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Imaging and printing in plastic and reconstructive surgery part 1: established techniques

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Abstract

Background: An increasing number of reconstructive surgeons are using modern imaging technologies for preoperative planning and intraoperative surgical guidance. Conventional imaging modalities such as CT and MRI are relatively affordable and widely accessible and offer powerful functionalities. In the first of a two-part series, we evaluate established three-dimensional (3D) imaging and printing techniques based on CT and MRI used in plastic and reconstructive surgery.

Method: A review of the published English literature dating from 1950 to 2017 was taken using databases such as PubMed, MEDLINE®, Web of Science and EMBASE.

Results: In plastic and reconstructive surgery, the most commonly used, free software platforms are 3D Slicer (Surgical Planning Laboratory, Boston, MA, USA) and OsiriX (Pixmeo, Geneva, Switzerland). Perforator mapping using 3D-reconstructed images from computed tomography angiography (CTA) and magnetic resonance angiography (MRA) is commonly used for preoperative planning. Three-dimensional volumetric analysis using current software techniques remains labour-intensive and reliant on operator experience. Three-dimensional printing has been investigated extensively since its introduction. As more free open-source software suites and affordable 3D printers become available, 3D printing is becoming more accessible for clinicians.

Conclusion: Numerous studies have explored the application of 3D-rendered conventional imaging modalities for perforator mapping, volumetric analysis and printing. However, there is a lack of comprehensive review of all established 3D imaging and printing techniques in a language suitable for clinicians.

Keywords: image processing, 3D printing, plastic and reconstructive surgery, CTA, MRA

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Introduction

Performing perforator-based flap reconstruction requires careful selection of the perforator, flap design and donor site. A suitable perforator is ideally harvested from a donor site with minimal morbidity and is large enough to facilitate microsurgical anastomosis and adequately supply all portions of the flap.[1] In recent times, an increasing number of plastic and reconstructive surgeons have begun using modern 3D imaging and printing technologies to aid preoperative planning, intraoperative guidance and medical education.[2,3] However, there is a lack of comprehensive review of these techniques that provides a global understanding of this novel field in a language suitable for clinicians.

Currently, a plethora of imaging modalities is being used in plastic and reconstructive surgery, mainly computed tomography angiography (CTA) and magnetic resonance angiography (MRA).[4–9] First reported for perforator-based flap planning in 2006,[6,7] CTA is widely used in preoperative investigations by institutions around the world and is considered the gold standard due to its high accuracy and reliability.[4,5,10–13] However, CTA poses the potential risk of additional radiation exposure, involves intravenous administration of iodinated contrast media and does not provide haemodynamic features such as flow velocity and direction.

Magnetic resonance angiography bypasses radiation exposure but is limited by only being able to detect vessels greater than 1 mm in diameter.[14] It also has lower spatial resolution[15] and poorer contrast differentiation from the surrounding soft tissue.[16] As a result, MRA has a lower sensitivity (50%) for detecting abdominal wall perforators than CTA.[9] Enhanced by recent advances in imaging techniques,[17] contrast agents[18] and increasing availability of higher field-strength scanners,[19] more recent studies have reported improved sensitivity in identifying perforators (91.3–100%).[8,20–24] As a result, MRA remains an investigation of choice for younger patients and for those with iodine allergy and impaired renal function.[25]

In this review, we evaluate the established 3D imaging and printing techniques based on CT and MRI.

Methods

We reviewed the published English literature from 1950 to 2017 from well-established databases such as PubMed, MEDLINE®, Web of Science and EMBASE. We included all studies that analyse 3D imaging and printing techniques used in surgery, especially plastic and reconstructive surgery. We used search terms such as '3D imaging', 'CTA', 'MRA', '3D image software', 'volumetric analysis', '3D printing', 'preoperative planning', 'intraoperative guidance', 'education', 'training' and 'customised implant'. We also retrieved secondary references found through bibliographical linkages.

3D imaging rendering software

Through our literature review, we identified the most commonly used 3D image rendering software suites in medical application. We identified their specifications, such as the software language on which they are based, cost, open-source capability and function, by accessing the manufacturer's website or from publications.

3D perforator mapping

We identified that CTA and MRA are the most commonly used imaging modalities for 3D perforator mapping. Hence, we evaluated the software suites based on these modalities.

3D volumetric analysis

We focused our analysis of 3D volumetric analysis based on conventional 3D imaging techniques, CT and MRI. We systematically identified a list of software suites used to analyse 3D volumetric data from CT or MRI and examined their application in plastic and reconstructive surgery.

3D printing

Studies using 3D printing for preoperative planning in plastic and reconstructive surgery were assessed using Oxford Centre for Evidence-Based Medicine levels of evidence.[26] Given that the most common 3D printing application in plastic and reconstructive surgery is mandibular reconstruction with free

Table 1. Summary of 3D image rendering software

Product	Manufacturer	Software language	Free	Open-source	Function
3D Slicer	Surgical Planning Laboratory (Boston, MA, USA)	C++ Python	Yes	Yes	Built on ITK and VTK Easy-to-use graphical user interface Creates 3D images of regions of interest suitable for 3D printing
OsiriX	Pixmeo (Geneva, Switzerland)	Objective-C	Yes	No	Built on ITK and VTK Enables both viewing and 3D rendering of anatomical structures Easy-to-use graphical user interface Has both 3D rendering techniques: volume-rendered technique and maximum intensity projection

ITK = Insight ToolKit VTK = Visualisation ToolKit. Sources: Fedorov and colleagues,[27] Rosset and colleagues.[31]

fibular flap, we performed a focused further qualitative analysis of this application.

Results and discussion

Numerous studies have explored the application of conventional imaging modalities for 3D perforator mapping, 3D volumetric analysis and 3D printing.

3D image rendering

Proprietary software provided by manufacturers of CT and MRI scanners generally offers only two-dimensional image-viewing capabilities. As a result, numerous free, open-source software platforms have been developed that are capable of 3D image rendering. They are built on robust, but limited, open-source software libraries that provide the basic architecture. In plastic and reconstructive surgery, the most commonly used free software platforms are 3D Slicer (Surgical Planning Laboratory, Boston, MA, USA) and OsiriX (Pixmeo, Geneva, Switzerland) (see **Table 1**).

3D Slicer

3D Slicer[27] is a well-supported, open-source platform built on Insight ToolKit (ITK) and Visualisation ToolKit (VTK) using C++ and Python.[2] Developed to segment brain tumours from MRI scans[28] 3D Slicer is used in a variety of medical applications ranging from lung cancer diagnosis[29] to cancer imaging.[30] This software is adept at generating volumetric images for 3D printing through thresholding and segmentation techniques.

OsiriX

The OsiriX[31] image-viewing software platform is built on ITK and VTK, for Macintosh computers only. It has an intuitive graphical user interface and fast processing speed make it popular with clinicians worldwide.[31] OsiriX enables viewing of multidimensional data such as positron emission tomography (PET)-CT[32] and cardiac-CT as well as standard tomographic scans (CT and MRI).[33] It is suitable for viewing 3D and 4D datasets but limited to 3D anatomical models of large organs such as long bones and the heart.

3D perforator mapping

In perforator based, free flap reconstruction, plastic surgeons commonly rely on CTA- or MRA-based 3D reconstructed images of the relevant perforators for preoperative planning (see **Figure 1**).

CTA

Computed tomography angiography is the most commonly used imaging modality for 3D perforator mapping, using maximum intensity projection (MIP) and volume-rendered technique (VRT) 3D software reconstruction techniques. Compared with Siemens Syngo InSpace 4D (Siemens, Erlangen, Germany) and VoNaviX (IVS Technology, Chemnitz, Germany), which are expensive, and virSSPA (University Hospitals Virgen del Rocio, Sevilla, Spain), which is not available outside the original institution, OsiriX software platform is free and has been demonstrated to be as accurate.

MRA

Modern magnetic resonance technology can provide superior 3D reconstructed images. However, they are expensive, time-consuming

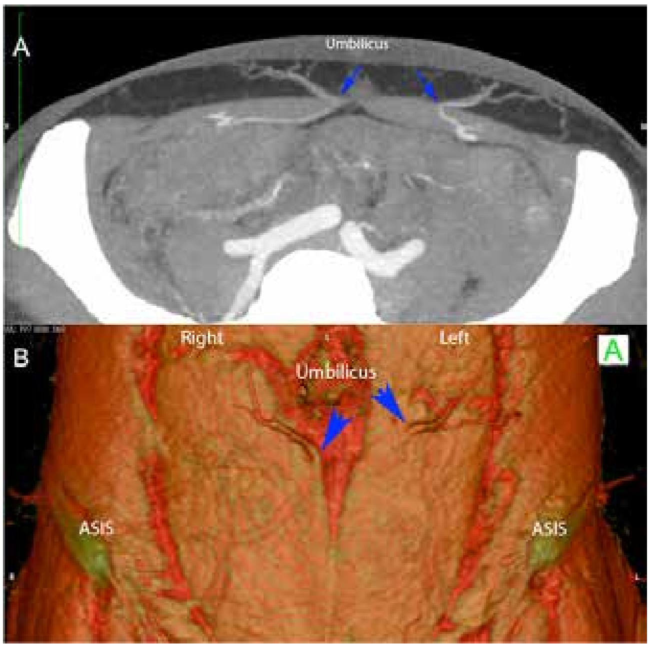

***Fig 1**. Computed tomographic angiography (CTA)-based three-dimensional (3D) perforator mapping in deep inferior epigastric artery perforator (DIEP) flap planning performed using OsiriX software. (A) Maximum intensity projection (MIP) reconstruction demonstrating the intramuscular and subcutaneous course of each perforator. (B) Volume-rendered technique (VRT) reconstruction demonstrating the location of the perforators (blue arrows) as they emerge from the rectus sheath in reference to the umbilicus (marked)*

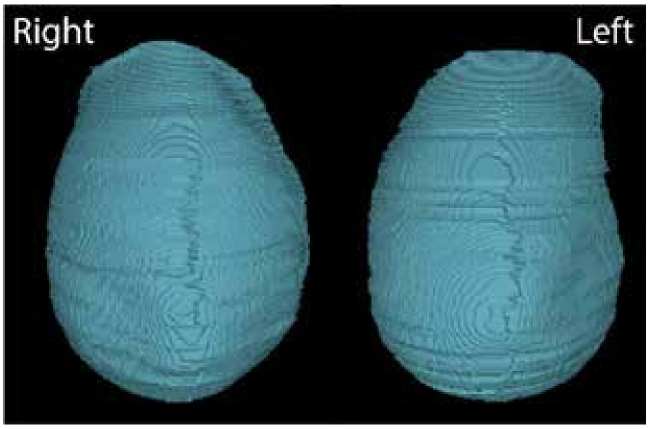

***Fig 2.** MRI-based 3D volumetric analysis in planning breast reconstructive surgery demonstrating 611 mL on the right breast and 635 mL on the left breast, performed using OsiriX software (Pixmeo, Geneva, Switzerland)*

and relatively difficult to perform. Similar to CTA, free OsiriX software can be used for 3D perforator mapping from MRA. Recently, investigators have developed a semi-automated plugin tool for analysing MRA images using OsiriX, However, it remains to be validated in a large cohort.

3D volumetric analysis

Accurate assessment of tissue volume is an important aspect of preoperative planning in plastic surgery.[34–38] Particularly in breast reconstructive surgery, volumetric analysis is paramount for achieving symmetrisation and a satisfactory outcome.[39–44] However, an accurate, reliable and convenient method of objective breast volumetric analysis has remained elusive (see **Figure 2** and **Table 2**).[45]

CTA

Calculating the flap volume from CTA and comparing it with the intraoperative flap weight, Eder and colleagues reported high correlation between the two measurements (r = 0.998, $p < 0.001$) demonstrating the high prediction accuracy of CTA (0.29%; –8.77 to 5.67%).[39]

In order to further improve its accuracy, Rosson and colleagues placed fiducial markers on the surgical incision line before the CTA and achieved accuracy of up to 99.7 per cent (91–109%).[43]

Lee and colleagues calculated a ratio using the volume of the breast and the potential deep inferior epigastric artery perforator (DIEP) flap from CTA and created a treatment algorithm.[46] If more than 50 per cent of the harvested flap is required for reconstruction, surgeons can make modifications to the flap design by increasing its height, capturing more adipose tissue by bevelling superiorly from the flap's upper margin, like Ramakrishnan's extended DIEP technique,[47] and incorporating multiple perforators if available. If more than 75 per cent of the flap is required, venous augmentation is performed with contralateral superficial inferior epigastric vein. Using this algorithm in 109 consecutive patients, the authors noted a significant reduction in perfusion-related complications (5.6 vs 22.9%, $p = 0.006$) and fat necrosis (5.6 vs 19.1%, $p = 0.03$).

MRI

In comparison to CT, MRI has superior soft-tissue resolution and is thus more accurate at measuring breast volumes (r = 0.928 vs 0.782, $p = 0.001$)[48] and has a mean measurement deviation of only 4.3 per cent.[49] Furthermore, Rha and colleagues show that MRI-derived breast volume is more accurate than the traditional volumetric method using a plaster cast ($r^2 = 0.945$ vs 0.625).[41]

Table 2. Summary of software platforms capable of performing 3D volumetric analysis from CT and MRI

Product	Manufacturer	Free	Open-source	Clinical application
CT				
OsiriX	Pixmeo, Geneva, Switzerland	Yes	No	Breast
Aquarius Workstation	TeraRecon Inc., San Mateo, CA, USA	No	No	Breast, DIEP flap
Mimics	Materialise NV, Leuven, Belgium	No	No	DIEP flap
Leonardo Workstation	Siemens AG, Munich, Germany	No	No	DIEP flap
ImageJ	NIH, Rockville, MD, USA	Yes	No	Orbital volume
Vevo LAB	Fujifilm ViewSonics, Toronto, Canada	No	No	Autologous fat graft in mice
SkyScan CTan	Bruker, Kontich, Belgium	No	No	Limb lymphoedema in mice
MRI				
OsiriX	Pixmeo, Geneva, Switzerland	Yes	No	Breast, Breast implant, Limb lymphoedema in mice
Volume Viewer Plus	GE Healthcare, Waukesha, WI, USA	No	No	Breast
BrainLAB	BrainLAB AG, Feldkirchen, Germany	No	No	Breast, Breast implant
Medis Suite MR	Medis Medical Imaging Systems BV, Leiden, The Netherlands	No	No	Breast, Breast implant
AW Server	GE Healthcare, Waukesha, WI, USA	No	No	Breast glandular tissue
				Muscle (pectoralis major)
Dextroscope	Volume Interactions, Singapore	No	No	Malar fat pad
ImageJ	National Institutes of Health, Rockville, MD, USA	Yes	No	Breast

DIEP = deep inferior epigastric artery perforator. Source: Eder and colleagues,[39] Rha and colleagues,[41] Rosson and colleagues,[43] Herold and colleagues,[44] Lee and colleagues,[46] Chae and colleagues,[51] Rha and colleagues,[52] Blackshear and colleagues,[131] and Corey and colleagues[135]

Using the manufacturer's specifications as gold standard, Herold and colleagues measured the volume of breast implants using MRI in patients with bilateral augmentation mammaplasty.[44] Furthermore, they compared the accuracy of three commonly available 3D image processing software platforms: OsiriX, BrainLAB (BrainLAB AG, Feldkirchen, Germany) and Medis Suite MR (Medis Medical Imaging Systems BV, Leiden, The Netherlands). BrainLAB had the lowest mean deviation of 2.2 ± 1.7 per cent, followed by OsiriX at 2.8 ± 3.0 per cent and Medis Suite MR at 3.1 ± 3.0 per cent. However, all software platforms correlated highly accurately with the reference overall ($r = 0.99$). Interestingly, software analysis is fastest using OsiriX at 30 seconds per implant, followed by BrainLAB and Medis Suite MR at 5 minutes.

To date, most software techniques remain manual, that is labour-intensive and reliant on operator experience, while validated evidence of commercially available automatic segmentation tool is scarce.[50,51] Interestingly, Rha and colleagues used ImageJ, a free NIH-developed image processing program, to successfully perform volumetric analysis of the orbit and breast from CT and MRI, respectively.[52] However, ImageJ has yet to be investigated in clinical application.

3D printing

In contrast to medical imaging modalities that are limited by being displayed on a 2D surface, such as a computer screen, a 3D-printed biomodel can additionally provide haptic feedback.[2,53–56] Three-dimensional printing, also known as rapid prototyping or additive manufacturing, describes a process by which a product derived from computer-aided design (CAD) is built in a layer-by-layer manner.[57–59] The main advantages of 3D printing are the ability to customise, cost-efficiency and convenience.[60,61] Since its introduction, the use of 3D printing in surgery has been extensively investigated.

In clinical application, two types of software platforms are required for 3D printing: 3D modelling software that can convert standard Digital Imaging and Communications in Medicine (DICOM) files from CTA/MRA into a CAD file; and 3D slicing software that divides the CAD file into thin data slices suitable for printing.[62] A range of modelling software is available but only the following are user-friendly and commonly reported: 3D Slicer,[51,63] OsiriX[64] and Mimics (Materialise NV, Leuven, Belgium).[65] Three-dimensional slicing software usually accompanies 3D printers at no additional cost and has a simple user interface such as Cube software (3D Systems, Rock Hill, SC, USA), MakerBot Desktop (MakerBot Industries, New York, NY, USA) or Cura (Ultimaker BV, Geldermalsen, The Netherlands).

In clinical application, a host of 3D printer types have been used including fused filament fabrication (FFF), selective laser sintering (SLS), stereolithography (SLA), binder jetting and multijet modelling (MJM).[2] Fused filament fabrication is the most common and most affordable 3D desktop printing technology available.[66–68] In an FFF 3D printer, a melted filament of thermoplastic material is extruded from a nozzle moving in the x–y plane and solidifies upon deposition on a build plate.[69] More recently, 3D metal printing using SLS has gained popularity in creating sterilisable surgical guides[70,71] and customised dental implants.[72]

Encouraged by its potential, surgeons from a wide range of specialities have applied 3D printing to their practice such as neurosurgery,[73–80] cranio-maxillofacial surgery,[81–88] cardiothoracic surgery,[89,90] orthopaedic surgery,[91,92] transplantation,[93–95] ear, nose and throat surgery[96,97] and breast cancer surgery.[98] Similarly, in reconstructive plastic surgery, 3D printing appears most useful for preoperative planning, intraoperative guidance, medical education and creating custom implants. 3D-printed bespoke implants overlap significantly with 3D bioprinting[99–101] and are beyond the scope of this article.

Preoperative planning

Three-dimensional printing has been most commonly used in plastic and reconstructive surgery for preoperative planning (see **Table 3**).

Autologous breast reconstruction

In 2014, Gillis and Morris reported the first case of a 3D-printed internal mammary artery (IMA) and its perforators, a common recipient site in free flap breast reconstruction.[102] Similarly, Mehta and colleagues 3D-printed a multi-colour, multi-material model of a deep inferior epigastric artery (DIEA) and its perforators.[103] Despite the benefits, both studies revealed the high cost of 3D printing (US$400–US$1200 per model), mainly due to having to outsource the manufacturing. In addition, outsourcing introduces delays of up to six to eight weeks that may not be appropriate in some clinical settings. As a result, Suarez-Mejias and colleagues developed their own 3D modelling software called AYRA (Virgen del Rocio University Hospital, Sevilla, Spain).[104] More recently, Chae and colleagues described an affordable and convenient technique of 3D printing using free software platforms and desktop 3D printers (see **Figure 3**).[51]

Soft-tissue modelling

In a case of lower limb reconstruction, Chae and colleagues 3D-printed a model of the soft-tissue defect that aided in flap design.[63] Similarly, Garcia-Tutor and colleagues used 3D-printed models of large sacral defects to perform qualitative and quantitative volumetric assessment.[64] Cabalag and colleagues fabricated a model of a giant squamous cell carcinoma that was useful for planning hemi-mandibulectomy and determining the length of the free fibular flap required.[105]

Bony modelling

Taylor and Lorio 3D-printed, in-house, a negative mould of a scaphoid/lunate defect from avascular necrosis from which a silicone model was created, sterilised and used intraoperatively for flap planning.[106] In an interesting application, Chae and colleagues described their technique of four-dimensional (4D) printing whereby multiple models of the thumb and wrist bones were 3D

Table 3. Use of CT/MRI-based 3D-printed haptic models for preoperative planning in plastic and reconstructive surgery

Clinical application		3D-printed model	Imaging	3D modelling software	3D printer
DIEP	**Case report**	Asymmetrical breast	CTA	Osirix (Pixmeo, Geneva, Switzerland)	Cube 2 (3D Systems, Rock Hill, SC, USA)
DIEP	**Case series of 35**	Breast	CTA	AYRA (Virgen del Rocio University Hospital, Sevilla, Spain)	FFF
DIEP	**Cadaver**	IMA perforator	CT	Mimics (Materialise NV, Leuven, Belgium)	ProJet x60 (3D Systems, Rock Hill, SC, USA)
DIEP	**Case report**	DIEP flap	CTA	Mimics (Materialise NV, Leuven, Belgium)	Objet500 Connex1 (Stratasys, Eden Prairie, MN, USA)
Lower limb soft-tissue defect	**Case report**	'Reverse' model of the defect	CTA	Osirix (Pixmeo, Geneva, Switzerland)	Cube 2 (3D Systems, Rock Hill, SC, USA)
Sacral soft-tissue defect	**Case series of five**	Sacral defect	CT/MRI	Osirix (Pixmeo, Geneva, Switzerland)	Cube 2 (3D Systems, Rock Hill, SC, USA)
Hemi-mandibulectomy	**Case report**	Mandible and giant invasive SCC	CTA	3D Slicer (Surgical Planning Laboratory, Boston, MA, USA)	MakerBot Z18 (MakerBot Industries, New York, NY, USA)
Bony defect of the wrist	**Case series of three**	Bony defect	CT	MeshMixer (Autodesk, San Rafael, CA, USA)	Micro 3D Printer (M3D, Fulton, MD, USA)
4D printing of thumb movements	**Case report**	Hand	4D CT	Osirix (Pixmeo, Geneva, Switzerland)	Cube 2 (3D Systems, Rock Hill, SC, USA)
Nasal cartilaginous defect Cadaver	**Human volunteer**	Nasal alar cartilage	MRI	GOM Inspect (GOM GmbH, Braunschweigh, Germany)	ZPrinter 250 (3D Systems, Rock Hill, SC, USA)
Augmentative rhinoplasty	**Case series of seven**	Individualised nasal implant	CT	Rhinoceros (McNeel, Seattle, WA, USA)	Cubicon Single (Hyvision System, Seongnam, South Korea

4D = four-dimensional CT = computed tomographic CTA = computed tomographic angiography DIEP = deep inferior epigastric artery perforator SCC = squamous cell carcinoma FFF = fused filament fabrication IMA = internal mammary artery. Source: Chae and colleagues,[51] Chae and colleagues,[63] Garcia-Tutor and colleagues,[64] Gillis and colleagues,[102] Mehta and colleagues,[103] Suarez-Mejias and colleagues,[104] Cabalag and colleagues,[105] Taylor and colleagues,[106] Visscher and colleagues,[107] Choi and colleagues,[108] Chae and colleagues[136]

printed from 4D CT scans to demonstrate their dynamic relationship.

Cartilage modelling

Three-dimensional assessment of nasal cartilaginous defect can be useful for planning reconstruction. Visscher and colleagues demonstrated that 3D printing alar cartilages using MRI showed a mean error of 2.5 mm.[107] Interestingly, most of the difference was found in 3D printing the medial crus but the lateral crus remained highly accurate, probably due to its more linear shape. Recently, Choi and colleagues 3D-printed a patient-specific negative mould from CT to create silicone nasal implants for augmentative rhinoplasty using

Fig 3. *3D-printed biomodel of breasts in planning reconstruction using Cube 2 printer (3D Systems, Rock Hill, SC, USA). Reproduced with permission from Chae and colleagues[51]*

Table 4. Summary of all studies investigating the use of an image-guided, 3D-printed surgical guide in mandibular reconstruction with a free fibular flap

Year	Patients	Source of 3D printing	Imaging	3D rendering software	3D printers
2017	18	In-house	CT	AYRA (Virgen del Rocio University Hospital, Sevilla, Spain) Osirix (Pixmeo, Geneva, Switzerland) 3D Slicer (Surgical Planning Laboratory, Boston, MA, USA) MeshMixer (Autodesk, San Rafael, CA, USA) Blender (Blender Foundation, Amsterdam, The Netherlands)	Objet30 Pro (Stratasys, Eden Prairie, MN, USA) Zortrax M200 (Zortrax, Olsztyn, Poland)
2017	3	Outsourced	CT	Osirix (Pixmeo, Geneva, Switzerland) MeshLab (ISTI, Pisa, Italy) Netfabb (Autodesk, San Rafael, CA, USA) Blender (Blender Foundation, Amsterdam, The Netherlands)	Formiga P 100 (EOS, Munich, Germany)
2017	7	Outsourced	CT	E3D Online (E3D Online, Oxfordshire, UK)	ProJet 3510 HD (3D Systems, Rock Hill, SC, USA)
2016	1	In-house	CT	Amira (FEI Company, Hillsboro, OR, USA) Blender (Blender Foundation, Amsterdam, The Netherlands)	PolyJet (Stratasys, Eden Prairie, MN, USA)
2015	1	Outsourced	CT	SurgiCase CMF (Materialise NV, Leuven, Belgium)	SLM
2013	68	Outsourced	CT	ProPlan CMF (Dupuy Synthes CMF, West Chester, PA, USA)	SLA
2013	48	Outsourced	CT	VoXim (IVS Technology, Chemnitz, Germany)	SLA
2013	10	Outsourced	CT	ProPlan CMF (Dupuy Synthes CMF, West Chester, PA, USA)	SLA
2013	38	Outsourced	CT	SurgiCase CMF (Materialise NV, Leuven, Belgium)	SLA
2012	1	Outsourced	CT	SurgiCase CMF (Materialise NV, Leuven, Belgium) Rhinoceros (McNeel, Seattle, WA, USA)	M 270 (EOS, Munich, Germany)
2012	1	In-house	CTA	AYRA (Virgen del Rocio University Hospital, Sevilla, Spain)	FFF
2012	9	In-house	CT	Mimics (Materialise NV, Leuven, Belgium)	SLA 3500 (3D Systems, Rock Hill, SC, USA)
2012	15	Outsourced	CT	Magics (Materialise NV, Leuven, Belgium)	SLA
2011	5	Outsourced	CT	N/A	SLS
2009	3	Outsourced	CT	Extended Brilliance Workspace (Philips Healthcare)	Objet Eden 500V (Stratasys, Eden Prairie, MN, USA)
2009	1	Outsourced	CT	SurgiCase CMF (Materialise NV, Leuven, Belgium)	SLS nylon

CTA = computed tomographic angiography SLM = selective laser melting SLA = stereolithography SLS = selective laser sintering FFF = fused filament fabrication. Source: Cohen and colleagues,[66] Bosc and colleagues,[109] Ganry and colleagues,[110] Liang and colleagues,[111] Mottini and colleagues,[112] Schouman and colleagues,[113] Seruya and colleagues,[114] Rohner and colleagues,[115] Saad and colleagues,[116] Hanasono and colleagues,[117] Ciocca and colleagues,[118] Infante-Cossio and colleagues,[119] Zheng and colleagues,[120] Hou and colleagues,[121] Antony and colleagues,[122] Leiggener and colleagues[123]

in-house software[108] and demonstrated a mean accuracy of 0.07 mm (0.17%) with no complications.

Intraoperative guidance

Use of 3D-printed fibular osteotomy guides for mandibular reconstruction has been studied extensively (see **Table 4**).[66,109–123] Investigators have demonstrated their accuracy of up to 0.1–0.4 mm.[66,110–112,117] Moreover, they can significantly reduce flap ischaemia time (120 minutes vs 170 minutes, $p = 0.004$)[114] and total operating time (8.8 hours vs 10.5 hours, $p = 0.0006$).[117]

Medical education

Educating junior surgical trainees and medical students about 3D pathological defects such as cleft lip and palate without hands-on interaction and demonstration is notoriously difficult. As the supply of cadavers for medical education continues to dwindle due to rising maintenance costs[124] and concerns regarding occupational health and safety,[125] the use of 3D-printed biomodels has become popular.[126,127] Zheng and colleagues have used 3D-printed negative moulds to fabricate soft silicone models of cleft lip and palate on which students directly perform cheiloplasty.[128] Subsequently, in a randomised clinical trial of 67 medical students, AlAli and colleagues demonstrated that the knowledge gained using 3D-printed models of cleft lip and palate was significantly higher than when using standard slide presentations (44.65% vs 32.16%, $p = 0.038$).[129] Similarly, clinicians have 3D printed negative moulds of paediatric microtia for practical demonstration.[130]

Conclusion

Many studies have explored the application of 3D-rendered conventional imaging modalities for 3D perforator mapping, 3D volumetric analysis and 3D printing.

There are numerous free, open-source software platforms that are capable of 3D image rendering, such as 3D Slicer and OsiriX. For perforator mapping, most plastic surgeons rely on CTA- or MRA-based 3D reconstructed images. Current 3D volumetric analysis technologies remain labour-intensive and are yet to be automatised.

Three dimensional printing has been most commonly used in plastic and reconstructive surgery for preoperative planning in mandibular reconstruction with a free fibular flap. The majority of these studies have a lower level of evidence, consisting of case series and reports. Furthermore, there is a lack of comprehensive review of all established 3D imaging and printing techniques in a language suitable for clinicians.

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