Multilayer Anterior Skull Base Reconstruction with Cortical Rib Bone Graft: Preliminary Experience

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■ OBJECTIVE: **During the past decades, different methods have been described for anterior skull base reconstruction. Regarding larger skull base defects, few investigators have described the use of bone grafts to foster support and prevent frontal lobe sagging, herniation, or falling. The aim of this study is to describe the use of a rib bone graft, which could be an option in these cases due to its rigidity and dimensions.**

■ METHODS: **We retrospectively collected preoperative, intraoperative, and postoperative data at the last follow-up of 10 patients who underwent multilayer anterior skull base reconstruction, including rib bone graft, for large anterior cranial base defects at 2 tertiary care academic hospitals.**

■ RESULTS: **Eight patients underwent endoscopic craniectomy for sinonasal malignancies, and the other two underwent transnasal endoscopic surgery for congenital meningoencephalocele. Anterior skull base defects measured on average 3.8 cm ± 0.9 SD antero-posteriorly (range 2.5–5 cm) and 2.3 ± 0.9 SD latero-laterally (range 0.9–4 cm). Multilayer reconstruction was performed in all cases, including a rib bone graft positioned as intracranial extradural layer. No patient experienced thoracic complications during the postoperative period. No side effects related to the bone graft or meningoencephalocele occurrence were reported after a mean follow-up of 8.0 ± 6.3 months.**

■ CONCLUSIONS: **The use of a cortical rib bone graft could be a safe and effective option in skull base reconstruction when managing large defects after cancer removal.**

INTRODUCTION

The primary aim of anterior skull base reconstruction is to provide a safe and effective separation between the sinonasal tract and intracranial compartment to reduce potentially life-threatening complications such as meningitis, tension pneumocephalus, and abscess formation.[1] In the last few decades, the transnasal endoscopic route has achieved consensus for the treatment of benign and malignant tumors of the ventral skull base and anterior skull base repair for spontaneous, post-traumatic, and iatrogenic cerebrospinal fluid (CSF) leakage. In the recent past, before the introduction of vascularized flaps, the transnasal endoscopic technique's failure rate was as high as 30%–40%.[2] Most small skull base defects (<1 cm; most commonly encountered during CSF fistula closure after trauma and iatrogenic injury) are reliably repaired using multilayered free grafts with rates of success >90% and minimal differences between methods or the material used.[3,4] For larger skull base defects (>3 cm), the materials used for free graft repairs have included turbinate mucosa, cadaveric pericardium,[5] acellular dermis,[6] fascia lata, and iliotibial tract. However, free graft repair of large skull base defect usually leads to a high rate of CSF leak (>30%).[5-7]

Key words
- Anterior
- Cranial fossa
- Endoscopic endonasal surgery
- Multilayer reconstruction
- Sinonasal malignancy
- Skull base
- Skull base reconstruction

Abbreviations and Acronyms
CSF: Cerebrospinal fluid
CT: Computed tomography

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The advent of the vascularized flaps, such as the nasoseptal flap, has drastically diminished the rate of postoperative complications for large anterior cranial base defect repair, reaching a rate of CSF leak of <6%.[8-10] This achievement has been strikingly evident for high-flow CSF fistula repair, for which the postoperative failure rate has decreased from 18% to 6%.[11] However, vascularized flaps, together with the most used free graft (e.g., iliotibial tract, fascia lata, autologous fat), do not provide rigid support to the frontal lobe and could expose the brain to some degree of herniation or sagging inside the nasal cavity, especially for larger defects. In this setting, a few investigators have described the use of bone grafts to foster support in skull base reconstruction and providing a certain degree of rigidity.[12-15] Fiacchini et al.[16] recently reported that the risk of frontal lobe sagging, herniation, or falling increases with multilayer reconstruction using both fascia lata and pericranial flaps as the dimension of the cranial defect increases.

The use of both heterologous and autologous rigid materials for skull base repair has been proposed by some investigators, albeit they reported limited indications and possible disadvantages such as a delayed healing, graft migration with possible nearby structure damage (e.g., titanium mesh),[17] a low coverage area and unavailability because of direct tumor invasion (e.g., septal bone or cartilage graft),[18] and/or high rates of donor site morbidity (e.g., calvarium bone).[12] In such settings, the use of distant autologous rigid material, which can also be harvested as a large graft, might be useful in preventing frontal lobe herniation to reduce neural involvement into an adjuvant radiation field.

We present a multilayer technique for skull base repair that includes the use of a rib cortical bone graft in 10 patients who underwent anterior cranial base reconstruction for different skull base diseases.

METHODS

Patients gave their full written informed consent to participate in our study. The project conforms to the code of ethics of the World Medical Association and was conducted in accordance with the guidelines of the Declaration of Helsinki. The local institutional review board approved the present study.

A retrospective medical record review was performed to identify patients who had undergone multilayer anterior cranial base repair using cortical rib bone at 2 tertiary care academic hospitals during the previous 3 years (2019–2022) by the senior author (L.P.). Ten patients were identified, and data about age, sex, body mass index, radiological presence of idiopathic intracranial hypertension (i.e., empty sella, distension of the optic nerve sheath, optic nerve tortuosity, posterior globe flattening, transverse sinus stenosis), obesity, multiple skull base defects, histologic findings, reconstruction type, and complications involving both the endonasal and the thoracic donor sites were collected. The cortical rib bone was used in a multilayer fashion to repair anterior cranial base defects after surgical resection of either neoplastic or congenital masses. In those cases, traditional repair with vascularized flaps or free grafts was unavailable for several reasons (i.e., septal infiltration) or was deemed inadequate to provide cerebral or dural support. Intraoperative variables, such as defect size and intracranial and extracranial reconstruction materials, were also collected.

Surgical Technique

A transnasal endoscopic approach was used for all cases. Due to the large size of the defects, the reconstruction was performed in a multilayer fashion with a combination of underlay and overlay positioning of free and vascularized flaps, including a cortical bone graft taken from a rib in all cases. The rib bone was grafted from 1 of the last 2 fixed ribs (sixth or seventh rib). A thoracic incision was performed, and only the outer cortical part of the rib was grafted without full-thickness interruption using a diamond burr, hammer, and chisel. The cortical rib bone graft was then modeled in length, width, and thickness to fit the defect using a drill and forceps (Figure 1). The mucosa was removed a few millimeters around the bony skull base defect during reconstruction to avoid the risk of postoperative intracranial mucocele development.[19]

Dural reconstruction was achieved using allografts, such as Duraform,[18] Redura,[20] or bovine pericardium in an inlay fashion. Next, the rib cortical bone graft was placed as an extradural intracranial support of dural reconstruction (Figure 2) after detaching the dura of the anterior skull base a few millimeters around the defect to provide stable positioning of the graft. The graft was first inserted posteriorly above the planum sphenoidale, lifted with a sickle knife until becoming intracranial, and then pulled anteriorly between the frontal lobe dura and frontal bone. The graft was then secured in place and fixed with small pieces of oxidized regenerated cellulose all around between the graft and the skull base resection borders to avoid postoperative displacement. Moreover, the average size of the autologous bone was approximately 3 mm longer than the skull base defect to achieve a stable position and restore the anterior cranial fossa floor shape. Those surgical maneuvers were performed by either the leading surgeon or with good use of a 2-nostril, 4-hand approach, depending on the extent of resection of the endonasal structures.[21,22]

After rib bone graft positioning, the third layer was chosen according to the neoplastic extension and histologic findings. A pedicled nasoseptal septal graft was used, when suitable, to obtain faster healing. When this graft could not be used (e.g., direct tumor invasion, risk of field cancerogenity), other grafts were used, such as the fascia lata or free mucoperiosteal flap. The entire reconstruction was then sealed with fibrin glue, oxidized regenerated cellulose pieces, and Gelfoam sponges (Pfizer, New York, New York, USA). The steps and layers of the multilayer repair are shown in Figure 3.

Postoperative Management

After surgery, all the patients were instructed to comply with 72 hours of bed rest and 48 hours of antibiotic therapy. None of the patients had lumbar drainage placed. Carbonic anhydrase inhibitors through oral administration (250 mg, 2 times a day) were given for 72 hours to all patients unless they had medical contraindications. Stool softeners (lactulose, 2 spoons 2 times a day) can also be administered, and patients should be counseled to sneeze with an open mouth. In accordance with the study by Eloy et al.,[23] the size of the anterior cranial fossa defect was calculated based on the bony defect identified on postoperative computed

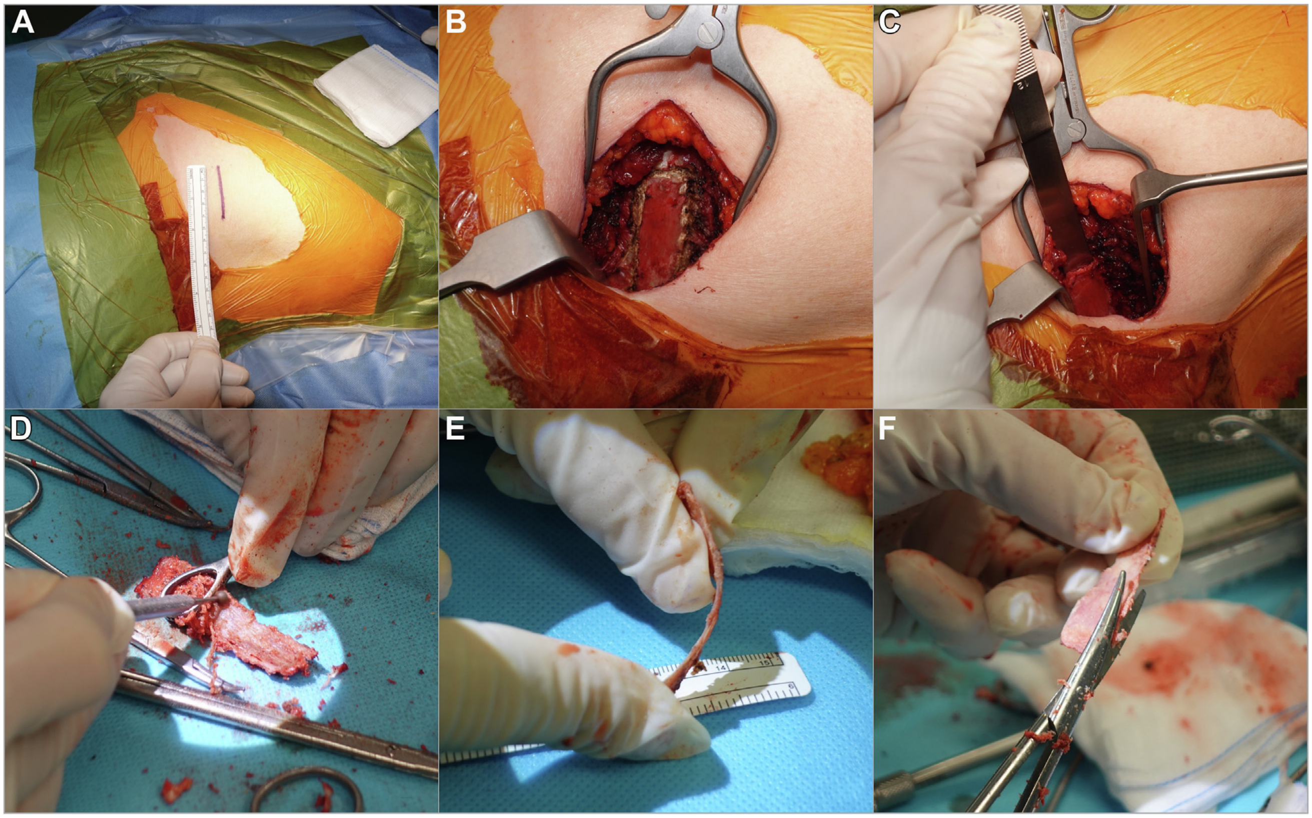

Figure 1. Cortical rib bone graft harvesting and remodeling. (**A**) Sterile field setup, marking of incision, and measurement. (**B**) Incision of subcutaneous layer and rib exposure (sixth or seventh rib bone preferably chosen). (**C**) Definition of margins of the graft with a diamond burr and detachment of the cortical rib portion from the medullary using a hammer and chisel. (**D**) Remodeling of the graft with a diamond burr. (**E**) Cortical rib bone graft flexibility allowing for reconstruction of the physiological curve of the anterior skull base. (**F**) Final remodeling of the graft margins with scissors.

tomography (CT) scans. Patients were advised to avoid nose blowing and any activity that could increase intracranial pressure, such as abdominal straining, leaning forward, or lifting items heavier than 15 lb. A postoperative CT scan was performed 24–48 hours after surgery (**Figure 4**) and again after 2 months to check the status of the reconstruction. The cases of patients with anterior skull base malignancies that required endoscopic craniectomy were systematically discussed by a multidisciplinary board to define the optimal treatment and eventually the adjuvant therapies. The postoperative outcomes were collected from the follow-up evaluations, with both endonasal and thoracic wall status recorded. In addition, pain, numbness, activity restrictions, and the cosmetic appearance of the donor site were estimated using a 10-point visual analog scale.

RESULTS

Ten patients (8 males and 2 females) matched the inclusion criteria. The mean age was 49.9 years (range, 12–80 years), and the body mass index was 26.9 ± 4.0 kg/m². Two patients presented with preoperative radiological signs compatible with intracranial hypertension (e.g., empty sella, distension of the optic nerve sheath, optic nerve tortuosity, posterior globe flattening, transverse sinus stenosis). One patient had previously undergone

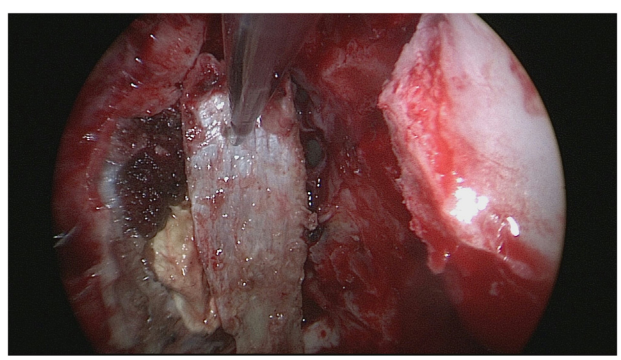

Figure 2. Remodeled cortical rib bone graft.

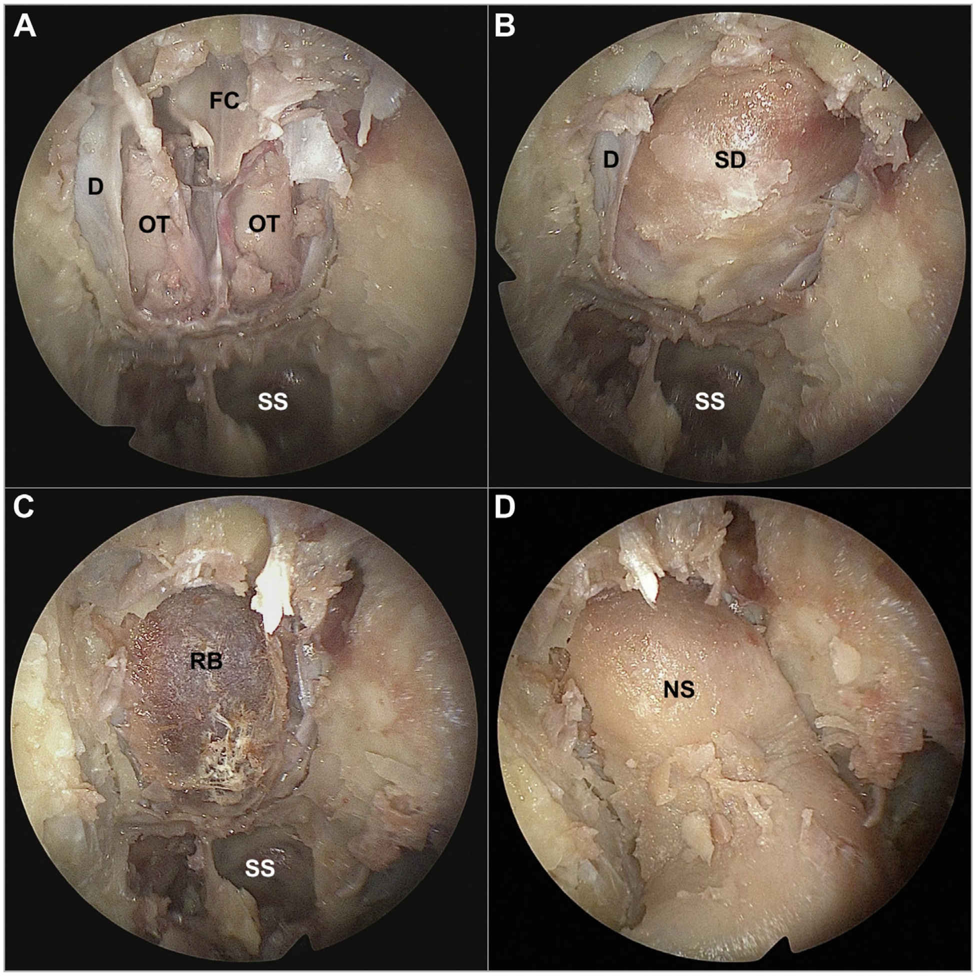

Figure 3. Ex vivo reconstruction in multilayer fashion. (**A**) Frontal lobe and olfactory tract exposure after crista galli removal. Multilayer anterior skull base reconstruction showing (**B**) intracranial intradural layer with free septal mucoperichondrium flap (heterologous dural substitute in in vivo case), (**C**) intracranial extradural layer with cortical rib bone graft, and (**D**) extracranial extradural layer with Hadad nasoseptal flap. D, dura; FC, falx cerebri; NS, nasoseptal flap; OT, olfactory tract; RB, cortical rib bone graft; SD, synthetic dura; SS, sphenoidal sinus.

neoadjuvant chemotherapy for sinonasal undifferentiated carcinoma. Only 1 patient had previously undergone sinonasal surgery for chronic rhinosinusitis with polyps.

Eight patients (80%) underwent endoscopic craniectomy for a sinonasal malignancy, and 2 (20%) underwent transnasal endoscopic resection of a congenital meningoencephalocele involving the anterior and posterior ethmoidal roof. The anterior skull base defects measured 3.8 $\pm$ 0.9 cm (range, 2.5–5 cm) anteroposteriorly and 2.5 $\pm$ 0.9 cm (range, 0.9–4 cm) laterally. The consequent defect area measured 9.8 $\pm$ 5.3 cm^2, with a maximal area of 20 cm^2 (**Table 1**).

Multilayer reconstruction included 3 different grafting materials: nonautologous tissue (heterologous dural substitute) as the intracranial intradural layer, a costal rib bone graft as the intracranial extradural layer, and a pedicled nasoseptal flap, free mucoperiosteal graft, or autologous fascia lata graft for the extradural extracranial layer in 7, 1, and 2 patients, respectively.[8,24,25] All patients affected by intestinal type adenocarcinoma underwent reconstruction with an autologous fascia lata graft as the third layer because of the risk of field cancerization of the mucosa.

No intraoperative complications regarding either the donor site or the endonasal or intracranial compartment were observed. An immediate postoperative CSF leak occurred in 1 patient treated for ethmoidal squamous cell carcinoma, which was conservatively managed with bed rest for 3 days. Early revision surgery was required for 1 patient, although asymptomatic, because early displacement of the cortical rib bone graft was observed on the

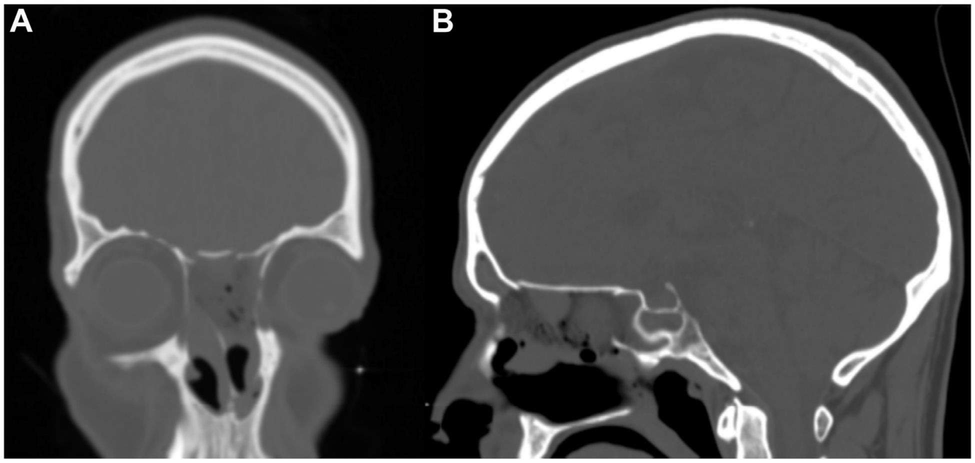

Figure 4. Postoperative computed tomography scan. (**A**) Coronal view. (**B**) Sagittal view.

postoperative CT scan. However, that was the first case performed, the graft edges were not sufficiently packed, and the patient did not comply with the 72 hours of bedrest after surgery. No patient experienced thoracic complications (e.g., chest wall hematoma, pneumothorax) during the postoperative period. A skin infection of the donor site wound was observed in 2 patients, both successfully treated with oral antibiotics.

The patients were discharged after 17.3 days on average (range, 7–52 days; median, 10 days). This was because 3 patients had required a longer hospital stay because they had developed general medical problems (i.e., renal insufficiency, ischemic heart disease) not related to the surgical procedure. The 2-month postoperative CT scan showed a regular multilayer reconstruction position with no signs of graft necrosis (Figure 5). Patients affected by a sinonasal malignancy underwent postoperative radiation therapy in accordance with the histologic findings and tumor grade and stage. No side effects in the endonasal or intracranial compartment or donor site were reported after a mean follow-up of 8.0 months (range, 2–21 months; Table 2). Crusting was observed for the first 6–12 weeks, with complete endonasal mucosal healing in all patients at the last follow-up visit (Figure 6). In this series, no patient reported restrictions in activity or donor site pain at the last follow-up. The degree of paresthesia reported by the patients was grade I in 4 patients, and 3 patients reported grade II in cosmetic appearance using the 10-point visual analog scale.

Table 1. Skull Base Pathology and Defect

Pt. No.	Pathology	Anteroposterior Defect (cm)	Lateral Defect (cm)	Area (cm^2)
1	Congenital meningoencephalocele	2.5	0.9	2.1
2	Congenital meningoencephalocele	3	1.6	4.7
3	SNUC	3.5	3	10.4
4	ONB	5	2.8	13.8
5	ACC	5	4	20
6	SCC	5	3	15
7	SNUC	3.3	2.2	9.1
8	ITAC	3.5	2.6	7.3
9	ONB	3.2	2.2	7.1
10	ITAC	3.9	2.2	8.6
Mean	NA	3.8	2.5	9.8

SNUC, sinonasal undifferentiated carcinoma; ONB olfactory neuroblastoma; ACC acinic cell carcinoma; SCC squamous cell carcinoma; ITAC intestinal type adenocarcinoma; NA, not applicable.

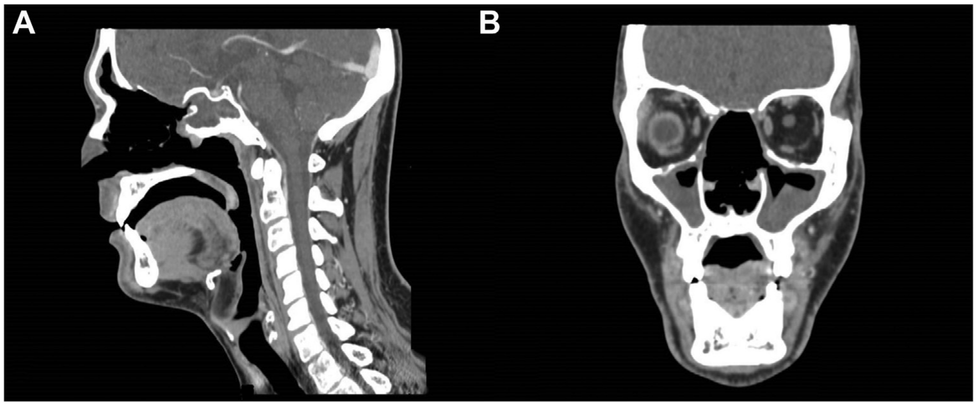

Figure 5. Follow-up computed tomography scan. (**A**) Sagittal view showing rib bone graft covering the entire skull base defect from the posterior wall of the frontal sinus to the planum sphenoidale, reproducing the cribriform plate profile. (**B**) Coronal view of the same patient showing the rib bone graft covering the anterior skull base from orbit to orbit.

DISCUSSION

The endoscopic technique has increased in popularity in the treatment of neoplasms and reconstruction of the anterior skull base. Its indications have expanded to include resection of large skull base defects extending from medial orbital wall to both sides laterally and from the posterior wall of the frontal sinus to the planum sphenoidale anteroposteriorly. However, for such anterior skull base defects, reconstruction free graft techniques showed unacceptable rates of CSF leak.[2] Therefore, pedicled flaps, such as the nasoseptal flap, have undoubtedly become the workhorse of anterior cranial base reconstruction, significantly reducing the postoperative CSF leak rate.[10,26,27] Currently, large skull base defects are widely repaired using a multilayered fashion technique[16] with autologous material (e.g., fascia lata, fat, iliotibial tract, calvarial bone, vomer)[12,13,15,16,28] or heterologous material (i.e., acellular dermal allografts, bovine pericardium, Redura, Duraform, titanium mesh, Medpor),[6,20] together with local or regional flaps (i.e., nasoseptal flap, pericranial flap).[14,15,29,30]

Although Eloy et al.[23] postulated that rigid material reconstruction is not necessary to obtain safe and effective skull base reconstruction, many investigators have suggested the use of rigid materials to better sustain the frontal lobes, preventing possible complications.[31,32] However, some investigators have argued that the use of rigid materials might be associated with a risk of major neurovascular complications due to graft displacement. In the present series, we did not observe any neural or vascular complications nor any signs of graft

Table 2. Demographic, Oncological, Reconstructive, and Follow-Up Data

Sex	Age (years)	Histopathologic Finding	Stage	Adjuvant RT	Complication	Hospital Stay (days)	Follow-Up (days)
Male	12	ME	NA	No	Donor site infection	7	102
Male	54	SNUC	CT4aN0M0	No	No	7	16
Female	27	ME	NA	No	No	8	152
Male	53	ENB	CT4aN0M0	Yes	No	9	621
Male	78	SCC	CT4aN0M0	Yes	CSF leak	52	175
Male	47	ACC	CT4aN0M0	Yes	Donor site infection	38	302
Female	64	ITAC	CT4aN0M0	Yes	No	12	157
Male	31	SNUC	CT4bN0M0	Yes	No	11	254
Male	80	ENB	CT4bN0M0	No	No	21	73
Male	53	ITAC	cT4bN0M0	Yes	No	8	38

RT, radiotherapy; NA, not applicable; ME, meningoencephalocele; SNUC, sinonasal undifferentiated cancer; ENB, esthesioneuroblastoma; SCC, squamous cell carcinoma; ACC, adenoid cystic carcinoma; ITAC, intestinal type adenocarcinoma.

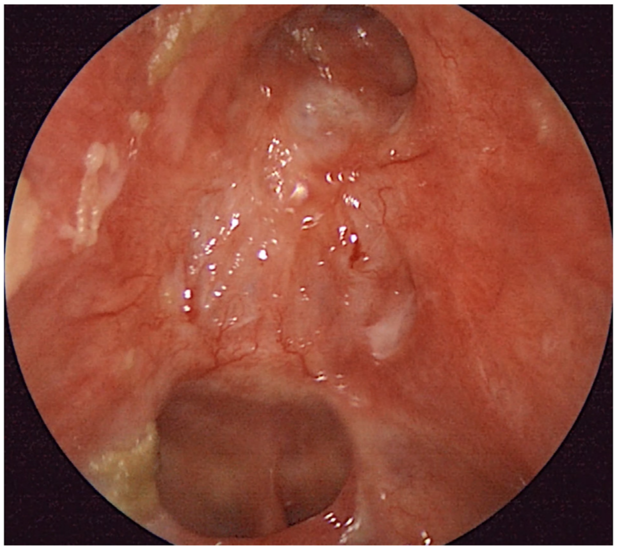

Figure 6. Endoscopic view of anterior skull base reconstruction after mucosal healing.

displacement on the last CT scan. This result might be because other rigid materials used in the literature have limited capacity of integration or had not been adequately remodeled. In contrast, the cortical rib bone graft can be adequately thinned, preserving its rigidity and reproducing the original profile of the cribriform plate. The cortical rib bone graft can be personalized according to the size of the anterior cranial fossa defect to properly fill the anteroposterior gap between the frontal bone and the planum sphenoidale. Moreover, the mass effect of the frontal lobe facilitates stabilization of the graft on the floor of the anterior cranial fossa defect's edges, avoiding any risk of migration.

The main complications after skull base repair include not only CSF leak but also brain and meninges herniation (i.e., arachnoidocele), resulting in an increased risk of meningitis and chronic headache. Moreover, when adjuvant radiotherapy is administered, brain descent into the endonasal field could increase the radiation dose over the cerebral structures, potentially leading to unnecessary side effects.

Fiacchini et al.[16] measured the degree of frontal lobe sagging after large skull base reconstruction and reported that with both pericranial flap and multilayer reconstruction, the degree of sagging and frontal lobe herniation increased with increases in the area of the defect. Moreover, they identified an area of 12 cm^2 as the "turning point," which also limited the postoperative outcomes with a pericranial flap, suggesting the necessity for the use of rigid material to sustain the reconstruction.

In our series, the anterior skull base area defect measured 9.8 cm^2, on average, with a maximum area of 20 cm^2, with 8 of 10 patients affected by cancer. In this setting, the rib bone graft can achieve satisfactory coverage of large anterior skull base defects, providing adequate rigidity and reproducing the original anterior skull base shape. This reconstructive strategy might reduce the risk of meningoencephalocele and frontal lobe exposure to the radiation therapy field. Heterologous rigid materials as Medpor[33] or titanium mesh[17] might provide good functional results but could also be associated with an increased risk of infection and healing delays.[34] Some investigators have suggested that autologous bone grafts are the most suitable option for rigid reconstruction and consider the nasal septum bone the most suitable.[35,36] However, harvesting a sufficiently large autologous bone graft from the nasal septum is usually difficult. In addition, the septal bone does not conform to the bone defect contour.[37] Finally, when infiltrated or close to the malignancy, it might not be an oncologically sound reconstructive choice. Calvarium provides large dimensions and good functional outcomes, and has been used by some investigators with regional flaps, leading to a better blood supply provided by the flap encircling the bone graft.[14,38] However, it requires a coronal incision and thus is associated with severe local morbidities. Different investigators have reported that costal cartilage or bone grafting is associated with a high incidence of donor site morbidity (e.g., pneumothorax).[39-42] In our series, no cases of donor site complications were observed, and the only reported complications were minor and conservatively managed, achieving good patient-reported donor site outcomes. This might be related to the harvesting technique, which consists of the removal of the outer cortical rib bone and keeping the internal rib bone and the thoracic pleura intact.

Displacement of the costal graft was observed in only 1 patient in the early postoperative period. However, this might have been because the patient had not adhered to the postoperative instructions for care or related to surgical inexperience at the beginning of the learning curve with this technique. The graft was properly repositioned with the patient under general anesthesia the day after without any further complications.

Cortical rib bone has 5 main features that make it an efficient choice for large anterior cranial base defect: 1) it provides a large area of coverage; 2) it is an autologous material; 3) it provides low donor site morbidity because the costal bone is not taken as a full-thickness graft; 4) its variations in length and curved contour can reproduce the hammock-shaped ethmoidal roof and 5) anterior skull base tumors very often invade the nasoseptal bones and surrounding mucosa, preventing the use of local free and pedicled flaps. Moreover, reconstruction with a costal cortical rib could increase in importance because patients with large and very large skull base defects very often undergo cranial endoscopic resection for oncological reasons; thus, the risk of late brain herniation results, not only from the continuous pulsatile behavior of the CSF, but also from the brain edema after postoperative radiation therapy. In addition, its placement is suitable through an endoscopic endonasal approach and could profit from a 2-nostril, 4-hand technique to shorten the operative time.

Study Limitations

This study has several limitations, such as its retrospective nature, the low number of patients included, and the heterogeneity of the pathologies for which they underwent surgery. Moreover, the short-term follow-up (range, 2–22 months) does not allow us to draw definitive conclusions regarding this reconstructive strategy.

However, these preliminary results encourage the possibility of using the cortical rib bone graft as a solid layer to support anterior skull base reconstruction.

CONCLUSIONS

Anterior skull base reconstruction using the rib cortical bone graft resulted in safe and effective in all 10 patients. Cortical bone taken from the rib could be an important adjunct in skull base surgeons' armamentarium, especially when managing large defects and defects occurring after cancer treatment. Its harvesting does not seem to be particularly time consuming and guarantees negligible additional morbidity to the donor site. Longer follow-up is needed to provide more reliable findings regarding this reconstructive strategy.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Matteo Fermi: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Edoardo Serafini:** Data curation, Formal analysis, Investigation, Writing – original draft. **Alessandro Rosti:** Data curation, Investigation. **Maria Olive:** Data curation. **Matteo Alicandri-Ciufelli:** Supervision, Writing – review & editing. **Vittorio Sciarretta:** Supervision, Writing – review & editing. **Ignacio Javier Fernandez:** Supervision, Writing - review & editing. **Livio Presutti:** Conceptualization, Writing – review & editing.

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