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Segmental mandibular reconstruction in patients with poor lower extremity perfusion, vessel-depleted necks and/or profound medical frailty

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Purpose of review
Options for segmental mandibular reconstruction in patients poorly suited to undergo fibula free flap (FFF).

Recent findings
Although FFF is the current 'gold standard' for segmental mandibular reconstruction, other reconstructive options must be considered when FFF is contraindicated or disfavoured and/or patient frailty precludes a lengthy anaesthetic. In addition to various nonvascularized and soft tissue only reconstructions, excellent osseous free flap alternatives for functional segmental mandibular reconstruction may be employed. The subscapular system free flaps (SSSFF) may be ideal in frail and/or elderly patients, as SSSFF allows for early mobility and does not alter gait. In extensive and/or symphyseal defects, functional mandibular reconstruction in lieu of a free flap is extremely limited. Pedicled segmental mandibular reconstructions remain reasonable options, but limited contemporary literature highlights unpredictable bone graft perfusion and poor long-term functional outcomes.

Summary
There are several excellent free flap alternatives to FFF in segmental mandibular reconstruction, assuming adequate cervical recipient vessels are present. On the basis of the current literature, the optimal mandibular reconstruction for the medically frail, elderly and/or patients with extreme vessel-depleted necks is limited and debatable. In qualifying (i.e. limited, lateral) defects, soft tissue only reconstructions should be strongly considered when osseous free flaps are unavailable.

Keywords
free flap, mandibular reconstruction, mandibulectomy, oral cavity cancer

INTRODUCTION

In 2021, approximately 35 540 people will be diagnosed with oral cavity squamous cell carcinoma (OCSCCa), which will ultimately yield an estimated 6980 disease-specific fatalities [1]. However, 5-year overall survival (OS) in OCSCCa patients has improved over the last half century, increasing from 57% (1973–1983) to 63% (1985–2012) over this period [2]. The incidence of OCSCCa with mandibular involvement ranges from 25 to 53%, and segmental mandibular defects most commonly arise from composite resection for advanced OCSCCa, followed by mandibular osteoradionecrosis (ORN), trauma, or other benign or malignant mandibular tumors [3,4▪▪]. Such defects present considerable oncologic, reconstructive and rehabilitative challenges.

Nonetheless, improved survival outcomes underscore the importance of optimizing both oncologic and functional results, with an emphasis on speech, swallowing, airway patency, oral competence, mastication and aesthetic outcomes, all of which substantially influence quality of life [4▪▪,5–12].

The indications for segmental mandibulectomy in OCSCCa include gross cortical mandibular invasion; tumour fixation with insufficient mandibular

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KEY POINTS

- FFF is the gold standard for segmental mandibular reconstruction, but may not be possible for all patients due to poor lower extremity perfusion and risk of resultant postoperative limb ischemia, patient preference, severe medical comorbidities and frailty, and/or lack of recipient vessels in the neck.
- There are a number of acceptable free flap alternatives when FFF is contraindicated for mandibular reconstruction, including SSSFF, OCRFFF, composite rib, iliac crest, and ALTOF.
- Soft tissue only mandibular reconstruction options are useful for limited lateral mandibular defects when free tissue transfer is not possible, but these options are generally inferior with regard to restoring form and function, particularly for large and/or anterior mandibular defects.
- Pedicled osseous flaps, such as the osseous pectoralis flap, warrant consideration for segmental mandibular reconstruction in highly motivated free flap noncandidates with good anticipated long-term survival, especially those with symphyseal and/or extensive mandibular defects. However, bony perfusion is potentially unreliable, and long-term function and cosmesis may deteriorate.

height for well tolerated rim mandibulectomy; and tumor affixed to a previously radiated mandible [2]. Following segmental mandibulectomy in the malignant setting, vascularized bony reconstruction yields optimal functional and cosmetic results, particularly with anterior mandibular arch defects that would otherwise result in extreme debilitation and disfigurement [4▪▪,13–15]. Bony reconstruction is also favored over soft-tissue reconstructions with a bridging titanium plate due to osteocutaneous flaps' ability to better withstand bite forces and to provide a soft tissue buffer against overlying facial skin contracture. Mandibular reconstruction with osseous free flaps thereby mitigates plate complications including fracture and exposure [16]. The fibula free flap (FFF) is embraced as the workhorse for mandibular reconstruction, but some patients are poorly suited or are not candidates for FFF or other free flaps. We discuss these scenarios and examine alternative reconstructive options.

Fibula free flap: the 'gold standard' and its limitations

Popularized by Hidalgo in 1989 [17], the FFF is viewed as the 'gold standard' for segmental mandibular reconstruction [4▪▪]. Benefits of FFF include its limited donor site morbidity [18,19▪,20,21], ease of harvest, distance from the head and neck allowing simultaneous two-team surgery, lengthy pedicle up to 12 cm with large vascular diameter [22], length of available thick cortical bone for harvest up to 25 cm [23,24], option for multiple osteotomies in the reconstruction of multiplanar defects (e.g. near-total mandibular defects) [22] and ability to reliably accept osseointegrated dental implants [25–29,30▪]. The FFF donor site has proven to be an amenable donor site for reconstructive modelling and guided osteotomies to aid in complex reconstruction, especially with the popularization of virtual surgical planning. FFF is ideally suited for young, healthy patients or elderly patients with younger functional age and minimal comorbidities [31]. However, head and neck cancer patients frequently have multiple, potentially severe comorbidities complicating the use of FFF, including severe peripheral arterial disease (PAD), difficulty with ambulation, chronic anticoagulation or coagulopathic disorders, mandibular ORN or osteomyelitis, diabetes, chronic smoking [32], and/or severely vessel-limited necks. Poor FFF candidacy commonly results from insufficient lower extremity vascularity, often detected by computed tomography arteriogram (CTA) showing dominant peroneal artery or inadequate three-vessel runoff due to terminal atherosclerosis [33]. Alternatively, obtaining the ankle-brachial index (ABI) of the proposed limb may be helpful to evaluate PAD if three-vessel run-off or doppler evaluation is equivocal (ABI $>$ 1 = no obstruction, ABI 0.91–0.99 = borderline PAD and ABI 0.9 or less = PAD) [34]. Relative contraindications include patient refusal of the FFF donor site, presence of a single lower leg, intact three-vessel perfusion but with severe atherosclerotic changes, prior deep vein thrombosis, previous lower extremity trauma or surgery, and significant systemic comorbidities increasing the risk of lengthy surgery. FFF may also be suboptimal for composite mandibulectomy defects involving an extensive soft tissue component, which may necessitate a second flap in some cases [35]. Alternative reconstructions should be considered in the presence of PAD, borderline PAD, symptomatic claudication or severe atherosclerosis at or distal to the branchpoint of the ipsilateral popliteal artery. Kim *et al.* [33] reported two patients with severe lower extremity PAD who underwent preoperative multivessel endovascular intervention on the donor leg prior to successful mandibular reconstruction with FFF, suggesting the ability to 'rescue' the FFF site in the presence of otherwise prohibitive PAD.

Although frequently ideal for mandibular reconstruction, FFF is not always a well-tolerated and reliable option. Free flap alternatives to FFF for

mandibular reconstruction include subscapular system free flap (SSSFF, including the lateral scapular border and/or scapular tip), osteocutaneous forearm (OCRFF), osteocutaneous rib, iliac crest, and anterolateral thigh osseus flap (ALTOF) (Table 1). When free flaps are impractical or impossible due to severe neck vessel-depletion or severe medical fragility, remaining reconstructive options are lacking but may include soft-tissue-only reconstruction (with or without titanium plate) or pedicled regional osseous flaps. Nonvascularized bone grafts may be employed for small mandibular defects [4▪▪,36,37], but use may be limited following OCSCCa extirpation due to frequent prior head and neck radiation and/or need for adjuvant radiation in this population.

Alternatives to fibula free flap in segmental mandibular reconstruction

Subscapular system free flaps

For many microvascular surgeons, the primary alternatives to FFF for vascularized bony mandibular reconstruction are subscapular system free flaps (SSSFF) based on various branches of the subscapular artery (SSA). Osseous SSSFFs, incorporating the lateral scapular border and/or scapular tip, are well suited for patients with lower extremity vascular disease, elderly patients, patients with gait concerns or those with extensive through-and-through composite facial defects. In fact, due to its numerous, potentially chimeric cutaneous, musculofascial and osseous components that can be harvested on a single SSA pedicle, the SSSFF is preferred by some surgeons to FFF. The SSSFF was first described by dos Santos [38] and popularized by Swartz *et al.* [39] in the early 1980s. The scapular tip and lateral scapular border represent distinct functional bony conduits within the subscapular system that can be harvested independently or in continuity. Moreover, the latissimus/serratus/rib free flap based on the thoracodorsal artery (TDA) provides a third bony reservoir based on the SSA and is discussed in a subsequent section. In addition, SSSFFs can be used to reconstruct bony defects separated in space based on a single SSA pedicle. This is achieved by harvesting the scapular tip supplied by angular artery and the lateral border supplied by circumflex scapular artery. In addition to using the scapular tip or lateral scapular border, one major benefit of SSSFFs is the large amount of soft tissue available in addition to bone, which makes it ideal for potentially extensive through-and-through facial defects including bone [40,41]. Furthermore, a 'mega flap' can be harvested from the SSA system, which may include any combination of latissimus dorsi myocutaneous component, lateral scapular border, scapular tip, serratus muscle, rib, and/or scapular/parascapular skin paddle. Unlike the lower leg, which is very susceptible to atherosclerotic changes [42], the SSA angiosome is typically not affected by systemic vasculitis or calcifications and is generally not susceptible to postharvest donor site ischemia. Likewise, the relative resistance of SSSFFs to peripheral vascular disease may also manifest as healthier flap vessels available for microvascular anastomosis. Therefore, preoperative imaging of the upper extremity is typically not warranted [43]. Moreover, unlike the FFF, SSSFF bone segments that include contiguous lateral border and scapular tip allow nonosteotomized simultaneous reconstruction of defects involving the mandibular body and angle (tip directed posteriorly and cut edge vertically to reconstruct the angle) or body and symphysis (bone oriented horizontally with tip reconstructing the symphysis). If more complex contouring is required, greenstick osteotomies may be performed with or without scoring of the outer periosteum and bone, taking care to avoid incision of the inner periosteum.

One drawback to SSSFFs is that patient positioning and proximity of the flap harvest to the ablative surgical field may interfere with simultaneous two-team surgery thereby potentially increasing operative time. Prior to Nishimura's. [44] description of eccentric shoulder roll placement to fully expose the scapula harvest site in modified supine position, SSSFF harvest typically required lateral decubitus positioning, which mandated patient repositioning twice (after ablation and again after flap harvest and closure). Nonetheless, a study by Dowthwaite *et al.* [45] comparing FFF and osseous SSSFFs did not demonstrate a significant difference in mean operative time (FFF: 9 h and 19 min; SSSFF: 9 h and 47 min). Several other positioning techniques have since been proposed allowing simultaneous tumor ablation and SSSFF harvest without intraoperative repositioning. Notably, Clark *et al.* [46] and Chepeha *et al.* [47] described supine and semi-decubitus harvest positions. Chepeha's addition of the Spider Limb Positioner to the semi-decubitus position and Eskander's use of a Mayo stand to support the donor limb from the supine position each eliminate the need for a second assistant to support the donor extremity during SSFF harvest [42,47]. Bender-Heine *et al.* [48▪] recently reported significantly shorter SSSFF operative times in 53 cases utilizing the Spider Limb Positioner compared to 52 cases requiring a second assistant and/or intraoperative repositioning. Other support systems typically employed by orthopedists, such as the Trimano Fortis support arm, are also being utilized to allow for simultaneous two-team work.

Table 1. Characteristics of osseous free flaps commonly employed for functional segmental mandibular reconstruction [4▪▪,15]

Free flap	Potential flap components	Arterial pedicle supplying bone segment(s)	Venous Pedicle to bone segment(s)	Maximum reported length of bone segment	Benefits	Major Drawbacks	Potential morbidity	Osseointegrated implants possible	Other considerations
Fibula free flap (FFF)	Bone: Fibula Skin: lateral leg skin Muscle: flexor hallicis longus muscle, soleus muscle	Peroneal	Peroneal	25 cm	- Lengthy, consistent calibre vascular pedicle (inherently shorter pedicle length with longer bone segment) - Large reservoir of robust cortical bone - Ideal for multiple osteotomies	-Contraindicated in patients with occlusive lower extremity PAD - Skin paddle dependent on presence of adequate cutaneous perforators, which may limit the size of skin paddle harvest - May be suboptimal for extensive composite defects, may necessitate second flap if large soft tissue coverage required	- Gait limitation, foot-drop, valgus deformity - Limitations in activities involving high-demand lateral pivoting (e.g. tennis or basketball)	Yes	For knee and ankle stability and protection of peroneal nerve, preservation of 7 cm of proximal and distal fibula recommended during harvest
Subscapular system free flaps (SSSFF)	Bone: 1) Lateral scapular border 2) Scapular tip 3) Rib Muscle: 1) Latissimus dorsi 2) Serratus anterior Skin: 1) Scapular 2) Parascapular 3) Latissimus	-Circumflex Scapular - Lateral border of scapula -Angular branch of thoracodorsal - Scapular tip -Thoracodorsal - Rib	- Circumflex Scapular - Lateral border of scapula - Angular branch of thoracodorsal - Scapular tip - Thoracodorsal - Rib	14 cm	- Multiple, potentially chimeric flap components with many degrees of freedom: ideal for extensive composite defects - Lateral border and tip may be harvested in continuity or separately, based on unique pedicles	-Potentially challenging surgical positioning, may hinder two-team operation - May require intraoperative repositioning and/or second assistant for stabilization of operative limb	- Shoulder weakness and limited range of motion - Risk of winged scapula if teres major muscle not appropriately resuspended	May require augmentation	- Spider limb (or similar) positioner or use of Mayo stand to support operative limb may facilitate harvest from semi-lateral or modified supine positioning and may eliminate need for second assistant -Two-team surgery also possible with limb positioner
Osteocutaneous radial forearm (OCRFF)	Bone: partial thickness radius (<40% typically recommended, up to 60% reported) Muscle: palmaris longus tendon, if present and desired Skin: volar forearm skin	Radial	- Venae comitantes of radial artery - Cephalic	12 cm	- Lengthy pedicle, less susceptible to atherosclerosis than peroneal vessels - Large skin reservoir (essentially entire volar forearm skin available for harvest) - Sensate skin paddle possible	- Traditionally suboptimal to rehabilitate young, dentate patients - Bevelled proximal and distal osteotomies limits length of useable bone in harvested graft (90-degree osteotomies theoretically increase radial fracture risk by creating stress points)	- Distal radius fracture (Risk reduced with modern plating and bone harvest methods) - Forearm skin graft failure, tendon exposure, and/or skin graft adherence - Dorsal thumb numbness	May require augmentation	- May consider consulting hand surgeon for plating of radius and/or planning bone harvest, particularly for large volume/large circumference radius graft - May augment bonestock with 'double barrel'/ stacked bone segment technique
Iliac crest Free Flap	Bone: Iliac Crest Muscle: internal oblique Skin: Oblique skin paddle overlying the iliac crest	Deep circumflex iliac (DCIA)	Deep circumflex iliac (DCIV)	16 cm	Ideal for through and through defects -good bone height for intraosseus implants	- Short vascular pedicle	- Hernia - Evisceration - Gait disturbance - Chronic Pain	Yes	
Latissimus-serratus-rib composite free flap (LSRFF)	Bone: 10th rib Muscle: Latissimus dorsi, serratus anterior Skin: Latissimus dorsi skin paddle	Subscapular artery	Subscapular vein	11 cm	-Long pedicle -Vessels not commonly effected by PVD -Donor site can be closed primarily -Cartilaginous portion can be used to reconstruct TMJ	-Risk of pneumothorax	-Scapular winging	May require augmentation	
Anterolateral thigh osteocutaneous flap (ALTOF)	Bone: Lateral aspect of distal femoral diaphysis Muscle: vastus lateralis Skin: anterolateral thigh skin	- Descending branch of lateral circumflex femoral - Transverse branch of lateral circumflex femoral may also contribute	Venae comitantes of Descending branch of lateral circumflex femoral	10 cm	Large amount of tissue bulk	Short bone segment	- Femur fracture	May require augmentation	May consider consulting orthopaedic surgeon for postharvest femur stabilization to reduce fracture risk (especially if >4 cm bone harvest planned)

Despite limited bone stock, Lanzer *et al.* [49] and Moscoso *et al.* [50] demonstrated the feasibility of dental implants in scapular bone. However, unlike FFF, scapular bone segments may require augmentation with additional vascularized or nonvascularized bone prior to consideration of osseointegrated implants.

Importantly, Clark *et al.* [46] demonstrated the low morbidity of the scapula donor site, reporting that their entire 14 patient cohort regained full shoulder range of motion within 6 months following SSSFF. In addition, SSSFFs do not impair gait speed or stability and do not introduce gait variability, which may be seen following FFF or iliac crest free flap [51–53]. Scapular harvest sites also do not increase the risk of distal radius fracture described in certain OCRFF harvest techniques [54,55]. Falls and orthopaedic injuries can have devastating effects in elderly and medically frail patients.

SSSFF contraindications include prior ipsilateral shoulder surgery and preexisting ipsilateral cranial nerve XI weakness. Limitations of SSSFF include the lack of innervated flap or nerve grafting options and its 14 cm maximum length of potential bone harvest [43]. An additional challenge of SSSFFs includes careful positioning of the various flap components to ensure favorable pedicle geometry. This is true particularly in chimeric settings due to the potential for multiple components pedicled on a short segment of the SSA.

Osteocutaneous radial forearm free flap

OCRFF represents an additional option for reconstruction of composite oral defects including a short mandibular segment. Flap harvest techniques and plating of the donor radius have been described by both Villaret and Futran [56] and Werle *et al.* [57]. In addition to mandibular reconstruction following tumor extirpation, OCRFF has also been successfully used for reconstructing bone defects in ORN with no reported flap failures and 100% postoperative ORN stabilization [58]. Benefits of the OCRFF include a long vascular pedicle, which is less susceptible to PAD than the peroneal vessels, as well as the ability to harvest a large, potentially sensate skin paddle [59].

Concerns regarding donor site morbidity (i.e. the potential for radius fracture), the limited amount of bone available for harvest, and the risk of bone devascularization following osteotomies have led to limitations in its use [14]. Further, the OCRFF does not reliably provide sufficient bone for dental implants, although Gonzalez-Castro *et al.* [60] demonstrated that double barrelled OCRFF would accommodate dental implants [59]. Comparing multiple types of osteocutaneous free flaps Kearns *et al.* [61] determined that the OCRFF is associated with higher rates of delayed healing (approximately 20%) compared with scapular (<10%) and iliac flaps (5%). In addition, due to the rate of donor site fractures, they recommend against using this flap in elderly men and postmenopausal women due to decreased bone density [61]. Likewise, Zenn *et al.* reported a donor radius fracture rate of 12% and recommended reserving OCRFFF for limited posterior mandibular defects with adjacent large mucosal loss [54]. However, multiple recent publications have demonstrated improved OCRFF donor site morbidity with prophylactic internal fixation [57,62–64]. Silverman *et al.* [65] reported outcomes for 155 OCRFF patients and emphasized the importance of preserving more than 50% of the cross-sectional area of the radius while using proximal and distal bevelled ('boat-shaped') osteotomies. The average length of harvested bone was 7 cm, and the observed radius fracture rate was 1.3%, which was independent of the length of bone harvested [65]. Similarly, multicenter retrospective review by Sinclair *et al.*' [66] included 218 patients who underwent OCRFF, and the median harvested radius length was 8 cm. Complications included 0.5% donor radius fracture rate with prophylactic plating, 3.2% mandibular malunion rate, and 15.6% mandibular hardware extrusion rate [65]. Swendseid *et al.* [67▪] evaluated long-term complications in osteocutaneous free flaps in head and neck reconstruction and demonstrated no significant difference in complications between OCRFF and other bony reconstructions. Bevelled (i.e. 'boat-shaped') proximal and distal osteotomies [68], conservative radial circumference harvest (40–50% or less) [65], and prophylactic radius plating [57,62–64] each reduce the risk of distal radius fracture following OCRFF harvest. Unfortunately, osteotomies employed in this technique also have the disadvantage of reducing the useable harvested bone. Therefore, some groups collaborate with orthopaedic hand surgery to optimize thickness and useable length of the radial bone graft while aiming to minimize fracture risk. Ninety-degree proximal and distal osteotomies, carefully planned longitudinal osteotomies to obtain the desired bony volume, and prophylactic distal radius plating are performed, potentially aided by the consulting hand specialist depending upon the comfort and experience of the reconstructive surgeon. Using this approach, harvest of up to 15 cm of bone at up to 60% of the radial bone thickness has been successfully achieved, without distal radius fracture (Verbal communication, Rohde, Vanderbilt).

Virgin *et al.* [69] reported 168 patients who underwent free flap reconstruction for segmental mandibulectomy (FFF = 117 patients, OCRFF = 51 patients) and found that OCRFFs were more commonly used in significantly older patients, with no

significant observed differences in donor site complications, flap failure, malunion, oral diet tolerance, or need for long-term enterogastric feeding tube. Militsakh *et al.* [58] compared OCRFF ($n = 108$) and other bony oromandibular reconstructions ($n = 56$) and determined that major donor site morbidity and functional outcomes were similar between the two groups, though length of ICU stay and overall hospital stay was significantly shorter in the OCRFF group.

In addition to OCRFF's excellent objective donor site complication profile, Sinclair *et al.* [66] also compared patient perceived donor site morbidity using the Disability of the Arm, Shoulder and Hand questionnaire (DASH) and found no significant difference in those patients who received OCRFF ($n = 30$) versus fasciocutaneous forearm flap ($n = 30$). As most patients do not pursue dental rehabilitation, these studies suggested that OCRFF's good morbidity profile and functional results make it an excellent first option for mandibular reconstruction.

Iliac crest free flap

The osteocutaneous iliac crest flap was first described in 1979 by Taylor *et al.* [70–72]. However, Urken *et al.* [73] first described the use of the internal oblique-iliac crest osteomyocutaneous free flap based off of the deep circumflex iliac artery and vein (DCIA and DCIV) for oromandibular reconstruction in 20 cases in 1989, including some who underwent primary osseointegrated implant placement. The technique has since been further refined by multiple publications [50,74,75]. The iliac crest free flap is ideal for through and through composite oral defects because of the availability of vascularized skin, muscle, and bone components. It is also ideal for primary intraosseous implants due to its composition of primary cancellous bone as well as its ideal height and width [76]. Preoperative arteriography is not required for this flap due to the consistency of perfusion by the DCIA. The maximum length of bone that can be used for reconstruction is 16 cm and the of the DCIA is approximately 1.5–3 mm and ranges in 5–7 cm in length from its takeoff from the external iliac artery. The most common donor site morbidity for patients receiving iliac crest osseomyocutaneuous flap is hernia formation (9.7%), femoral nerve palsy (4.8%), and postoperative pain at the donor site. Evisceration has also been noted as a rare but serious potential complication of iliac free flap [4▪▪,15].

Latissimus-serratus-rib composite free flap

The review by Brown *et al.* [35] examining vascularized mandibular reconstruction in articles published between 1990 and 2015 demonstrated the rarity of latissimus-serratus-rib free flap's (LSRFF) use for this indication, representing only 63 out of 9499 total reported osseous reconstructions (0.66%). The advantages LSRFF are that it allows for simultaneous two team surgery, has low donor site morbidity and possesses a long vascular pedicle. LSRFF can be designed to reconstruct most defects in the oral cavity and provides ample bone for total or subtotal mandibular reconstruction. The cartilaginous rib is also available to reconstruct the temporomandibular joint if needed. Further, the rib bone may be oriented independent of the soft tissue component of LSRFF, and the donor site can be closed primarily with an inconspicuous scar in the axillary line [77–79]. LSRFF's primary disadvantage is its relatively thin bone graft with minimal cortical bone, making osseointegrated implants difficult [77]. In addition, LSRFF pedicle length may be limited to the thoracodorsal takeoff in patients in whom prior ipsilateral flaps based on the circumflex scapular artery have been harvested (e.g. lateral scapular border). LSRFF is not an option in patients who have had prior ipsilateral free flaps pedicled on the subscapular vessels (e.g. combined lateral border and scapular tip, megaflap, etc.) or thoracodorsal system (e.g. scapular tip, latissimus etc.). See publications by Kim and Blackwell [77] and Penfold *et al.* [79] for description of flap harvest [80].

Kim and Blackwell [77] reported nine intraoperative pneumothoraces among 29 LSRFF patients in a multicentered study, including five who required chest tubes. However, chest tube durations were short-lived (48–72 h) and did not significantly lengthen hospital stays [77]. They also reported three postoperative wound complications, including one case each of orocutaneous fistula, partial flap skin paddle necrosis and neck skin marginal necrosis [77]. The series of 12 LSRFFs published by Trignano et al. [78] included five mandibular reconstructions in which two cases of excessive flap bulk, two cases of postoperative haematoma, three cases of scar contracture and one case of lower lip incontinence were reported. However, there were no cases of pneumothorax or winged scapula.

Anterolateral thigh osteomyocutaneous flap

The anterolateral thigh osteomyocutaneous flap (ALTOF), based on the descending branch of the lateral circumflex femoral artery, was first described by Acartürk in 2011 [81] for composite lower extremity reconstruction. Brody *et al.* [82] subsequently described ALTOF in head and neck reconstruction in six patients including four composite

mandibular defects. No donor site fractures or orthopedic injuries had been reported at the time of publication. One patient experienced partial flap necrosis, although the femoral bone graft remained viable [82]. Please see Acartürk [81] and Brody *et al.* [82] for ALTOF harvest techniques [83]. ALTOF is ideal in cases wherein other bony flaps are not an option due to aberrant anatomy, peripheral vascular disease, prior surgery, or prior trauma. Benefits of this flap include the large amount of available soft tissue and bone (up to 10 cm), ability to close the donor site primarily, and potential for early postoperative ambulation [82]. LoGiudice *et al.* [84] described the use of ALTOF for reconstruction of two composite oral cavity defects including small segments of mandible. They recommend harvesting less than 4 cm femoral length and less than 20% circumference at the distal diaphysis. If a larger bone segment is required, prophylactic plate fixation of the femur should be performed. Shanti *et al.* [83] described an additional case of ALTOF for oral cavity composite reconstruction including mandible reconstruction and reported that in this case orthopedic surgery performed prophylactic nailing of the femur in order to lessen post-harvest femur fracture risk. Worley *et al.* [85] conducted a cadaveric study to compare the force and torque required to sustain femoral fracture in controls, osteotomized femurs without fixation, and osteotomized femurs with fixation. They noted significant improvement in posterior to anterior force to fracture and therefore recommended routine intraoperative stabilization with an intramedullary nail [85].

Management of segmental mandibular defects when free flap is impossible, impractical, or unadvised

Restoring cosmesis and function in poor osseous free flap candidates with segmental mandibular defects is particularly challenging due to a paucity of capable alternatives. Still, numerous patient factors may each necessitate a reconstructive plan without a free flap, including multiply treated, vessel-depleted necks, multiple prior failed reconstructions, poor oncologic prognosis disfavoring a potentially morbid reconstruction, and extreme medical frailty [86▪]. In vessel-depleted necks, free tissue options may be restored in otherwise unfavourable candidates via measures such as vein grafting to improve pedicle length (e.g. to contralateral neck) or use of alternative/atypical donor vessels or vascular loop (Table 2).

Soft-tissue-only reconstruction warrants consideration for limited posterolateral segmental defects confined to the mandibular body [87], although this may lead to mandibular swing, malocclusion, and facial contracture [88]. Moreover, this technique is not advised in multisegment and/or anterior/symphyseal defects due to unacceptable cosmetic and functional results [13,89]. The native mandibular contour, facial cosmesis and residual postablative

Table 2. Potential recipient vessels for microvascular anastomosis in vessel-depleted necks

Rescue donor vessel options in vessel-depleted necks previously reported in the literature	
Donor artery	**Donor vein**
Superior Thyroid	Superior Thyroid
Facial (Anterograde or Retrograde)	Cephalic
Thoracodorsal	External Jugular
Thoracoacromial	Corlett Loop
Superficial Temporal (Anterograde or Retrograde)	Thoracodorsal
Occipital	Transverse Facial
Postauricular	Occipital
Subclavian	Facial (Anterograde or Retrograde)
Transverse Cervical (Anterograde or Retrograde)	Subclavian
Transverse Facial	Prior flap vein
External Carotid (End-to-End or End-to-Side)	Internal Jugular
Lingual	Arteriovenous Loop
Arteriovenous Loop	Deep Temporal
Internal Mammary	Transverse Cervical
Internal Carotid (End-to-side)	Internal Mammary
Corlett Loop	Concomitant Vein of Hypoglossal Nerve
Lateral Thoracic	Thoracoacromial Trunk
Dorsal Scapular	Thyrolinguofacial Trunk
Prior flap artery	Dorsal Scapular
Contralateral Vessel with or without Vein Graft	Common Facial
	Anterior Jugular
	Superficial Temporal (Anterograde or Retrograde)
	Contralateral Vessel with or without Vein Graft

Table 3. Characteristics of pedicled regional osseous flaps for segmental mandibular reconstruction

Pedicled flap	Flap components	Arterial pedicle supplying bone segment	Venous pedicle to bone segment	Largest series (*n*)	Maximum reported length of bone segment	Benefits	Major drawbacks	Other
Pectoralis major osteomyocutaneous Flap (PM-OMC)	Pectoralis major muscle, 5th and/or 6th rib, overlying skin paddle	Pectoralis branch of thoracoacromial trunk (Nonaxial/periosteal perfusion only)	Pectoralis branch of thoracoacromial trunk	>400 (No detailed outcomes published) [100]	11 cm (5th rib) [104]	- Ease and efficiency of harvest (~1 h) -Costochondral angle well suited to reconstruct mandibular angle [98], -Greenstick osteotomies possible without disrupting perfusion to rib [105]	- No axial blood supply to rib - Risk of pneumothorax - Poor bone stock, unlikely to accept osseous implants without augmentation - Risk of acute/chronic bone resorption/necrosis - Poor maneuverability of bone segment relative to skin paddle	Likely first line pedicled osseous option for mandibular reconstruction, but with notable limitations
Pectoralis/sternum [106]	Pectoralis major muscle, outer table of sternumor full thickness sternum [92,93] overlying chest skin	Pectoralis branch of thoracoacromial trunk (Nonaxial/periosteal perfusion only)	Pectoralis branch of thoracoacromial trunk	27 (partial thickness) [93] Case report (full thickness sternum) [92]	Not Specified	-Low reported complication rate [106]	- Lack of axial perfusion to the sternal graft - Risk of acute/chronic bone resorption/necrosis -High morbidity and mortality associated with theoretical risk of deep or superficial sternal infection [107]	
Rectus abdominis, rib	Upper abdominal skin, rectus abdominis muscle, 6th rib	Internal mammary	Internal mammary	Case reports	13 cm [97]		-Risk of thoracic instability due to resection or fracture of costal synchondroses via extrapleural approach -Poor bone stock, unlikely to accept osseous implants without augmentation	Noted by authors to be a 'last resort' in tertiary mandibular reconstruction [97]
Pedicled internal mammary osteomyocutaneous chimeric flap (PIMOC)	6th/7th ribs, rectus abdominis muscle, overlying skin paddle	Internal mammary, deep superior epigastric	Internal mammary	5 [108]	Not specified	Each component with distinct axial blood supply -Lengthy pedicle (up to 21 cm) - Harvest as free flap theoretically possible	-Very high technical complexity flap harvest -Inverted L-sternotomy and intrapleural dissection required, availability of surgeon with cardiothoracic expertise mandatory -Pedicle dissection 'tedious' -Pneumothorax risk, chest tube required postoperatively - Theoretical mediastinal infection risk -Not appropriate if poor ventilatory function, prior harvest of IMA for cardiac revascularization -May require surgical mesh placement for thoracic and abdominal closures -Poor bone stock, unlikely to accept osseous implants without augmentation -Loss of 6 cm of pedicle length if draped over clavicle	
Trapezius, scapular spine	Trapezius, scapular spine (sparing acromion)	Transverse Cervical	Variable: external jugular (80%) and/or subclavian [109] Transverse cervical also reported	8 [110]	9 cm [109]	Cosmetically favorable donor site	-Variability of vein positioning relative to accessory nerve and brachial plexus - CN XI sacrifice required in one-third of cases [109] -Poor bone stock, unlikely to accept osseous implants without augmentation	Likely considered only when free flap is contraindicated, due to high rate of required CN XI sacrifice, which is unpredictable and dependent on patient anatomy

Table 3 (*Continued*)

Pedicled flap	Flap components	Arterial pedicle supplying bone segment	Venous pedicle to bone segment	Largest series (*n*)	Maximum reported length of bone segment	Benefits	Major drawbacks	Other
Compound flap of clavicle and sternocleidomastoid muscle (SCM)	Clavicular head of SCM, Full or partial thickness of clavicle (periosteum intact)	-Sternocleidomastoid branches of occipital [94] -Superior thyroid also described (Nonaxial/periosteal perfusion only in either scenario)	External jugular	18 [94]	13 cm [94]	Ease of harvest - Low morbidity	Risk of clavicle and/or graft fracture if partial thickness harvest - Risk of bone resorption/ necrosis - Inconsistent, potentially unreliable perfusion of flap components [111]	
Osteomuscular dorsal scapular (OMDS) [112]	Rhomboid major muscle, medial border of scapula	Dorsal scapular	Dorsal scapular	40	10.9 cm		-Poor bone stock, unlikely to accept osseous implants without augmentation - Requires prone positioning - No available skin paddle	May be considered in 'fragile patients not eligible for microsurgical reconstruction'
Pedicled latissimus-serratus-rib [102]	Latissimus dorsi muscle, serratus anterior muscle,10th rib	Thoarcodorsal	Thoracodorsal	Case reports	13 cm [113]	Largely same technique as free flap harvest	- Large flap volume - Poor manoeuvrability of bone segment relative to skin paddle - Reported challenges affixing bone to reconstruction plate -Poor bone stock, unlikely to accept osseous implants without augmentation	-May be considered if candidacy for free flap is poor and PM-OMC declined by patient

occlusion can be maintained with the combination of soft tissue reconstruction and bridging titanium plate. However, downfalls include high rates of plate exposure (up to 80%) and plate fracture [4▪▪], which is amplified in dentate patients (up to 26%) [16,86▪,87,90]. Plate complications resultantly increase the need for revision surgeries and antibiotics, worsen quality of life, and in rare scenarios may precipitate delayed flap failure [16,86▪,87,90,91]. For limited mandibular defects in nonirradiated patients, options may include nonvascularized autologous bone grafts (defects < 6 cm) or distraction osteogenesis. A major drawback of distraction includes slow distraction (1 mm per day or less) leading to protracted external appliance placement [4▪▪,36,37]. Pedicled osseous mandibular reconstructions have also been described, predominantly in publications from decades ago and/or outside of the North American literature [92–97], with varying degrees of success. The pectoralis major osteomyocutaneous flap (PM-OMC) has been well described historically as a pedicled mandibular reconstructive alternative. The osseous segment of the PM-OMC includes a portion of the fifth or sixth ribs perfused via periosteum attached to the pedicled pectoralis major muscle [98,99]. Savant *et al.* [99,100] reported having performed over 400 PM-OMC flaps prior to 1996 in Mumbai, India with low morbidity and acceptable function and cosmesis. Nonetheless, this flap has since fallen out of favor for mandibular reconstruction, likely due to a variety of shortcomings. PM-OMC's pitfalls include tenuous periosteal perfusion and potential acute or delayed rib graft loss, poor bone paddle maneuverability relative to the skin island, bone resorption, and diminishing cosmesis (i.e. risk of developing an 'Andy Gump' deformity) with long-term follow-up [101]. Other less common regional pedicled osseous flaps employed for reconstructing the mandible include pectoralis with sternum or clavicle [92,93], rectus abdominis muscle with rib based on the internal mammary artery [97], pedicled latissimus-serratus-rib flap [102], sternocleidomastoid muscle with clavicle [94], and osteomuscular dorsal scapular (OMDS) flap, which includes medial scapular border and trapezius with scapular spine based on the transverse cervical vessels [95,96,103] (Table 3). Currently, unpredictable outcomes of pedicled mandibular reconstructions combined with the contemporary acceptance of osseous free flaps as the unequivocal gold standard have largely relegated PM-OMC and other pedicled osseous mandibular reconstructions as obsolete. However, pedicled osseous flaps may be considered for mandibular reconstruction in highly motivated free flap noncandidates with good anticipated oncologic and functional prognoses. If free flap is not possible,

patients with extensive and/or symphyseal defects may benefit most from pedicled bony flaps because reconstruction without vascularized bone would yield unacceptable cosmetic and functional results.

CONCLUSION

When FFF is contraindicated for segmental mandibular reconstruction, other osseous free flaps remain the first choice for mandibular reconstruction, as alternative methods do not match their reliability, functional outcomes, or safety profile. If needed, reconstruction of limited, lateral mandibular defects may be reliably addressed with soft-tissue-only options, albeit with potential functional and cosmetic deficits [88]. However, the best reconstructive option for extensive and/or symphyseal defects in patients who cannot undergo free flap is not clear. If osseous free flap reconstruction is not possible, PM-OMC is historically the most utilized pedicled reconstructive alternative, but surgeons should counsel patients thoroughly regarding its potential downfalls including acute or chronic bone loss and deteriorating cosmetic and functional outcomes.

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