alloplastic biomaterials have revolutionized craniofacial reconstruction. Commercially available bone substitute cements allow easy contouring and application, as well as avoidance of postoperative donor site complications. Hydroxyapatite and carbonated apatite are commercially available biomaterials currently being used as moldable bone substitutes in craniofacial reconstruction. This study presents 35 patients with 46 sites of reconstruction using hydroxyapatite or carbonated apatite. The characteristics, effectiveness, advantages, and limitations of each biomaterial are discussed.

The development of alloplastic biomaterials has revolutionized craniofacial skeletal reconstruction. Bone substitutes have, in some cases, obviated the need for autologous bone grafts, thus eliminating donor site morbidity, decreasing operative time, and minimizing contouring difficulties, while allowing successful results. Recent alloplastic materials include a variety of polymers that were associated with infection, extrusion, and other difficulties. For example, methylmethacrylate hardening is associated with an exothermic reaction that can lead to tissue injury. It then becomes encased in a fibrous capsule over time and demonstrates foreign body giant cell reactions. In addition, it does not allow for tissue incorporation.1 Problems such as these have prompted the development of calcium phosphate–based materials.

Ceramic hydroxyapatite in block form demonstrated good tissue compatibility, but contouring of the material into defects proved difficult. Granules of ceramic hydroxyapatite are easier to contour but lack the architectural stability for adequate reconstruction.2 Ceramic hydroxyapatite cement is composed of tetracalcium phosphate and dicalcium phosphate (anhydrous). In the presence of water and at physiologic pH, the salts react isothermically to form a dense paste. The paste can then be shaped intraoperatively and allowed to set for 15 to 30 minutes. The reactants are then reprecipitated until the entire material is converted to microporous hydroxyapatite. The conversion takes approximately 4 to 6 hours in vivo.3 Ishikawa et al4 found that mixing the hydroxyapatite cement in 0.25M sodium phosphate buffer decreased the setting time significantly.

Since the development of hydroxyapatite cement, numerous reports have described the uses of this biomaterial. In 1991, Friedman et al5 demonstrated successful frontal sinus obliteration in 9 cats. Full-thickness calvarial defects were successfully repaired with hydroxyapatite in cats by Costantino et al6 in 1992. Shindo et al7 performed supraorbital augmentation on dogs with hydroxyapatite cement and subsequently showed progressive osteointegration without volume loss. Other animal studies demonstrated successful malar and supraorbital augmentation8 as well as repair of zygomatic arch fractures.9 These animal studies paved the way for human use.

Kamerer et al10 reported watertight closure and obliteration of “dead space” following temporal bone surgery. Kveton et al11 demonstrated successful recon-
construction of suboccipital craniotomy defects in 5 of 7 patients. Costantino et al\textsuperscript{11} used hydroxyapatite cement to reconstruct cranial vault defects. In their series of 21 patients, they reported no complications or loss of volume over time. Recently, sphenoidethmoidal cerebrospinal fluid (CSF) leak repair was accomplished in 21 patients with hydroxyapatite.\textsuperscript{12} The biomaterial was very effective in halting recalcitrant CSF leaks. Complications did arise in this series, though the authors attributed them to technique rather than the biomaterial.

The use of hydroxyapatite cement has also been evaluated in the developing skeleton. Lykins et al\textsuperscript{13} showed safe reconstruction with hydroxyapatite in 12-week-old cats. Another study evaluated the effects of secondary craniofacial reconstruction in a series of pediatric patients. In this series, the authors found retention of implant volume, absence of recurrent contour defects, and no visible evidence of impaired craniofacial growth. However, the study failed to present the data on head circumference and followed up the patients for a mean of only 20 months.\textsuperscript{14}

Although hydroxyapatite cement has proven its utility, it is not without its drawbacks. Early cements had to be applied and set in a dry field, and it would tend to wash out in the presence of blood, CSF, or other fluids. In addition, postoperatively the wound had to be kept free of fluid to allow for proper conversion. Otherwise, crumbling of the biomaterial and subsequent complications would often occur. Friedman et al\textsuperscript{15} reported a 5.8% surgical site infection rate in 103 patients. In another study, Friedman et al\textsuperscript{16} reported an 8% infection rate in a series of hydroxyapatite frontal sinus obliterations and fronto-facial defect reconstructions.

More recent formulations of commercially available cements (hydroxyapatite and carbonated apatite) have been easier to use in a wet field and have provided an excellent substance for repair of cranial defects. Commercially available carbonated apatite consists of monocalcium phosphate, tricalcium phosphate, and calcium carbonate (Norian CRS; Synthes-Stratec, Paoli, Pa). Hydroxyapatite consists of tetracalcium phosphate and dicalcium phosphate dihydrate (BoneSource; Stryker Leibing, Flint, Mich).\textsuperscript{17}

In our institution, both carbonated apatite and hydroxyapatite cement have been used for craniofacial reconstruction. This study presents a comparison of these biomaterials and their varying uses in craniofacial skeletal reconstruction. The goal is to evaluate the ease, effectiveness, and complications of carbonated apatite and hydroxyapatite cement. Advantages and drawbacks of each of these biomaterials in various settings are discussed.

### METHODS

A retrospective chart review was performed on 35 patients who had hydroxyapatite and/or carbonated apatite cement used for craniofacial reconstruction (Table). The patients all were informed of the use of the materials prior to surgery, and consent was given for their use. The 35 patients consisted of 27 males and 8 females with an age range of 1.5 to 73 years. The mean age of our patient group was 30.4 years. The materials were used at a total of 46 sites. Two primary surgeons (R.M.K. and S.A.T.) were involved in all of the cases.

The hydroxyapatite cement was mixed in a phosphate buffer solution prior to application. The mix was allowed to set in a dry field for 10 to 30 minutes. Carbonated apatite cement was mixed in the company-supplied device prior to application. Adequate time was allowed for setting in a field devoid of excess blood or fluid. The wounds were drained when appropriate for both types of cement.

Of the 46 total sites, hydroxyapatite was used in 20 sites, and carbonated apatite in 26 sites. Twelve patients had repair of cranial defects with the cement. Frontal sinus obliteration was performed in 16 patients (Figure 1). The orbital floor was repaired in 5 patients with 1 intraoperative failure. Two patients had repair of the anterior skull base. Two patients had nasofrontal defect repairs. One patient had the outer cortex of the mandible reconstructed. The maxilla or malar eminence was the site of reconstruction in 4 patients.

Titanium mesh was used in 5 patients (patients 2, 12, 23, 27, and 30), both with hydroxyapatite and carbonated apatite (Figure 2). Carbonated apatite was also used with an acellular dermal material (AlloDerm) for soft tissue augmentation in the temporal area (patient 12).

### Abbreviations

- CA: carbonated apatite
- HA: hydroxyapatite
RESULTS

Forty-two of the 46 sites had successful intraoperative reconstruction. Implant placement into the surgical site and contouring proved to be technically easy in these cases. The contouring allowed us to sculpt the implant into a cosmetically pleasing result in cases that involved the cranium, orbital rim, frontal sinus, and maxilla. Use of the biomaterial with titanium mesh enhanced the contouring and application of the biomaterials (patients 2, 12, 16, 23, 27, and 30), and in cranioplasty, the mesh served to protect the cement from the repetitive trauma of dural pulsations. AlloDerm was also successfully used with carbonated apatite to add bulk to a soft tissue defect overlying a bony defect (patient 12). In all cases, the cosmetic outcomes of our patients have been excellent and have persisted in follow-up from 2 to 48 months.

Four failures of the cement were encountered intraoperatively (patients 2, 3, 21, and 28). In patient 2, hydroxyapatite was used to reconstruct the orbital floor. The material crumbled, and its use was aborted. In patient 3, the hydroxyapatite crumbled in the setting phase and calvarial bone grafting was used in the defect (Figure 3). The hydroxyapatite used in these cases were the early formulations and not the commercially available reformulated hydroxyapatite. Another failure occurred with carbonated apatite in patient 21. Reformulated hydroxyapatite was then successfully used as a replacement. In the fourth failure, carbonated apatite failed in reconstruction of an orbital floor defect secondary to excessive fluid in the surgical field. No other alloplastic material was used as a substitute.

In this series, 6 patients (patients 14, 21, 22, 25, 26, and 27) developed infection at the reconstruction site. Half of the infections occurred with hydroxyapatite and the other half with carbonated apatite. Patient 14 underwent extensive resection of a nasoseptal squamous cell carcinoma. The patient had hydroxyapatite used to obliterate the frontal sinus. After radiation therapy, the patient had exposed hydroxyapatite. Despite intravenous antibiotics and hyperbaric oxygen therapy, the patient eventually underwent implant removal. Patient 21 underwent resection of a mandibular arteriovenous malformation. The patient’s outer cortex was reconstructed with hydroxyapatite cement. The patient developed an infection at the site presumably from a compromised tooth. The tooth was extracted, and long-term intravenous antibiotics were given. However, he eventually required explantation of the cement. Patient 22 had successful frontal sinus obliteration with carbonated apatite for an anterior and posterior frontal sinus fracture. Three months later, the patient presented with acute ethmoid sinusitis and supraorbital abscess. He underwent functional endoscopic sinus surgery and explantation of his carbonated apatite implant. At the time of explantation, the osteoplastic flap was found to be partially necrotic and was debrided in its entirety (Figure 4).

In patient 25, carbonated apatite was used to augment the anterior skull base after resection of sinonasal squamous cell carcinoma. The patient had eventual intranasal exposure of the biomaterial. In addition, he developed an epidural abscess that necessitated surgical drainage. He was treated with long-term intravenous antibiotics and hyperbaric oxygen therapy. Eventually, the nasal mucosa grew over the exposed biomaterial. Patient 26 had frontal sinus obliteration after a frontal sinus fracture. He eventually had exposure of the implant in the glabellar region. The patient received intravenous antibiotics and hyperbaric oxygen therapy. The exposed area was then closed successfully with local flaps. Patient 27 had hydroxyapatite implanted with titanium mesh to augment a preexisting orbital and malar defect after previous resection of an orbital rhabdomyosarcoma. The patient developed exposure of the biomaterial at the lateral orbit. Despite long-term intravenous antibiotics and hyperbaric oxygen therapy, the patient underwent surgical explantation.

In this series we encountered infection in 17% of our patients and 13% of our surgical sites. In all but 2 of the 6 patients, infected biomaterial necessitated explantation. Interestingly, all of the infections had exposure to the nasal or oral cavity.

One foreign body reaction was encountered in our series. Patient 24 had undergone a frontal craniotomy to repair a CSF leak. Carbonated apatite was used for frontal cranioplasty. The patient developed persistent forehead pain and was taken back to the operating room for V1 neurectomy. Loose particles of carbonated apatite were found causing inflammation and foreign body reaction.
around the nerve. The loose particles were removed, and the patient’s symptoms diminished. Other than the cases described above, no other implant has been removed.

One case of resorption was observed in patient 12. This has been a late finding and relatively minor in appearance. We have not encountered any growth retardation in any of the sites in our pediatric patients.

**COMMENT**

Hydroxyapatite and carbonated apatite cements are user friendly. They are easy to mix and contour to a defect. The currently available preparations set quickly and dependably. Both of the materials are equally effective in contouring ability and postoperative appearance. We have not seen significant contour changes develop postoperatively with either material. Both of these materials may also be used in conjunction with other alloplastic materials. For example, in patient 12, carbonated apatite was successfully used with AlloDerm for frontal cranioplasty with an associated soft tissue defect. The materials were also used in conjunction with titanium mesh for orbital floor reconstruction and cranioplasty. The use of hydroxyapatite and carbonated apatite cements in conjunction with other materials provides numerous possibilities for craniofacial reconstruction.

In addition to increasing the surgeon’s armamentarium, hydroxyapatite and carbonated apatite can theoretically decrease the cost of procedures. The materials save money in operative time required to harvest an autologous specimen. They also save in donor site morbidity. However, hydroxyapatite and carbonated apatite are not without cost or complications. The additional cost of their intraoperative and postoperative failures must also be taken into account.

In this series, we encountered intraoperative failures as well as postoperative infections. Intraoperative failures occurred in 4 cases (patients 2, 3, 21, and 28). The first 2 cases occurred before the development of the reformulated hydroxyapatite. During the long setting time, the hydroxyapatite began to crumble, presumably from the field being too wet. In patient 21, carbonated apatite failed to set. The reformulated hydroxyapatite was then used successfully in the repair. As this has only occurred once in our experience, it would be interesting to compare further failures with successful uses of alternative materials. The third case involved a wet field with limited exposure, and the use of the biomaterial was not feasible. Intraoperatively, hydroxyapatite has been easier to use in a wetter field since the emergence of the reformulated product. The reformulation has allowed for faster setting times by mixing the product in a 0.25M phosphate buffer. This has effectively decreased setting time and failure rate for the hydroxyapatite. Reformulated carbonated apatite has recently become commercially available as well. This new material will likely provide the same advantages as the reformulated hydroxyapatite.

Postoperative infections occurred in 13% of our operative sites. Three of the infections occurred with hydroxyapatite, and 3 of the infections occurred with carbonated apatite. It is suggested from these data that the incidence of infection is similar for both biomaterials. Friedman et al found an infection rate of 8% in their series of 38 patients who underwent frontal sinus obliteration or frontofacial reconstruction with hydroxyapatite. Friedman et al suggest that patients without significant history of frontal sinus disease (trauma patients) who undergo obliteration with hydroxyapatite are safe. The infection rate in our series was 3 (19%) of 16 in the cases of frontal sinus disease.
Both carbonated apatite and hydroxyapatite are equally effective in craniofacial reconstruction. Both biomaterials are user-friendly and easy to use with other alloplastic materials. No difference exists between the currently available preparations in terms of ease of use, contouring, or postoperative results. The incidence of infection in certain sites is significant. Use of the materials with exposure to the sinonasal or oral cavity places the implant at risk for infection. Caution is recommended when using the materials in these situations. An infected implant generally requires explantation. However, the use of long-term intravenous antibiotics and hyperbaric oxygen therapy have shown some benefit. These biomaterials add to the surgeon’s armamentarium in craniofacial reconstruction.

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