

REVIEW ARTICLE TECHNOLOGY AND IMAGING

Advances in perforator imaging through holographic CTA and augmented reality: a systematic review

Robert Phan MBBS,BBiomedSci,DipSurgAnat  0000-0002-4444-0353^{1,2} Michael P Chae MBBS,BMedSc  0000-0002-8313-1959^{1,2} David J Hunter-Smith MPH,FRACS,FACS  0000-0001-5660-0572^{1,2,3} Warren M Rozen MD,PhD,FRACS  0000-0002-4092-182X^{1,2,3,a}

¹ Frankston Hospital, Frankston, Victoria, AUSTRALIA. ² Monash University, Clayton, Victoria, AUSTRALIA. ³ Section Editor, *Australasian Journal of Plastic Surgery*, St Leonards, NSW, AUSTRALIA.

Keywords: CTA, perforator flap, augmented reality, technology, reconstruction

Submitted: 2020 September 20 AEST Revised: 2021 February 2; May 25 AEST Accepted: 2021 July 13 AEST Published: 2022 March 31 AEST Corrected: 2022 August 29 AEST (citations reordered). *You are viewing the most recent version of this article.*

DOI: <https://doi.org/10.34239/ajops.v5n1.263>

Australasian Journal of Plastic Surgery

Vol 5, Issue 1, 2022 | March 31 2022 AEST

Introduction

Free tissue transfer has become a mainstay in reconstructive plastic surgery, and techniques to plan such surgery continue to evolve. Novel technologies and increases in computational power have enabled computed tomographic angiography (CTA) data augmentation onto patients to assist in pedicle identification and dissection. Given the rapidly evolving field and research in this domain, a systematic review was undertaken to establish the evidence for its usefulness in pedicle identification and dissection.

Methods

An extensive search using keywords in EMBASE and PubMed® with bibliographic linkage following PRISMA guidelines was performed. We identified 107 articles. Duplicate articles were removed prior to review. Two reviewers independently screened the titles for appropriate topic relevance. Full articles were then screened for review.

Results

Eleven articles were appropriate for review. Two articles analysed the time taken to identify perforators using augmented reality (AR) compared to Doppler ultrasound. The remainder of the articles analysed time to perforator identification, differences between projected location and dissected perforator location, qualitative feedback from surgeons on the use of AR systems for perforator identification and proof of concept and the usefulness of AR in perforator flap surgery.

Conclusion

This review demonstrates that while established methods of data rendering and projection can achieve holographic projection and AR, there is a lack of objective outcome data to demonstrate its usefulness. This, combined with a cost analysis, are the main obstructions to this technology being more widely adopted.

Introduction

Since the advent of free vascularised tissue transfer approximately 40 years ago¹ significant improvements, particularly in the preoperative planning phase, have led to improved patient outcomes.² Techniques to identify perforators have evolved from handheld Doppler ultrasound^{3,4} to computed tomographic angiography (CTA) and magnetic resonance angiography (MRA). This is important due to the high degree of anatomical variation and intricacy of surgical dissection required. Individual patient anatomy may vary due to differences in development and subsequent changes due to previous surgery and scarring. Methods to account for such variations for preoperative perforator mapping have been developed^{5,6}. This approach reduces the amount of operative time required and risk of unanticipated anatomy that may compromise the perforator flap, hence increasing patient safety and the success of free tissue transfer.

Current imaging modalities are restricted by being represented in two-dimensional platforms, such as a computer screen or X-ray films. Clinicians have sought novel methods of using scan data from CTA or MRA to improve preoperative planning and surgical efficiency such as augmented reality (AR), where additional data is overlaid onto patients to help more accurately trace of the path of vessels through various tissues.

Due to the rapidly evolving field of AR in pedicled and free flap reconstruction to identify and dissect perforators, we conducted a systematic review of the literature to determine its usefulness in flap surgery.

Methods

This manuscript critically appraises the current literature on the use of AR to assist surgeons in surgical planning and dissection in accordance with PRISMA guidelines (Figure 1). A systematic search was performed by the primary author on EMBASE from January 2000 until May 2021 and PubMed[®] bibliographic databases to identify all English literature using keywords: ‘flap’ and ‘mixed reality’, ‘flap’ and ‘augmented reality’,

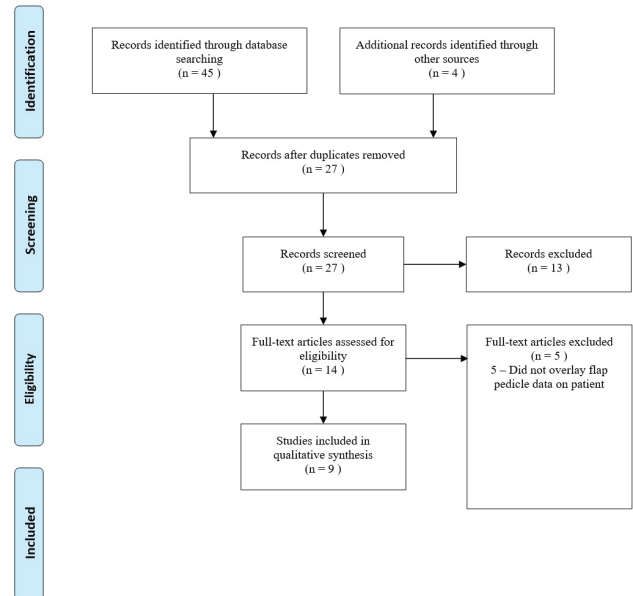


Fig 1. PRISMA flow chart demonstrating the selection process for articles

‘flap’ and ‘virtual reality’, ‘flap’ and ‘holographic/hologram’. We also identified relevant articles through bibliographic linkage.

To be included in this systematic review, the augmentation technology must have been used to identify perforating vessels by overlaying data onto tissues. Articles were excluded if they did not address the above inclusion criteria, were abstracts for conferences or previous systematic reviews.

A total of 103 articles were identified. Duplicate articles were removed prior to review. Four articles were identified from bibliographic linkages. Two reviewers independently screened the titles for appropriate topic relevance, with each abstract of each citation analysed to identify manuscripts suitable for review. Upon discussion, the full text of concordant papers were screened for review by RP and WR. Any disagreements were resolved by discussion.

As most articles did not report on standardised parameters such as time to perforator identification or dissection time, no statistical analysis was performed. Rather, qualitative aggregation of data was performed.

Results

Following article appraisal, eleven articles were included in the systematic review (Table 1). All articles were single institution case reports or series.

Method of augmented reality overlay

Five of the eleven papers used augmented reality headwear to overlay data onto the patient.^{7,12,14,16,17}

Other methods of projection included the use of a portable projector mounted on a fixed handstand and aligned with anatomical landmarks for preoperative marking,^{9,11,10} with one author reporting it took approximately 10 minutes from setting up the equipment to mapping out perforators¹⁵ and use of a smartphone to overlay flap data onto patients.^{8,13}

Flap harvest time

Two studies analysed perforator identification time using augmented versus non-augmented reality perforator identification methods.^{11,13} Pereira and colleagues used a smartphone and superimposed pedicle data onto camera data with the image aligned over anatomical landmarks and compared to handheld Doppler and intraoperative findings, noting a 20 per cent reduction in flap harvest time, on average from 90 minutes to 72 minutes.¹³ Hummelink and colleagues used a proprietary device that aligned the image based on markers placed on the patient that corresponded with anatomical landmarks. Conducting a randomised controlled trial with Doppler ultrasound planning as the comparison, they reported in deep inferior epigastric perforator (DIEP) flap harvest a decrease

Table 1: Characteristic of articles included in systematic review

Reference	Modality	Study design	Total number of participants	Outcome
Bosc et al ⁷	CTA: AR headwear	Single institution case series	12	Proof of concept, no data recorded
Cifuentes et al ⁸	Dynamic infrared thermography	Single institution case series	3	Median time to identify perforator 3.5 minutes
Hummelink et al 2015 ⁹	CTA: Projector	Single institution case series	9	Preoperative: 98/100 projected perforator locations had audible doppler signal Intraoperative: 19/34 transplanted perforators were correctly identified with unidirectional doppler, 29/34 with projection method
Hummelink et al 2017 ⁴ ¹⁰	CTA: Projector	Single institution case series	6	Doppler signal audible in 41/42 projected perforator locations
Hummelink et al 2019 ¹¹	CTA: Projector	Randomized controlled trial	60	Flap harvest time decreased by 19 minutes (12%) using projection when compared to doppler identification of perforators
Jiang et al ¹²	CTA: AR headwear	Single institution case series	6	Mean value of system error 3.474 +/- 1.546 mm between projected position of perforator and actual position on dissection
Pereira et al ¹³	CTA: Smartphone	Single institution case series	30	20% reduction in flap harvest time, from average 90 minutes to 72 minutes
Pratt et al ¹⁴	CTA: AR headwear	Single institution case series	6	Surgical team feedback - preferred over Doppler ultrasound
Sotsuka et al ¹⁵	CTA: Projector	Case report	1	Whole procedure from setting up projector to mapping out perforator took approximately 10 minutes
Nuri et al ¹⁶	CTA: AR headwear	Case report	1	Perforator location using AR was identified more accurately than using handheld doppler by 1 cm
Wesselius et al ¹⁷	CTA: AR headwear	Single institution proof of concept	0	Proof of concept, no data recorded

in time on average by 19 minutes (12%) when compared to preoperative ultrasound mapping (136 minutes versus 155 minutes respectively).¹¹

Perforator identification accuracy and time

Several studies compared the accuracy and time taken for perforator identification. Cifuentes and colleagues reported perforators identified through AR using thermography correlated with Doppler sound signals, with 3.5 minutes the median time to identifying perforators.⁸ Hummelink and colleagues demonstrated projection-based AR

technique to identify perforators using handheld projector and proprietary software in two case series.^{9,10} In the first series comparing AR to Doppler ultrasound in DIEP flap reconstruction,⁹ a greater number of perforators were identified compared to the Doppler ultrasound, and at a higher accuracy (84.3% versus 56.9%, $P = 0.03$). The authors, in their second series,¹⁰ using similar methods were able to identify a corresponding Doppler signal in 41 of 42 projected perforator locations. Nuri and colleagues reported their AR identified perforator corresponded with its actual location, which was 1 cm away from where the Doppler ultrasound

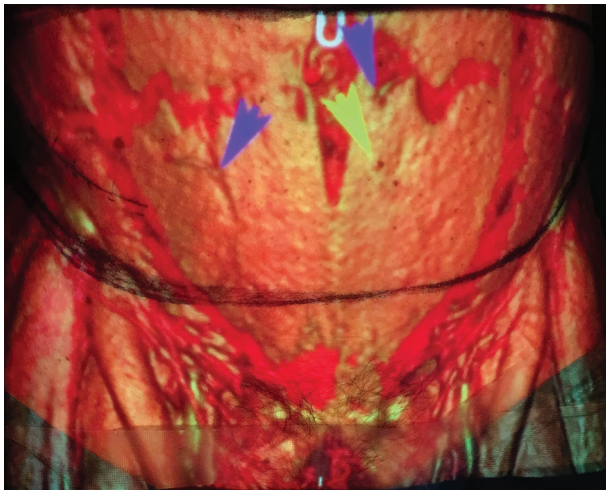
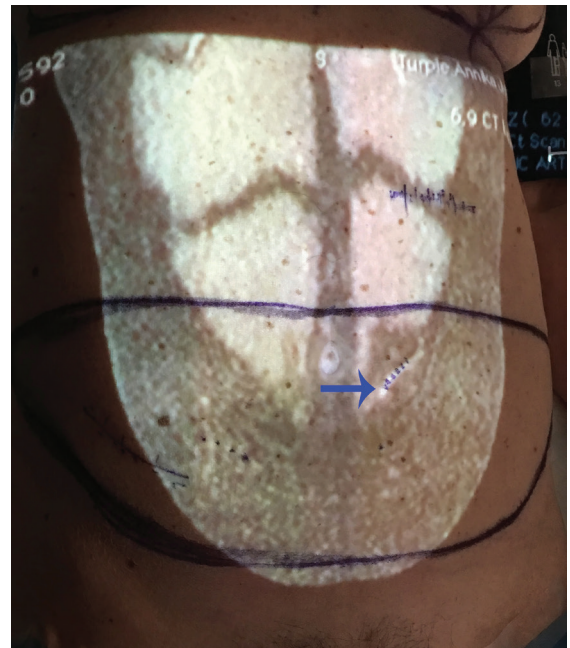
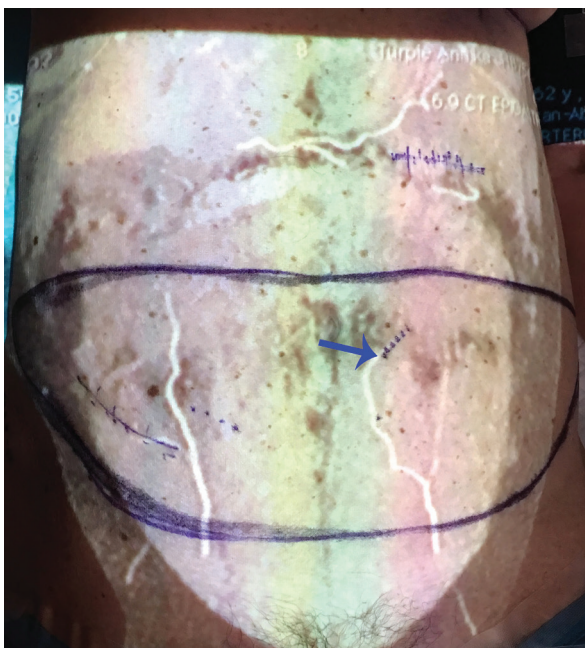


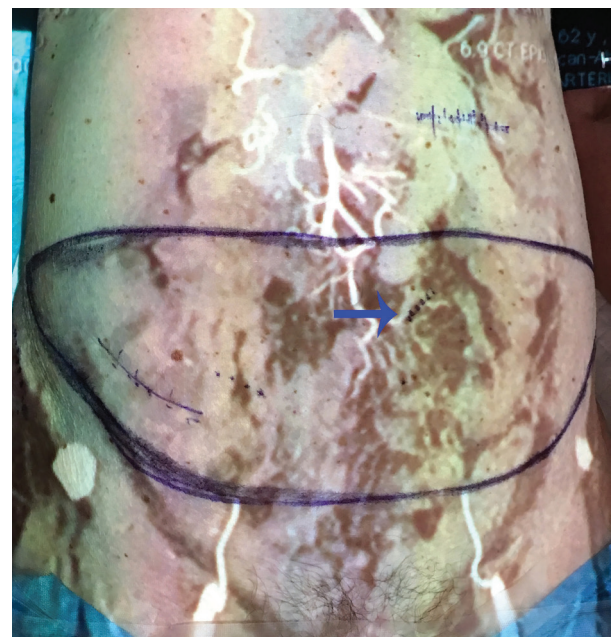
Fig 2. Direct augmented reality computed tomographic angiography technique for deep inferior epigastric artery perforator flap planning
A. Maintaining the same distance of the projector away from the patient at calibration, the 3D-reconstructed image of deep inferior epigastric artery perforators are projected onto the patient's abdomen, marking the cutaneous perforator location (blue arrow), yellow arrow demonstrates smaller perforators



B. View of the perforator projected onto the patient's abdomen to show the subcutaneous course of the perforator selected



C. Projection of the selected perforator's intramuscular course



D. Projection of the source vascular pedicle

had localised the perforator, although this was in only one patient.¹⁶ When comparing AR localised perforators and intraoperative findings, Pereira and colleagues demonstrated 100 per cent correlation.¹³ Jiang and colleagues study, which developed and used a proof-of-concept AR system on dogs, determined a system accuracy of 3.5 mm and was useful for raising thoracodorsal artery perforator flaps.¹² More recently, Wesselius and colleagues were able to demonstrate a technique that allowed real-time patient position to be compensated by the AR system via quick response markers attached to the patient.¹⁷

Surgeon feedback

The use of AR in operations performed in theatre has recently been demonstrated in a case series by Pratt and colleagues¹⁴ to aid the surgeon in identifying, dissecting vessels and navigating anatomy for both harvesting pedicled and free flaps to repair lower limb tissue defects. In all cases in this series, the surgeon noted no discrepancy between the AR projection of vasculature and the actual surgical position of the vasculature, preferring AR over ultrasound identification of perforators.

Discussion

Pioneered by Boeing scientists Caudell and Mizell,¹⁸ AR is a technology that augments the user's visual field with superimposed real-time images that can be displayed either directly on the object in real-life, known as the projection method, or indirectly on a portable device, such as a head-mounted display (HMD) or a smart phone.¹⁹ Its use has been well documented in the literature. Examples include calibrating stereotactic instruments in neurosurgery,²⁰ planning²¹ and fashioning craniofacial implants in maxillofacial surgery,^{22,23} enhancing visualisation in laparoscopic surgery²⁴ and identifying sentinel lymph nodes in breast cancer surgery.²⁵ In plastic surgery, it has previously appeared most broadly useful for preoperative planning, intraoperative navigation and surgical training.²⁶ As proof of concepts, several authors including our group have been able to demonstrate the usefulness of AR on living tissue^{7,27} to assist surgical planning (**Figure 2**).

Due to the high resolution provided by CTA, it is logical that there would be identification of more perforates in a shorter period of time when compared with conventional techniques such as handheld Doppler ultrasound, with a higher degree of accuracy and hence reduced operative time

associated with perforator dissection. Although there was one study that reported setting up AR projection to be fast at 10 minutes,¹⁵ there was a lack of studies that analysed the time difference between setting up and identifying perforators using AR with conventional Doppler ultrasound. This may negate any benefit from the time saved for perforator dissection using AR, which was faster by 12 per cent⁹ and 20 per cent¹³ when compared to other methods, with similar complication rates between the alternative technologies used.

While several articles used open source software, several authors used proprietary software for data analysis and rendering, and no articles analysed the cost of AR technology. The use of proprietary software coupled with novel hardware could lead to a significant cost burden on clinicians which choose to adopt such technologies, and may be a barrier to its uptake as an adjunct for flap reconstruction.

All of the articles analysed presented, to varying degrees, a method of data acquisition, analysis and rendering. However, all but one article addressed how to overcome the limitation of only being able to project AR onto static tissue. As identified by Hummelink and colleagues, a major limitation identified in regard to image projection is in relation to the operator, since the projector must be held steadily above the patient at a correct height without movement in order to give an accurate image of the anatomy.⁹ In cases where the projector device or patient was in a fixed position, there was no software that was able, in real time, to automatically segment raw data and perform volumetric rendering for real-time model alignment to correct for tissue deformation, such as when pressing on tissue to dissect. Of note, 3D visual technologies are being used anecdotally in other surgical specialities, such as orthopaedics, and while high-level evidence is lacking in these other fields, there is increasing interest in its usefulness to aid the surgeon.

Another limitation of projector-based AR not addressed by the articles is interference from ambient lighting. Projectors in general only have several hundred lumens of brightness. Although only projected onto an area less than one metre squared, this translates to a low lux level compared to theatre lighting which has been reported anywhere from 1000 to 100,000 lumens.²⁸ This is a significant impediment as it would mean, when trying to achieve adequate visualisation, all lights in the operating theatre must be significantly dimmed or turned off for the projection to be

visible, which may disrupt theatre flow and may compromise efficiency.⁸

Apart from data acquisition from AR technology, Hummelink and colleagues in their second series of six patients¹⁰ were also able to perform volumetric analysis of the breast using 3D scanning in order to calculate flap volume required, and hence project the ideal flap design onto the patient, something that has not been previously explored in the literature. Although novel and encouraging, current 3D surface imaging technologies have a reported error rate of 13–16 per cent,²⁹ and hence such techniques should be used with caution, as flaps may be undersized for what is required.

Conclusion

Advances in computer modelling of imaging data have led to holographic projection and AR being of great potential to influence the future of surgery. While the literature demonstrates that established methods of data rendering and projection onto patients can achieve true AR, there is a lack of objective outcome data to demonstrate its usefulness in assisting surgeons when compared to previous methods of perforator identification or dissection. This, combined with a cost analysis, are the main obstructions to this technology being more widely adopted.

Patient consent

Patients/guardians have given informed consent to the publication of images and/or data.

Disclosure

The authors have no financial or commercial conflicts of interest to disclose.

Funding declaration

The authors received no financial support for the research, authorship, and/or publication of this article.

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