CHAPTER 10

RECONSTRUCTION OF FRONTAL SINUS FRACTURES

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Fractures of the frontal sinus are the third most common facial fracture, making up approximately 5%-12% of fractures of the maxillofacial skeleton.[19] They are most often the result of a high-energy impact to the upper third of the face. In order to sustain a frontal sinus area fracture, force must be generated greater than twice that needed to fracture the mandible and five times that needed to fracture the maxilla.[13] It is widely believed that the increased ability of the frontal sinus to withstand fracture is the result of the buttressing effects of its pneumatization and its thick anterior and thinner posterior plates of bone. As a direct consequence of the higher energy required to generate these fractures, associated intracranial and/ or cervical spine injuries are often seen and should always be diligently sought. Although many acute serious injuries can occur at the time of frontal sinus fractures, serious complications can also develop years later (e.g., mucoceles or mucopyoceles).

Motor vehicle accidents are the cause of frontal sinus fractures in more than 70% of cases.[18] With the increased use of seatbelts and airbags, the incidence of frontal sinus fractures is anticipated to decrease.

ANATOMICAL CONSIDERATIONS

During the fourth month of intrauterine life, the frontal sinus begins as a superior extension of the nasal capsule in the frontal recess. Generally, it is not radiographically identifiable until 2 to 3 years of age. Progressive pneumatization of the frontal bone continues until up to 20 years of age in most individuals. Considerable variability in pneumatization exists, ranging from extensive aeration to nonexistent frontal sinuses (in 5% of the normal population). The average dimensions of the frontal sinus are 2.8 × 2.7 × 1.7 cm, with a volume of approximately 7 ml (Figure 1).[7]

Several drainage patterns of the nasofrontal duct exist in the nasal cavity. In 55% of patients, the frontal sinus drains intranasally, anterior to the infundibulum of the osteomeatal complex (Figure 2). In the remainder, the nasofrontal duct drains either above (30%), directly into (14%), or posterior to (1%) the infundibulum.[17] Under normal circumstances, the frontal sinus is lined with respiratory type mucosa (ciliated, pseudostratified columnar epithelium) that is in direct continuity with the nasal mucosa. In the para-

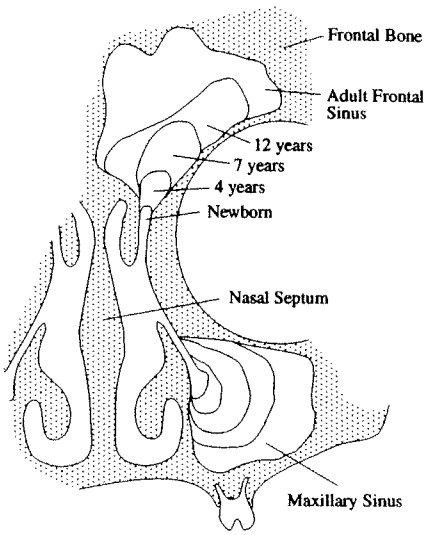

Figure 1: Coronal view of the development of the frontal sinus over time.

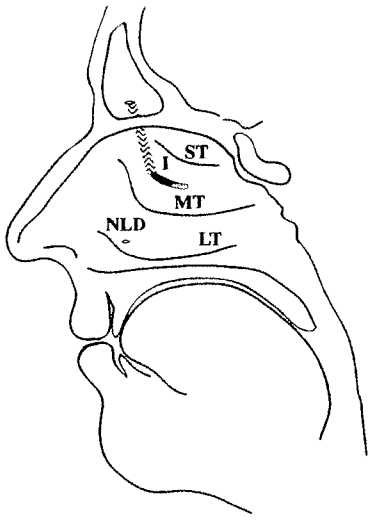

Figure 2: Sagittal view of the location of the nasofrontal duct (NLD) and its drainage into the middle meatus of the nose. ST = superior turbinate; MT = middle turbinate; LT= lower turbinate; I = infundibulum.

nasal sinuses, the ciliated epithelium propels a physiologically important bilaminar mucous blanket toward the naturally draining ostia, at an average rate of 1 cm per minute.[8] In the frontal sinus, retrograde mucociliary flow increases the risk of intranasal infection.[8] When the two different mucosal layers come into direct contact, disruption of the mucociliary clearance system exists, resulting in sludging and stasis of secretions at this transition zone. Under normal circumstances, the nasofrontal duct and frontal recess are widely patent. Following trauma to this area, partial obstruction of the nasofrontal duct occurs more commonly than complete bony obstruction. This partial narrowing results in stasis of the frontal sinus secretions and increases the risk of delayed frontal sinus infection.

The mucociliary drainage system of the frontal sinus is distinct from that of the other paranasal sinuses, in that it is susceptible to forming mucoceles when exposed to trauma.[5] Enlarging frontal sinus mucoceles, caused by the progressive accumulation of secretions within them, have a marked ability to erode bone. Some authors have also suggested a possible osteoclastic resorption of bone at the mucocele-bone interface.[5] Infection of mucoceles can result in the formation of mucopyoceles, leading to osteomyelitis and extracranial and intracranial empyema.

The blood supply to the frontal sinus is primarily from the supraorbital and anterior ethmoid branches of the ophthalmic artery. Venous drainage occurs through the external (angular and anterior facial veins) and the internal (superior ophthalmic veins) venous systems. In addition, the presence of numerous small foramina (of Breschet) within the posterior and superior walls of the frontal sinus allows for direct communication between vessels of the sinus mucosa and the subarachnoid space.[10] Within these foramina, the frontal sinus mucosa is tethered, necessitating careful intraoperative removal with rotating burrs during the obliteration or cranialization procedure. The term "cranialization" is used to indicate complete removal of the frontal sinus mucosa and posterior frontal sinus table. If not removed, this retained mucosa may result in future mucocele formation.

Clinical Assessment

Frontal sinus fractures are commonly associated with intracranial, orbital wall, malar, LeFort, and nasoethmoid injuries. Many patients with frontal sinus fractures lose consciousness follow-

ing the traumatic event. Pain, supraorbital/supratrochlear paresthesias, and epistaxis are often seen. Palpable disruption of the anterior table may be noted. However, a depressed anterior bony wall fracture may be obscured early after injury by tissue edema or by an overlying hematoma. Severe hemorrhage from a frontal sinus fracture should prompt one to strongly consider injury to the superior sagittal sinus.

If nasal or aural discharge is evident, cerebrospinal fluid (CSF) leakage needs to be ruled out. Historical tests for glucose concentration (greater than two thirds of serum levels) and observation of a positive "halo" sign are not as accurate as immunochemical estimation of β_2-transferrin content.[14] The β_2-transferrin test is most specific for CSF and is noted even in the presence of blood. However, it should be noted that β_2-transferrin is also elevated in the serum of cirrhotic patients. In such cases, with a known cirrhotic patient, CSF leakage can be evaluated with simultaneous serum and fluid leak assays for β_2-transferrin. If confirmation is required in localizing the site of CSF leakage, metrizamide computed tomography (CT) cisternography is helpful. Most CSF leaks from acute trauma will resolve on their own within 2 weeks. Pneumocephalus and meningitis are potential complications of nonsealing leaks. If a patient requires surgical repair of a frontal sinus fracture and an active CSF leak is found, it should be repaired. Repairing a dural tear primarily or with autogenous flaps or grafts (e.g., pericranium, temporalis fascia, or fascia lata) is usually sufficient. However, if the patient does not require surgical exploration for other reasons, conservative treatment of the leak is warranted. This treatment may vary from expectant observation to intermittent lumbar puncture drainage or placement of a lumbar drain. If conservative treatment fails to seal the leak after 2-3 weeks or the patient appears to be developing a complication, surgical intervention is warranted. Depending on the clinical scenario, there are various surgical approaches that may be utilized to repair the CSF leak, including extracranial (transethmoid, transnasal, transfrontal) or intracranial (transfrontal) approaches.

CT is the primary radiological means to evaluate patients suspected of having a frontal sinus fracture. Often, these patients undergo CT in search of cerebral or facial injury, and disruption of the frontal sinus is noted as an additional finding. An initial CT should be obtained as soon as possible after the trauma to assess craniocerebral injury and to rule out immediately life-threatening conditions such as intracerebral hemorrhage or tension pneumocele. Magnetic resonance (MR) imaging is less useful in the assessment of these injuries due to its inherent weaknesses in visualizing bony disruptions (fractures) and the logistical problems of transporting the intubated patient with multiple trauma in the physically confined space of MR scanners. Cerebral angiography need not be routinely obtained unless significant vascular injury is suspected. MR angiography (MRA) may be considered instead of angiography if required. However, MRA is subject to the same physical space constraints as those outlined for MR imaging. Intracranial pressure monitoring should be considered in patients who are comatose as a result of severe head injury.

Once there has been a thorough assessment of the patient and stabilization of imminently life-threatening injuries performed, a treatment plan should be formulated. In determining the best approach to frontal sinus fractures, one should attempt to classify the injury according to the sites involved. Generally, frontal sinus fractures may involve the anterior wall, the posterior wall, the nasofrontal duct, and/or the fronto-orbital region (floor).

Fractures of the anterior wall may be described as simple or compound, linear or comminuted, and nondisplaced or displaced (Figure 3). Posterior wall fractures are commonly displaced and comminuted, with a high incidence of CSF leakage. Injury to the nasofrontal duct area has traditionally been the most difficult to demonstrate radiologically. Frontonasal duct injury is found in approximately 45% of patients who have frontal sinus fractures.[19] Nasofrontal duct injuries usually occur in conjunction with other frontal sinus wall fractures. If frontal floor fractures are displaced, the bony fragments may be found within the frontal or ethmoid sinuses, or within the orbit. "Through and through" frontal sinus injuries imply disruption of both anterior and posterior sinus walls, with an increased association of dural tears and frontal lobe injury.

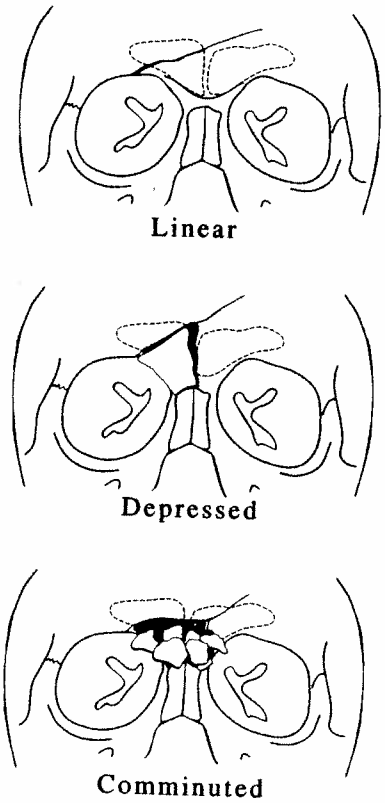

Figure 3: Types of anterior frontal bone fractures.

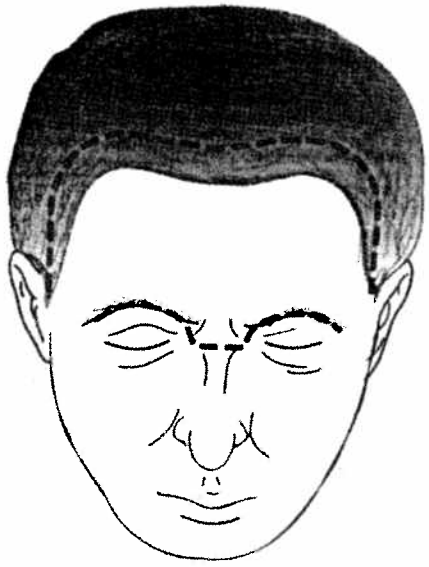

Figure 4: Options of skin incision to expose the frontal sinus: butterfly and coronal.

SITE-SPECIFIC TREATMENT

Anterior Wall Fractures

Anterior wall fractures are the most commonly involved subsite of frontal sinus fractures. Patients with isolated anterior wall fractures tend to have fewer and less serious associated injuries compared to other subsites.

An isolated, linear, nondepressed fracture of the anterior wall usually requires no specific treatment as long as no other sinus subsites are involved. Usually there is no cosmetic deformity, and long-term mucosal lining problems are generally not seen. On the other hand, depressed fractures of the anterior wall require exploration and reduction. Often, tissue edema or an overlying hematoma may camouflage what can undoubtedly become a significant cosmetic deformity. In untreated depressed anterior wall fractures, flattening and depression of the frontal area result in facial contour deformities. Furthermore, untreated depressed fragments impacted into the sinus increase the risks of mucocele formation. Accordingly, all depressed anterior wall fractures should be reduced.

General approaches to the frontal sinus include the coronal incision, mid-forehead incision, or butterfly incision (bilateral suprabrow incisions connected by a horizontal incision over the nasal bridge) (Figure 4). If a significant existing laceration of the forehead is present, one can utilize it for exposure. If exposure is inadequate, a pre-existing large laceration can be extended into one of the forehead creases. If a laceration is not of significant size (<5 cm), then one of the other approaches should be considered. The mid-forehead approach gives good exposure and is cosmetically acceptable in cases where there are deep forehead creases in which to place the incision; however, many trauma and assault victims are young and thus lack deep forehead creases, making this approach cosmetically less acceptable. In the case of an older patient, especially one with significant recession of the anterior hairline, this approach is excellent. The butterfly incision is the simplest and most direct approach to the area, giving excellent exposure. However, cosmetically it results in a more notice-

able scar as compared to the other approaches.

One of the most useful and common approaches for frontal sinus fractures is the coronal flap incision. It is cosmetically acceptable and provides excellent exposure. The coronal incision should be made 2-3 cm posterior to the anterior hairline. This results in a well-camouflaged scar. Some surgeons have advocated making the coronal incision closer to the vertex to avoid areas of anesthesia. However, with this more posterior incision, surgical exposure is much more limited at the level of the orbital rims. The coronal flap incision is made through the scalp, subcutaneous tissue, and galea. Dissection continues between the galea and pericranium to within 2 cm of the supraorbital rims, at which point an incision is made through the pericranium in order to allow for subpericranial dissection to preserve the supraorbital neurovascular bundles. Dissection is also acceptable. Subpericranial dissection is also acceptable. If a more extended lateral dissection is required, one should try to preserve the frontal branch of the facial nerve. This is best accomplished by dissecting superficial to the deep temporal fascia, down to the temporal line of fusion between the superficial and deep layers of the deep temporal fascia. At this level, if exposure of the zygomatic arch is needed, incision of the superficial layer of the deep temporal fascia exposes the superficial fat pad into which dissection may be safely taken down to the zygomatic arch. This technique will allow for more consistent preservation of the frontal branch of the facial nerve if this more extended lateral exposure is required.

Utilizing one of the above approaches should allow for complete visualization and access to any depressed anterior wall bone fragments. As much bone as possible should be preserved. Elevation of fracture fragments may be readily carried out with bone hooks. Any mucosa adjacent to the fracture line should be removed, preferably with a rotating burr, to prevent entrapment of mucosa. Prior to replacing the fractured bony fragments, one should thoroughly inspect the frontal sinus, especially the integrity of the posterior wall and the nasofrontal duct area. The nasofrontal duct area is especially difficult to evaluate on CT. Intraoperative evaluation consists of direct inspection as well as instillation of sterile solution dyed with methylene blue into the sinus. If the nasofrontal duct appears intact and there is good flow of dye into the nose, then concomitant nasofrontal duct injury is less likely. Once other subsites have been inspected and found to be normal, the bony fragments may be reduced and secured in good anatomical position with either 26-gauge wire or miniplates, according to the surgeon's preference (Figure 5). Exposure of bone should only be enough to perform fixation, since surrounding periosteum is important for bone vascularization. If there is inadequate bone present to reconstitute the anterior wall, split calvarial bone grafts can be used. These are readily harvested by dissecting posteriorly from the coronal flap incision to expose the superior parietal area of the skull, from which calvarial grafts are ideally taken. In most cases, bone gaps greater than 1.5 cm should be bone grafted to prevent subsequent deformity.

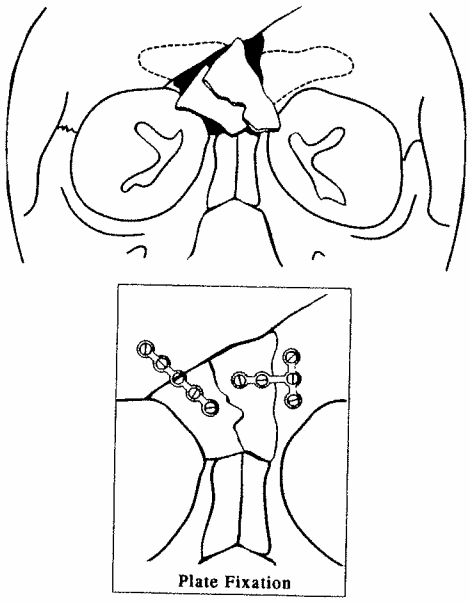

Figure 5: Comminuted anterior frontal sinus wall fracture with reduction and plate fixation.

Posterior Wall Fractures

Fractures of this subsite are generally associated with a significantly higher force per unit area than isolated anterior wall fractures. Thus, with this fracture, concomitant intracranial in-

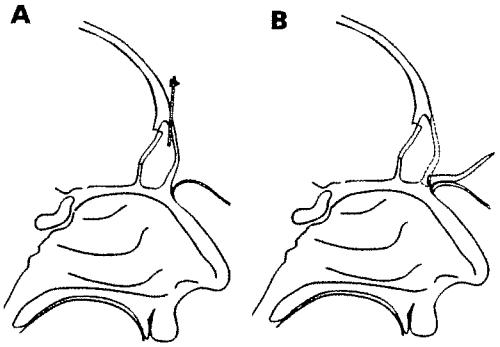

Figure 6: Osteoplastic flap approach to explore the frontal sinus. **A)** Osteotomy with the sagittal saw through the superior aspect of the frontal sinus. **B)** The bone flap being rotated down, keeping the periosteum attached inferiorly.

juries occur more often than with anterior wall fractures. In the case of anterior wall fractures, minor degrees of displacement are easily recognized on CT. This is not always the case with fractures of the posterior wall. Small, but nevertheless significant, degrees of displacement can be easily missed on CT. Given the fact that minor degrees of displacement can lead to entrapment of mucosa, failure to explore these patients may result in delayed intracranial complications, such as intracranial mucocele, brain abscess, or meningitis. In addition, nondisplaced posterior wall fractures may be associated with occult dural tears. Thus, in general, most posterior wall fractures should be explored. Only in rare instances in which an isolated posterior wall fracture is limited and nondisplaced or minimally displaced should the surgeon consider conservative management.

In the case of an intact or mostly intact anterior sinus wall, the best approach to the posterior wall fracture is by a standard osteoplastic flap[9] (Figure 6). In this approach, a 6-foot Caldwell facial x-ray view is obtained preoperatively to create a template of the frontal sinus. This template will be used intraoperatively to define the exact margins of the sinus for drilling the borders of the osteoplastic flap. Only 1 cm of periosteum around the margins of the bony cuts should be elevated, to allow for approximation of the periosteal edge during closure and to preserve blood supply to the underlying bone. Since Caldwell views give a 5% enlargement of sinus size, the osteotomy cuts should be made slightly within the boundaries of the template and angled obliquely toward the sinus cavity. This beveling serves not only to prevent inadvertent intracranial penetration, but allows for more accurate reapproximation of the osteoplastic flap at the end of the procedure. The flap, consisting of periosteum and bone of the anterior sinus wall, is freed from the intersinus septum and left pedicled to the periosteum inferiorly. After transposing the osteoplastic flap inferiorly, the frontal sinus and posterior wall fracture may be inspected.

When a simple, nondisplaced linear fracture of the posterior wall is encountered with no CSF leakage, controversy exists as to what is the best course of treatment. If the mucosa appears healthy and the nasofrontal duct area is undisturbed, then non-obliteration of the frontal sinus may be a reasonable choice with a good long-term outcome.[19] If there is any doubt regarding the reliability of follow-up, integrity of the nasofrontal duct, or health of the mucosa, one should proceed to obliterate the sinus.

Once obliteration of the frontal sinus has been decided upon, all frontal sinus mucosa should be meticulously removed. To remove any remnants of mucosa trapped within the foramina of Breschet, a rotating burr is used to drill away a 1-mm layer of bone inside the sinus. The mucosa of the nasofrontal duct area is then turned in on itself and the area is plugged with temporalis muscle or fascial graft (Figure 7). At this point, the sinus may be safely obliterated with subcutaneous fat, harvested from the left lower quadrant of the abdomen to avoid any confusion with an appendectomy scar in patients who have not undergone an earlier appendectomy. Right-sided removal may be performed if the patient has already undergone an appendectomy. Cancellous iliac bone chips or a pericranial flap are also efficacious in obliteration. The osteoplastic flap is then placed back in its original position and secured with either wires or miniplates.

During fracture repair, any loose, nonattached, or devitalized fragments of posterior wall bone should be removed. In doing so, fractures with significant comminution will result in significant defects in the posterior wall. When more than 25% of the bone of the posterior wall

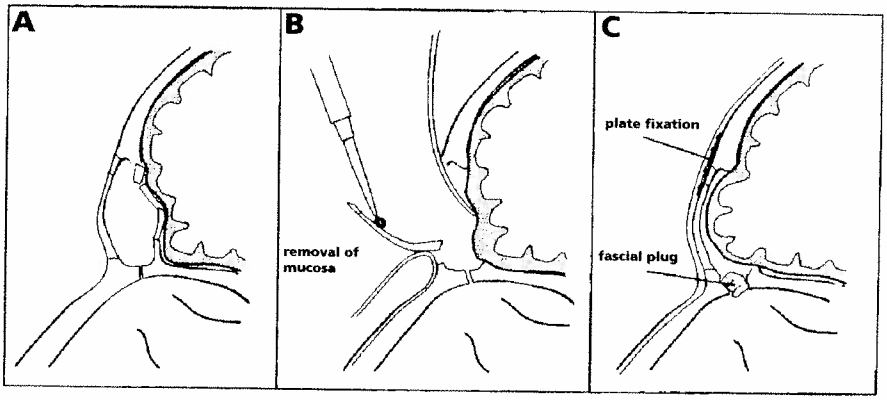

Figure 7: Cranialization of the frontal sinus. **A)** Comminution of the posterior wall in the frontal sinus. **B)** Removal of all of the mucosal remnants in the sinus and the posterior sinus wall. **C)** The nasofrontal duct is plugged with fascia and the frontal lobe is allowed to expand.

is missing, significant fat graft resorption occurs within the frontal sinus.[4] If significant fat resorption occurs, the dead space can become reepithelialized, infected, and prone to mucocele formation. Thus, with greater than 25% posterior wall defects or severe comminution, cranialization of the frontal sinus should be strongly considered. As outlined previously, the mucosa needs to be completely removed and the nasofrontal duct area closed. Complete removal of the posterior wall will allow for obliteration of the dead space by expansion of intracranial contents to fill the void.[3] The disadvantage of cranialization is that the anterior cranial fossa will be situated above the nasofrontal duct, thus potentially exposing the intracranial cavity to the respiratory tract.

During exploration, CSF leakage should always be ruled out or, if present, the dural tear repaired. In cases of a linear dural tear, simple reapproximation is usually adequate. In more complex tears, temporalis fascia or fascia lata grafts should be considered to ensure a watertight closure.

Nasofrontal Duct Injury

Fractures at the inferior wall of the frontal sinus are notoriously difficult to diagnose from CT scans or plain x-rays. Unsuspected disruption may be noted during sinus exploration for fracture of other subsites. Inferior frontal wall fractures are considered to be fractures of the anterior skull base. Potential injuries from inferior wall fractures include nasofrontal duct obstruction and disruption of the cribriform plate, orbital plates, and sphenoid. The possibility of nasofrontal duct injury should be suspected when there is persistence of an air-fluid level within the frontal sinus for more than 2 weeks after trauma. A unilateral air-fluid level implies patency of the contralateral nasofrontal duct. Initially, unilateral nasofrontal duct injury can be managed conservatively. In some instances, removal of the intersinus septum may be required to allow for both frontal sinuses to drain into the unobstructed duct. Removal of the septum can be performed by an enlarged trephination port or by an osteoplastic flap. The latter technique allows for wider exposure and is usually recommended. One can also manage unilateral nasofrontal duct obstruction with sinus obliteration as previously described.

When disruption of both nasofrontal ducts is evident during exploration or is implied by persistent bilateral air-fluid levels, complete sinus obliteration should be performed. Attempts to surgically reconstruct the nasofrontal duct have a failure rate of approximately 30% due to delayed scar formation and stenosis.[1] In fact,

Schenck[15] has suggested that procedures designed to maintain the patency of the nasofrontal duct during frontal sinus trauma should be considered of historical interest due to high failure rates. A nasofrontal duct repair should be considered only in instances in which the fracture is nondisplaced and limited, and the surgeon can easily enlarge the orifice with a stent or mucosal flap.

An alternative to obliteration of the frontal sinus is to remove the sinus in its entirety by Reidel's method or one of its modifications. However, significant disadvantages include severe frontal contour disfigurement, increased frontal lobe vulnerability, and the need for secondary surgery to restore normal frontal contour. This very aggressive approach of removing the entire sinus is not commonly performed. However, it remains a safe technique when the more conservative procedures cannot be performed.

"Through and Through" Injury

This severe type of injury implies penetration and complete violation of the frontal sinus with consequent exposure of brain and dura. The majority of these unfortunate patients die immediately or shortly after the injury. Direct brain parenchymal injury is commonly present. In most instances, these patients undergo a frontal craniotomy as part of the initial management in order to remove necrotic brain tissue, control hemorrhage, and repair any dural defects. With this type of injury, cranialization of the frontal sinus is usually performed. The posterior wall should be removed with a rongeur or cutting burr. Removal with a burr may allow for the larger bone fragments to be used for anterior wall reconstruction. After thorough removal of mucosa from these bone fragments, they should be placed in an iodine solution during the operative procedure, along with any loose anterior wall fragments. Prior to reinsertion into the patient, the bone fragments should be rinsed in sterile saline solution to avoid the tissue irritative effects of iodine. For primary skull reconstruction, it has been shown to be quite safe to use contaminated fragments of skull bone when cleaned in the manner described above.[12] One can also harvest calvarial bone grafts either from the outer table in the parietal area or from the inner table of the frontal craniotomy bone window flap.

After cranialization, the dura and injured brain will usually expand, filling the empty space left by removal of the posterior wall of the frontal sinus. On occasion, when excessive devitalized brain parenchyma requires removal, a significant dead space may be created in the anterior cranial fossa. In this case, if the dead space cannot be filled completely, cranialization should be avoided, as it would result in further expansion of the empty void. In this circumstance, free adipose tissue grafts can be placed to obliterate this dead space. However, one should also place these grafts in conjunction with a well-vascularized flap (e.g., a pericranial flap, a galeal-frontalis flap, or a temporalis muscle flap) to prevent atrophy of the adipose tissue.[16] Adherence to these techniques can give favorable outcomes with minimal complications[18] (Figure 8).

For compound fractures, the most common organism leading to infection is *Staphylococcus aureus*.[2] In one prospective study investigating prophylactic antibiotics in open and basilar skull fractures, the incidence of infection in the antibiotic-treated group was 0.9% versus 8.7% in the untreated control group.[2] Although not a substitute for early wound exploration, prophylactic antibiotics should be considered for through and through injuries of the frontal sinus.

Orbitofrontal Injury

Penetrating orbitofrontal wounds deserve early ophthalmological consultation. One should carefully consider the possibility of foreign material implanted in either the orbit or intracranial cavity. Noteworthy is the paucity of radiological findings with implanted wood fragments. These are associated with high rates of infection and should always be searched for during exploration in the appropriate clinical setting.[11]

These combined injuries are usually best explored through a coronal flap approach and a fronto-orbital craniotomy. The orbit may be explored by removing the superior and lateral orbital walls as a free graft and replacing these grafts at the termination of the procedure. Subsequent intraoperative findings will dictate the specific procedures required.

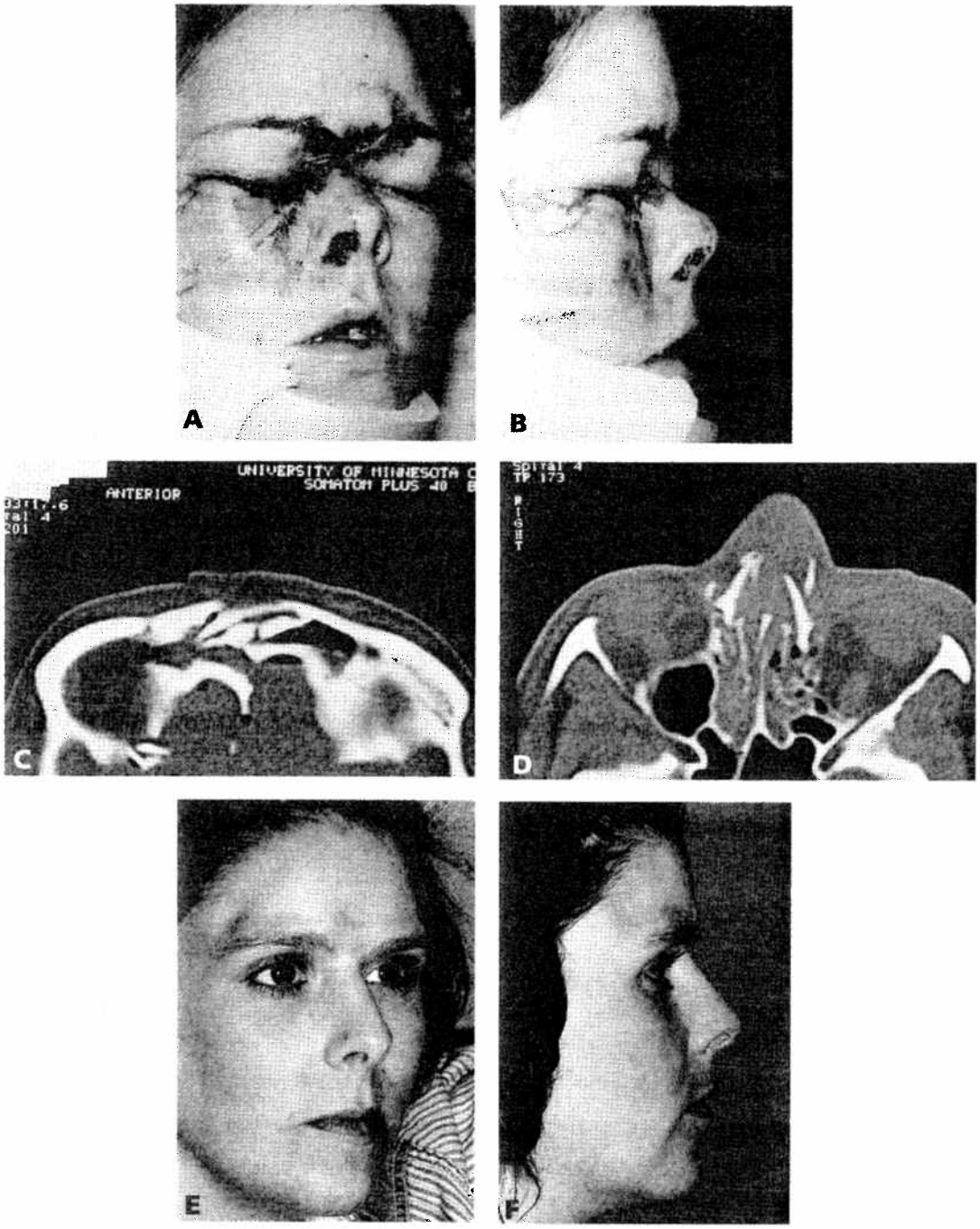

Figure 8: Photographs of a 29-year-old woman involved in a motor vehicle accident, who sustained an open, comminuted, through and through, frontobasilar nasal ethmoid complex fracture. **A** and **B)** Preoperative views (oblique and lateral). **C** and **D)** CT scans of the frontal and ethmoid sinuses (axial views). **E** and **F)** Post-operative views (oblique and lateral). (Courtesy of David B. Hom, MD)

Late Repair of Frontal Defects and Long-Term Follow-Up

Even with good planning and meticulous intraoperative technique, poor frontal contour or frank frontal deformity can occur. If the patient desires to undergo esthetic reconstruction of the defect, the preferred method of reconstruction is the use of autogenous grafts. Calvarial bone grafts and rib grafts have been used with good success.[6] If autografts are of insufficient quantity, one can consider the use of alloplasts. Historically, methyl methacrylate has been commonly used since it can be molded in situ. However, shortcomings include its exothermic reaction during mixing and increased risks for delayed infection. Silastic blocks were used in the past, but provide a less than ideal long-term esthetic result. It is important to note that reconstruction utilizing autogenous material can be carried out soon after the initial injury and repair. This is in sharp contrast to reconstruction with alloplasts, which generally should be delayed for at least 18 months.[6]

Over time, fat grafts within the frontal sinus can be absorbed and lead to mucocele formation. Mucosa from the nasofrontal duct can grow into the sinus and, without adequate drainage, mucoceles or mucopyoceles can develop. Thus, if the fat is resorbed, the frontal sinus must be followed over several decades by serial radiographs to detect any evidence of chronic sinusitis or mucocele formation.

Conclusion

Frontal sinus fractures should be approached by considering the specific subsites of the sinus that is affected. Treatment should be tailored to the needs of the patient, based on careful preoperative planning and imaging. Wide exposure is usually best achieved via the coronal flap. Intraoperative findings may dictate a change in the surgeon's plan; thus, detailed preoperative contingency plans should be part of the informed consent. If not adequately recognized and treated, frontal sinus fractures can result in the long-term sequela of mucocele formation.

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