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Virtual Surgery Brings Back Smiles

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Millions of children worldwide are born with defects known as cleft lips and palates (see the "Cleft Defects" sidebar). These defects cause major deformities to a person's face, see Figure 1, and can lead to other health problems. Unfortunately, many children with such defects cannot afford the surgery required to correct the problem.

The Smile Train

A number of charities thus provide free cleft surgery to these children. Most of these charities send teams of doctors to the specified country, where they spend around two weeks performing surgeries on as many children as possible. Due to the lack of staff and the limited time period available, many children who show up get turned away—typically only one of three get helped. The Smile Train (http://www.smiletrain.org), established in 1999, takes a different approach. Founded by Charles Wang (chair of Computer Associates at the time) and Brian Mullaney (who has been involved with children's reconstructive surgery charities for more than 12 years), the two took a business approach to the problem and analyzed a country's need by population, birth rate, and poverty level.

Cleft Defects

A cleft lip is a hole in the upper lip between a newborn's mouth and nose. It can occur on the left or right side (unilateral) or on both sides (bilateral). A cleft palate is where the roof of a newborn's mouth is not joined completely. Because the lip and palate can develop independently, some children can be born with defects in both. A cleft lip is usually less serious than a cleft palate. Figure A shows a virtual patient with a unilateral defect.

The exact cause of these defects is not known. Early embryonic changes (during the fourth and tenth weeks of gestation) might result in clefting. These changes might be due to genetic or environmental factors (for example, the mother might have been exposed to chemotherapy, radiation, alcohol, or certain types of prescribed drugs). About 22 percent of facial clefting has a genetic origin and if the family has a history of clefts, the risks increase. Other factors that increase the chance of such deformities include the mother's age (older than 35 or younger than 18); lack of prenatal care; or smoking cigarettes, not eating a balanced diet, or abusing drugs during pregnancy.

In the US, one in 700 babies is born with a cleft lip and/or palate. Among some populations, the incidence is as high as one in every 400 live births. For example, in China and India it is estimated that 35,000 children are born each year with clefts. According to The Smile Train, the governments of these countries offer little support or assistance to these children and more than 80 percent of them never receive any treatment due to poverty.

These children not only suffer from having a physical facial deformity but also might have difficulty hearing or speaking clearly. Speech problems can develop in palate cases, especially if the cleft is repaired when the child is older. The earlier the palate is repaired the better the speech correction results (before one year old is best). Children with a cleft palate are also prone to ear infections because the cleft can interfere with the function of the middle ear.

Children with cleft defects might also have trouble feeding themselves and thus be malnourished. Dental

A 3D rendered model of a patient with an open unilateral cleft lip.

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"We then determined that it was less expensive, more productive, safer and smarter to empower local doctors and hospitals to help the children with clefts in their community," explained Mullaney. "We can help a single local doctor operate on thousands of children for 80 percent less than what it costs to send an American medical team." The group achieves this by providing free training, education, and equipment as well as other financial support. Such a strategy has resulted in more than 110,000 children being operated on in 55 countries since 1999. "This is three times the number of surgeries completed in the last 20 years by conventional charities," noted DeLois Greenwood, The Smile Train's vice president.

The factors making The Smile Train a success include a global network of partners and programs in combination with leveraging technology to accelerate learning results. The technology comes in three forms: an online searchable library containing thousands of research articles related to cleft surgery; Smile Train Express, a free, secure, Web-based patient database accessible to the global cleft community; and a virtual surgery CD-ROM collection that includes training videos. The CD-ROM content leverages the power of virtual technology and advanced 3D animation software.

In 2003, The Smile Train received a Laureate award from Silicon Valley's Tech Museum of Innovation for their unique approach. Jyotsna Murthy, a member of The Smile Train's Indian Medical Advisory Board, commented in her recommendation for this award that "although training and empowering local doctors is a slow process, it's the only long-term solution to this problem. Better trained surgeons mean more kids getting the surgeries they would have never otherwise received—surgeries that give them a second chance at life."

"Mullaney and Wang also had the vision to take cleft surgery expertise and create a virtual surgery CD-ROM," added Greenwood.

1 An 8-year-old girl from China, showing her unilateral defect before it was repaired.

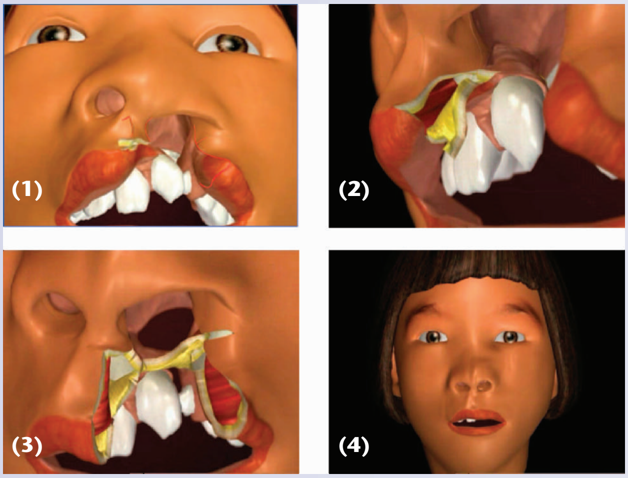
problems are another concern, involving missing, deformed, or out-of-position teeth. But perhaps most damaging to these children is the emotional trauma of being different from other children.

Surgical solution

A cleft lip can range in severity from a slight notch in the upper lip to a complete separation of the lip extending into the nose. Surgery is generally done when the child is about 10 weeks old. First, the surgeon makes an incision on either side of the cleft from the mouth into the nostril, see Figure B1. Next, the dark pink outer portion of the cleft is turned down, see Figure B2, followed by closing the separation by pulling the muscle and the skin of the lip together, see Figure B3. Muscle function and the normal shape of the mouth are restored, see Figure B4. The nostril deformity often associated with a cleft lip can also be repaired during this surgery or in a later operation.

Cleft palate also varies in severity, from involving only a tiny portion at the back of the roof to a complete separation that extends from front to back. It can occur on one or both sides of the upper mouth. The corrective surgery—a palatoplasty—for this problem is more complicated and is usually done when the child is 9 to 18 months old. The surgeon makes an incision on both sides of the separation, followed by moving tissue from each side of the cleft to the center or midline of the roof of the mouth. This rebuilds the palate, joining muscle together and providing enough length in the palate so the child can eat and learn to speak properly. Construction of an adequately functioning soft palate is key to a successful surgery.

Over the years, surgeons have improved their techniques and developed new procedures. However, according to The Smile Train, most surgeons in developing countries are still using outdated techniques and therefore secondary surgeries might be required.



B Animations showing: (1) How the incision is made during surgery. (2) How skin is retracted using forceps. The yellow area depicts the fat following the skin. The bottom and skin edges of a flap always passively follow the movement of the top layer. (3) How the unilateral lip is closed. (4) The finished repair.

The Smile Train CDs

The first disc focuses on the basic principles of primary unilateral cleft lip and nose reconstruction (http://www.smiletrain.org/medpro/vs/unilateral.mpg). The disc compares and contrasts four components of this repair: rotating downward on the medial segment, correcting the primary nasal cavity, mobilizing the lateral lip and alar base, and repairing the lip. Figure A shows an animated schematic of the anatomy involved during cleft repair.

The second disc presents the basic principles of primary bilateral cleft lip and nose reconstruction (http://www.smiletrain.org/medpro/vs/bilateral.mpg). It describes lip repair details, including muscle repair, central vermilion reconstruction, and philtral column construction. This disc also describes the new concept of primary nasal cartilage repositioning.

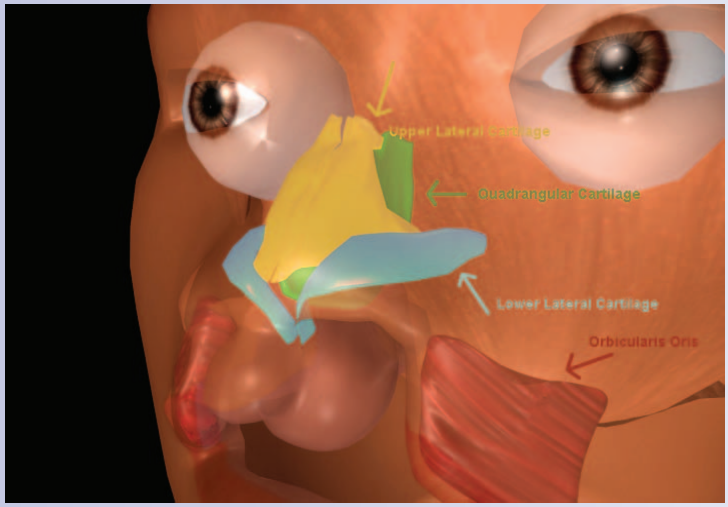
The third disc looks at the procedures that make up a modern cleft palate repair, including repair of both hard and soft tissue (http://www.smiletrain.org/medpro/vs/palate.mpg). The techniques presented on this disc have significantly reduced the need for secondary palate surgery.

Since the videos were first released in 2002, more than 10,000 copies have been distributed—80 percent of them in English and 20 percent in Mandarin. Thousand of doctors—in remote locations, medical schools, and teaching symposiums—now work with The Smile Train CDs.

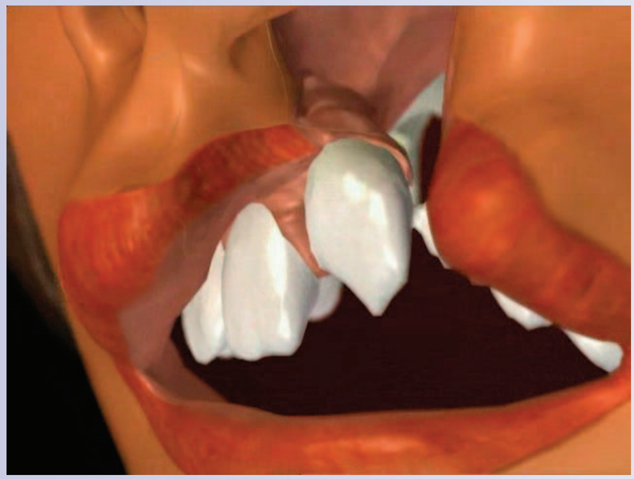
A survey sample by The Smile Train organization of 1,000 CD recipients found that 98 percent would recommend the videos to other surgeons or medical professionals and 95 percent felt the videos made cleft surgery easier to understand. More than 60 percent use them to train others, including Murthy, who uses the CDs to teach cleft surgery to postgraduate students.

Many also felt the videos showed things traditional videos can't. For instance, a traditional video can't show the deepness of an incision or provide views from multiple angles or show certain angles impossible to obtain with a real camera, see Figure B. "Animation gives a visual impression of the movement of tissue that is sometimes difficult to show on regular video," noted Murthy.

In addition, the CDs have been extremely useful in treatment planning for special cases like wide cleft and excessive buckling of lower lateral cartilage, allowing the surgeon to execute an appropriate technique for each specific case.



A Animated schematic of the anatomy involved during cleft repair. Multiple angles can be viewed during the animation, unlike a traditional video.



B Lifting the M-shaped flap on the medial side of the lip is a constant in several lip repairs. This particular image was taken from the molar repair.

Virtual surgery project

Partnering with New York University (NYU), one of the leaders in cleft care, The Smile Train funded The Smile Train Virtual Surgery Laboratory to develop interactive software that surgeons can use to learn, practice, and perfect techniques in cleft lip and palate repair. Phase I of the project involved the development of three CD-ROMs (see "The Smile Train CDs" sidebar) that take surgeons step by step through the various stages involved in the repair of clefts, using a combination of animation with actual live surgical video (submitted by the world's top surgeons) of state-of-the-art procedures. The software for these CDs was developed using computerized tomography (CT) and magnetic resonance imaging scans from two Chinese children who traveled to New York in 1999 for their cleft lip and palate repair (see Figure 1).

Court Cutting, a prominent plastic surgeon and associate professor at NYU and Joseph McCarthy, director of NYU's Institute of Reconstructive Plastic Surgery (http://www.med.nyu.edu/irps/) led the virtual surgery CD project. Cutting is also an expert in computer technology and previously developed an intraoperative VR system for tracking and positioning of facial skeletal fragments. Another important member of the team was Aaron Oliker, currently Chief of Programming and

Animation at NYU Medical Center's Virtual Surgery Research Laboratory.

"The CD project was born out of my own personal frustration with how difficult it is to teach surgeons how to perform cleft surgery. I always felt there had to be a better way," Cutting explained. "I've been teaching surgery for 25 years and books did not do it justice. With a 2D drawing, you can't really get the message across because this type of surgery is very 3D and includes complicated geometry." For instance, cleft surgery involves 3D manipulation of tissue flaps from one location to another to correct a cleft defect. Intraoperative video is also limited to 2D because it's filmed via a stationary camera without rotation.

The team believed the best tool available to illustrate cleft surgery was animation software. They chose the Maya v3.0 program to simplify and refine the reference models. They used this software, which was donated for free by Alias (http://www.alias.com), to produce all the surgical animations for the CDs.

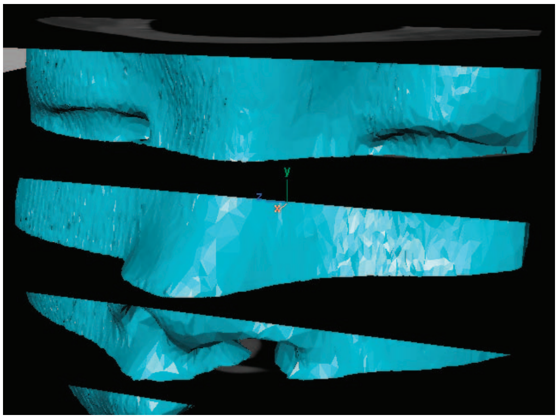
The current version of the software, Maya 6, comes with a wide range of features, including a full complement of sophisticated polygon modeling tools, nonuniform rational B-spline (NURBS) surface modeling, subdivision surface modeling, and deformers (the manipulation of geometry or particles into any desired shape). However, some of these features were not available in the earlier version, thus requiring modifications to the software for The Smile Train application. The team accomplished this using the Maya API and software developer's kit to create plug-ins. The API, written in object-oriented C++, provides access to high-level polygon operations, and enables development of standalone applications that open Maya in noninteractive batch mode. Plug-ins can operate in either interactive or batch mode.

"We assumed that the use of the current generation of animation software would be straightforward for this application," said Oliker. "It quickly became evident that standard animation programs at the time did not contain the tools necessary to illustrate surgery."

Creating the models

Cutting selected two Chinese children, an 8-year-old girl with a unilateral cleft and a 9-year-old boy with a bilateral cleft, to use as models. Cutting created reference models of their heads using dense CT 1-mm scans. He made 3D anatomic surface models of relevant structures with software that he and his PhD student, Andre Gueziec, previously developed at the Virtual Surgery Research Laboratory. They based this previous software on the fact that by adjusting the luminance of a CT scan, it's possible to extract soft tissue from bone. Thus, it allows the user to create a 3D volumetric model from the stacked data based on the luminance values tweaked in the CT, see Figure 2. (In the past five years other software packages have been created that can also create these types of 3D models from stacked data.)

Some parts of the patients' cartilage tissue—quadratic arm, lower and upper lateral areas—could not be seen on the CT scans and so the project team used data obtained from the National Institute of Health's Visible Human Project (http://www.nlm.nih.gov/research/visible). The NIH project was established in 1989 to build a digital-image library of volumetric data representing complete, normal adult male and female anatomy using sliced up cadavers. The virtual surgery project used the male data set, which consisted of axial CT scans of the entire body taken at 1-mm intervals at 512 × 512 pixel resolution, with each pixel made up of 12 bits of gray tone. Anatomical cross sections were taken at 1-mm intervals to coincide with the CT images. At the time, the female data was not available.



2 CT scan sectioned by a dense volumetric model of the unilateral patient.

The group imported the rough reference models into the Maya animation package. Polygonal models of skin, bone, cartilage, and muscle were smoothed and simplified using the animation program's NURBS tools. They then resurfaced the models using a unique technique developed by the Virtual Surgery Research Laboratory within Maya. The first step was the creation of NURBS patches along the surface of the stacked data. This was necessary because the data was dense, with many polygon artifacts. Then, the group converted the NURBS patches back into polygons to create the model.

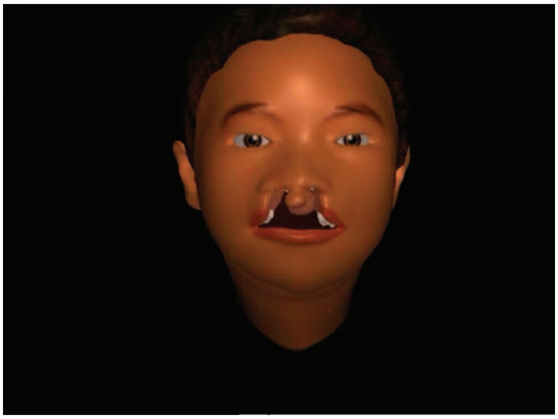
This technique has several advantages: creating a reference model that has retained fidelity, smoothing, a significantly reduced size (from 200,000 polygons to about 5,000 polygons), and is easier to manipulate and texture. Figure 3 (next page) shows the finished resurfaced model for the bilateral patient.

Technical challenges

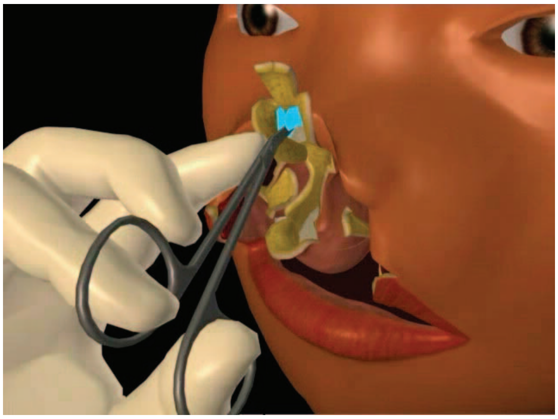
To perform 3D surgical animation, the team developed special plug-ins to realistically simulate the steps during the surgery. These plug-ins included tools for incision, suture, texture, fat, and hook or forceps that allows folding back tissue. The incision, fat, and forceps tools provided the most challenges.

These plug-ins were required because conventional animation software only records surface changes. With surface changes there is always a 1:1 ratio of points; however, an incision changes the number of points. In contrast, during real-life surgery there is a layer of fat underneath the skin so when an incision is made, topological changes occur. In other words, the fat must follow the skin, requiring two layers of geometry that must move together uniformly.

With the conventional Maya program, every time an



3 3D rendered model of a patient with an open bilateral cleft lip.



4 Lower lateral cartilages (in blue) are separated from the skin of the bilateral patient.

incision was required, a new animation scene had to be created. To create a single surgical animation, many separate scenes had to be linked together in the final editing process. Thus, it was necessary to program a fat tool to create an underlying layer of fat on the single layer skin models. The team created the fat tool with the Maya Embedded Language. This was not difficult to implement because of Maya's open MEL interface. The difficulty centered on the conceptualization of the fat tool.

The first attempt to simulate fat used Boolean operations and a double layer model. Although the team successfully completed one surgical animation with this approach, the result was less than satisfactory (the animation did not look realistic). They redesigned the fat tool to create thickness after an incision is made. In other words, after a single layer is animated, the fat is applied after the animation is completed. This avoids the problem of animating two layers of geometry at once. The fat tool thus automatically creates a system where the fat follows the skin, see Figure B2 in the "Cleft Defects" sidebar. This plug-in also automatically textures the side of fat and the bottom layer of fat to create the illusion of full thickness skin.

The team also created the hook or forceps tool plug-in using C++ to mimic tissue retraction. Although Maya has a rich set of object deformers (algorithms that tell the program how a set of points should move), none of these created realistic-looking skin retraction. In other words, the deformers were unable to duplicate the biophysics of folding back a skin flap. It was thus necessary to create two custom software plug-ins that would provide realistic looking tissue retraction. Combining the forceps tool with the fat tool creates a realistic appearance of surgically transposed skin, see Figure 4.

The team used a simple trigonometric equation based on a cosign wave to create the illusion of skin deformation. At the time of the animation production, Maya's general animation tools did not allow the creation of the desired transformation without a great deal of time and effort. With the forceps plug-in, the proper deformation was created in minutes, giving the properties of skin at the touch of a button.

Advantages of animation

In combination with the plug-ins, several standard animation tools become particularly useful for the illustration of surgical concepts on the CDs. Positioning a virtual camera from almost any angle provides the viewer with the best vantage point for each maneuver and shows all three dimensions of a procedure. Virtual cameras can also zoom into small areas (only several millimeters wide) that are impossible to view in intraoperative footage.

Transparency is useful in surgical animation, letting the surgeon see underlying dynamic motion of the anatomy during the repair, while maintaining a view of the overlaying tissue's relationships, which is otherwise obscured in real surgery by blood or instruments. "Movement of nasal cartilages under the skin is difficult to appreciate in traditional video," noted Murthy. Figure 4 shows a nasal cartilage dissection.

Transparency also provides insight into the placement of sutures, as well as the ability to see the effect of the cartilage and muscle directly during a dissection. All of these scenarios are impossible to observe in vivo or with intraoperative footage. In addition, the representation of motion allows the modeling of anatomical mechanics not possible with static illustrations.

Digital editing allows for the splicing of surgical video with 3D animation, which allows you to clarify and emphasize key maneuvers that might not be obvious in the surgical video. This also provides a familiar frame of reference for the surgeon to better understand the animation.

Compositing is a technique that allows the overlaying of pointers, words, and images onto animations and surgical footage. For example, labeling both the animations and the surgical video can highlight surgical landmarks.

Another advantage of using digital surgery is the ability to illustrate inferior techniques. For example, the triangle repair for the unilateral cleft lip is still a widely used procedure in developing countries. Animations can show the consequences of this outdated repair, which creates an undesirable and unnatural outcome, see Figure 5.

Simulating surgery with animation

Phase II of the virtual surgery project is the creation of interactive simulators that can recreate the experience of surgery in a safe, digital environment, based on the plug-ins and scripts created in Maya. A prototype was completed in 2004. This simulation allows the novice surgeon to practice the procedure and make mistakes, without putting patients at risk.

According to Oliker, the animations were a learning experience in terms of understanding the basic steps necessary to create virtual surgery. "We understood from the start of the simulator project that we had to create skin deformers, a fat tool, and an incision tool," Oliker explained. "In the animations we were forced to manually tweak the models for each step of the animation, even though we had created plug-ins for the skin deformation."

5 Animation showing the undesirable outcome of an outdated triangle repair technique.

In the simulator, the deformers are based on algorithms involving limited spring networks that generate their deformation on the fly based on the distance of the selected deformer point to the bone. First, the user selects a point on the skin and then a vector is established from this point in the direction of the bone. Next, the barometric center of the closest polygon is located. A volumetric deformer is then estimated based on the location on the lip and the distance from the bone. In a real-time environment, there is no opportunity to modify the model manually.

Phase III of the CD-ROM project began in July 2004 and is expected to take several years to complete. This CD will take a closer look at more complicated cleft and nasal deformities, as well as provide tips on performing secondary surgeries to fix speech and other problems. It will combine animation with simulation.

Using proprietary software, the CD will let users export simulations into Maya to create their own surgical animation. "It's a more efficient process," explained Oliker, "because the user doesn't have to be an expert in Maya or animation software."

Virtual surgery expands

Fortunately, The Smile Train is no longer the only organization with animation software geared toward medicine. Many institutions and companies are implementing and using 3D animation to articulate surgical and anatomical concepts. For instance, BioDigital Systems (http://www.biodigitalsystems.com) custom develops 3D medical animations for clients, including one that involved adrenal surgery.

As simulation realism continues to improve Cutting expects virtual surgery will become more widely available for other complicated operations involving the heart and brain. "The novice surgeon should practice and make mistakes using simulation not real patients," he emphasized. ■

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