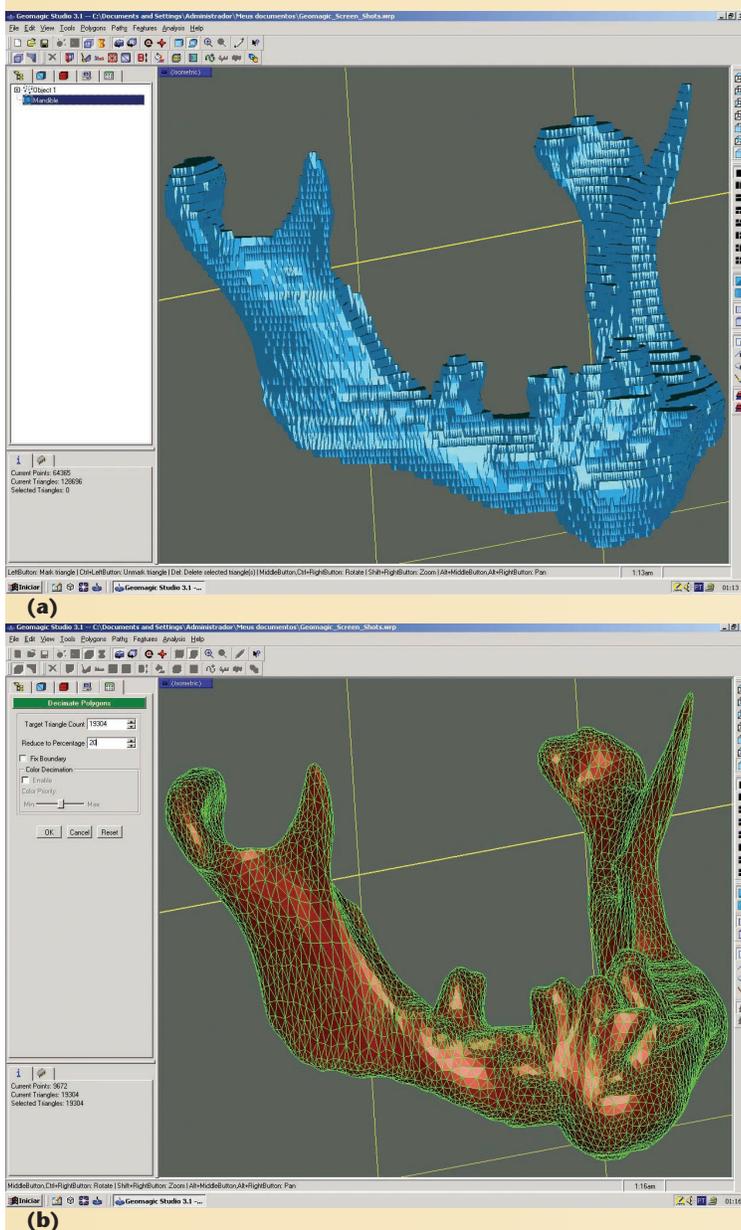
The common thread among the three examples of oral health care techniques discussed in this article is the CAD/CAM software they use (or will

use) from Raindrop Geomagic. The company develops technologies that automatically turn physical parts and objects into digital models for use in design, engineering, manufacturing, and marketing. Ping Fu, an expert in 3D geometric modeling and visualization, and Herbert Edelsbrunner, an internationally recognized expert in computational algorithms, geometry, and topology, started the company in 1996. They currently have 15 software engineers and the software is primarily developed within the company. They use OpenGL as the rendering engine and optimize the software for the nVidia graphics processors with real-time support of color, texture, and bump maps.

Geomagic software was based on many years of research rooted in combinatorics, geometry, and topology—three areas of mathematics that prove essential for a solid understanding of shape and space. Important attributes to the software include automation, accuracy, repeatability, simplicity, speed, high resolution, and support of industry standards. The company tailors its software for the needs of specific industries, then customizes it for each company. Geomagic also sells customers a license to use its software. Fu emphasized the way their CAD-based software works: "Our approach resembles the art of photography. The skill is in the machines, not the users' artistic ability." Figure A shows the graphical user interface (GUI) for Geomagic Studio 3.0.

CAD/CAM software isn't monopolized by Raindrop Geomagic, so why is Geomagic software so prominent in the oral health care industry? Right now there's little competition. This can partly be explained by the fact that it owns a particularly useful patent for automatic conversion from points to shape. The competition it faces is mostly on the industrial side of business, not in the medical field. Fu stated, "With Geomagic software, companies can produce millions of models, uniquely fit to human shape, within the tolerance required by the most demanding

**A** Examples of the Geomagic Studio 3.0 GUI. (a) The starting point of CT scans (raw data). (b) A representation of a smoothed CT image with a reduced number of polygons overlaid. This reduction creates a manageable number of polygons without losing precision.



manufacturing processes. [This is] a benchmark not achieved by any other software, at a price point and throughput required to make customized manufacturing a profitable and practical process." The cost of the software depends on the area of use, but a ballpark figure is \$20,000 plus a one-time engineering fee for customization. Users can run it on a PC with Windows or Unix.

Raindrop Geomagic plans to continue developing software for use in multiple fields. It aims to streamline the processes that companies use to create the article of interest. One way that Geomagic does this is by creating templates. By using templates adapted for each case, users can save a lot of time, and the technology may be more cost effective.

### TomoVision

TomoVision (<http://www.tomovision.com/>) produces medical imagery programs that enhance researchers', physicians', and medical professionals' operational and clinical effectiveness. Aside from surgical planning and implant design, this software is used to calculate anatomical volume and surface by body composition physicians, generate accurate 3D anatomical models by biomedical engineers, and enhance 2D and 3D visualizations by radiologists. Each of these health care fields uses specific tools such as fast image display and processing, measurement, segmentation, editing, and filtering.

According to Yves Martel, founder of TomoVision, the company is a one-man show. The first version of the software was an in-house tool at the Montreal Polytechnical School designed for a researcher segmenting magnetic resonance images (MRIs) of a rat. The first commercial release was in 1994 in collaboration with the School of High Technology (Ecole de Technologie Superieure, or ETS) in Montreal. At first it ran on a SGI workstation using SGI's original GL graphics library. Since January 2000, it has been ported to Windows using OpenGL. The program is written in C, and the interface is done with Yves' Tools, a proprietary interface toolkit that lends more flexibility and portability than conventional interface tools. Figure B shows the GUI.

The software runs on a Windows (95 to 2000) platform on any PC with a good OpenGL graphics card and plenty of memory. A typical user wants to be able to analyze hundreds of medical slices, and each of these can take up to 1 Mbyte. SliceOmatic comes in three modules: Basic, Tag, and 3D. The Basic module lets users read the images, do some 2D measurement on them, reslice them, and select a region of interest in the images. Martel admitted, "The first module doesn't get you very far, but some researchers don't require more than Basic." The Tag module lets users segment the images, and the 3D module



**B** GUI of sliceOmatic. The image is a 2D axial cut of a CT scan prior to any manipulation. This is what radiologists and surgeons typically see.

uses the segmented images to create rough 3D surfaces.

Each module costs \$2,000. Martel said that while the software isn't generally customized, he can do that: "If somebody wants something specific, I'll probably do it for them." Martel tried to make the interface as intuitive as possible, but it's a powerful tool. It comes with a tutorial that users can download with the software from the TomoVision Web pages.

The competition for TomoVision includes software called Analyze, which was created at the Mayo Clinic (<http://www.analyzedirect.com/>); Materialise, based in Europe (<http://www.materialise.com>), and 3D Doctor, designed by Able Software Corporation (<http://www.ablesw.com/3d-doctor/>). The Tag module, which permits segmentation, is what differentiates sliceOmatic from the competition and makes it a desirable software package for Cesar Oleskovicz. "No other software on the market does that," Bartel noted. TomoVision is striving for better segmentation in new editions. The company continues to collaborate with researchers at the ETS to ensure that the software uses the latest segmentation techniques.

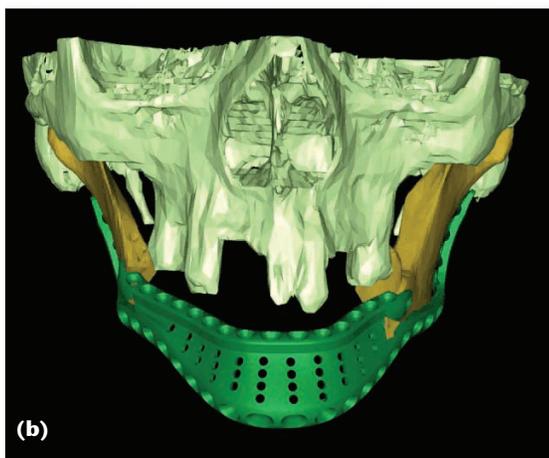
### Teaming up

Despite the power of TomoVision's software, some researchers and practitioners use more than one software package to achieve their goals. For example, Oleskovicz's oral and maxillofacial surgery practice uses sliceOmatic and Geomagic Studio to create graphics because Geomagic Studio has capabilities that sliceOmatic doesn't. For instance, sliceOmatic-created images have a staircase look instead of the smooth and natural look that Geomagic Studio images have because of a filtering process. Another advantage to teaming up the two types of software is that Geomagic Studio has the capability to manipulate images. The graphics in Figure 5 (next page) from Oleskovicz's cases came from animations he created using both sliceOmatic and Geomagic Studio.



**5** Images of facial structures created using TomoVision's sliceOmatic and Geomagic Studio 3.0. (a) A computerized image of the lower half of the skull. This patient suffered from a bone tumor in the lower jaw. (b) The upper jaw bone and skull are highlighted in green. (c) The lower jaw bone. (d) The lower jaw bone with the problem area to be removed highlighted in red. (e) The lower jaw bone with the problem area (red in Figure 5d) virtually removed.

**6** Image of (a) the maxillo-facial implant and (b) how it will replace the removed bone.



images of the facial structures with which he will work during the surgery, as Figure 5 shows.

Once Oleskowicz obtains the images, he can determine how much bone he must remove and then replace it with an implant. Oleskowicz chose Geomagic software because it was less expensive than any other software that was available and he got support from Raindrop Geomagic to get started: "They spent time with me to help me learn how to use the software."

The procedure for modeling the surgical implants resembles the one used to model dental implants. The

computer virtually removes the problem areas from the patient's computerized image, then models and adjusts the implants for that specific case. CAM then makes the implants from the surgical steel alloy. Figure 6 shows images of the implant and how it will replace the removed bone. In the computer, the surgeon can make changes that can't be done during surgery.

### Equalizing the cost

In Brazil, only fairly wealthy patients can afford maxillofacial surgery. Traditionally, each surgery costs about \$2,000, and health insurance isn't common. The direct cost of using the computer graphics technology is still more than a single surgery to correct facial bone malformations—it's more than double. So why use something that people can't afford? It saves time for the design and makes the procedure more accurate. Yet computer graphics has another profound benefit. Now that the structures can be computer modeled and the implant designs can be perfected prior to a patient ever going under anesthesia, the need for second surgeries has been practically eliminated. In the end, the cost is almost equal for patients that would have required more than one surgery. Oleskowicz believes that in time, the technology will become more cost efficient as more practitioners begin to use it.

### What's next?

Until recently, the role of software in a dental practice was limited to managing patient information and billing. With the advent of 3D modeling software for biological uses, it has become an integral part of many oral health care practices. The applications range from cosmetic to restorative, but all of these uses have begun to change the face of oral health care. What's next? With the progress in optics and the decrease in computer chips' size, it's possible that someday software will help manage fundamental endodontics procedures such as precision drilling and root canals. All it's going to take is some powerful software, a decent computer, and a little innovation. ■

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