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CLINICAL ARTICLE

Augmented Reality for Lymphovenous Anastomosis Planning Based on ICG Lymphography Anatomy of the Healthy Limb

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ABSTRACT

Background: When indocyanine green lymphography (ICG-L) fails to display a linear pattern, preoperative planning for lymphovenous anastomosis (LVA) becomes challenging. Given the anatomical symmetry of lymphatics in extremities, the healthy limb can serve as a template for the affected one. This study introduces an accessible technique that uses augmented reality (AR) to mirror the lymphatic anatomy of the unaffected limb onto the affected side to assist in surgical planning.

Methods: Twelve patients with unilateral secondary lymphedema of the upper or lower extremity (Stage II or less) were included. After standard ICG-L mapping, the unaffected limb was photographed when it showed a linear lymphatic pattern. The image was mirrored and superimposed onto the affected limb using an AR smartphone app to guide incision planning for LVA. Volume reduction and clinical outcomes were measured postoperatively.

Results: A total of 39 LVAs were successfully performed at the planned locations, with 100% intraoperative accuracy. No modifications or extensions of incisions were needed. Patients experienced an average operative time of 142.5 min. Volume excess was reduced by 47% over a follow-up period of 3–24 months, with a notable reduction in episodes of cellulitis and improvements in symptoms and quality of life.

Conclusions: "Mirror the lymph" is a reliable, low-cost AR-based planning method for identifying lymphatic vessels in patients with unilateral lymphedema when ICG-L mapping shows early dermal backflow. This technique improves surgical precision and efficiency and offers an innovative tool for resource-limited settings.

1 | Introduction

Accurate location of lymphatic vessels and precise lymphedema staging are indispensable for effective surgical planning (Rodriguez and Yamamoto 2022). Although following venous-axis surgical approaches may be considered, the reliability of lymphatic vessel identification remains uncertain, potentially leading to larger incisions and extended operative times (Winaikosol and Surakunprapha 2022; Hara and Mihara 2021a). Indocyanine green lymphography (ICG-L) has proven useful in assessing lymphatic function and anatomy, although it is limited by poor visualization of deeper lymphatics under 1–2 cm or when early dermal backflow is found (Narushima et al. 2015; Yamamoto, Yamamoto, et al. 2011; Yamamoto, Narushima, et al. 2011; Pereira and Koshima 2018; Hayashi et al. 2018; Czedik-Eysenberg et al. 2020). Furthermore, its high cost restricts its widespread use (Winaikosol and Surakunprapha 2022). When ICG-L fails to reveal a linear pattern in the affected limb, alternative imaging modalities like MRI (Pons et al. 2019) or ultrasound

(Hayashi et al. 2018) can be employed. However, these options may not be available in resource-limited settings. One potential solution involves utilizing the healthy limb as a template for the affected limb, taking advantage of the bilateral symmetry observed in limb lymphatic anatomy at the extremities (Narushima et al. 2015; Gentileschi et al. 2017). By identifying lymphatic vessels in the healthy limb and replicating this pattern on the affected side, surgical planning can be guided effectively.

Pereira et al. previously introduced the use of Augmented Reality (AR) for lymphovenous anastomosis (LVA) planning (Pereira and Venegas 2019). AR technology overlays digital information on real-world environments, enhancing task efficiency (Pereira and Venegas 2019; Pereira et al. 2022, 2019) by superimposing the ICG-L patterns onto the affected limb using a smartphone app. AR can optimize the use of resources and reduce operative time (Narushima et al. 2015; Yamamoto, Yamamoto, et al. 2011; Yamamoto, Narushima, et al. 2011; Pereira and Koshima 2018).

This article presents the novel use of AR for LVA planning, by mirroring the image of the healthy limb projected onto the affected limb. We demonstrate the efficacy of this approach through a series of cases.

2 | Patient and Methods

Patients with unilateral secondary lymphedema Stage II or less (ISL Staging) affecting the upper or lower extremities were included. Primary, bilateral, or Stage III cases were excluded. All patients signed a written consent authorizing their inclusion in the study. This research was conducted by following the principles of the Declaration of Helsinki (World Medical Association 2013) and obtaining approval from the Scientific Ethics Committee. Limb circumferences were measured before and after surgery. Volumes were calculated using the truncated cone formula (Pereira and Koshima 2018; Taylor et al. 2006) to quantify volume reduction.

2.1 | ICG Lymphography

Lymphography was performed on both limbs by injecting 0.1 mL of ICG subcutaneously. Linear ICG-L pattern of the unaffected limb was traced with a marker and standardized photographic documentation was taken. In cases when a linear pattern could not be visualized in the affected limb, the healthy limb was used as a template (Figure 1). We performed the procedure described by Mihara et al. (Mihara et al. 2014) to use the anatomy of the healthy limb evidenced in lymphography (standard technique) and compared with our AR technique named "Mirror the lymph".

2.2 | "Mirror the lymph"—AR-Assisted Planning

The AR-based planning procedure involved flipping the image of the healthy limb and overlaying it onto the affected limb using a smartphone app (Tracing Projector App with AR, Photility, Steve Doge). Two joints and the anterior border of the tibia were included in the photographic frame to enhance alignment during image overlay, especially when discrepancies in limb width were present. Anatomical landmarks were aligned using the app (Figure 2, Videos S1 and S2).

FIGURE 1 | ICG-Lymphography of a patient with right leg lymphedema showing a diffuse and stardust pattern in the affected limb and a linear pattern in the healthy left limb.

All patients underwent complex decongestive therapy (CDT) prior to surgery, and a quality-of-life survey was answered before and 3 months after surgery (Pereira et al. 2020). LVAs were performed under general or regional anesthesia. Two to three centimeters incisions were made according to the mirrored linear pattern, guided by the flipped image of the healthy limb (Videos S1 and S2). End-to-end LVAs were executed using 11–0 nylon sutures (Crown-jun, Kono Seisakusho Co. Ltd., Japan), and compression garments were applied immediately after surgery.

3 | Results

Lymphovenous anastomoses were performed in 12 patients with secondary extremity lymphedema using the "mirror the lymph" technique. Nine lower extremity lymphedema, and three upper extremity lymphedema (Table 1). The preoperative planning procedure took 3–4 min per patient using "mirror the lymph" technique versus 15–20 min per patient using the standard procedure.

A total of 39 LVAs were performed at the preoperatively planned locations, achieving 100% accuracy since no adjustments or extensions to the surgical incisions were necessary. No complications were recorded. The average operative time was 142.5 min. The follow-up period ranged from 3 to 24 months. During this time, patients had a mean reduction in volume excess of 47%. Furthermore, all patients experienced a decrease in cellulitis episodes from four episodes to none. Symptomatically, patients reported reductions in limb heaviness and swelling, with a significant enhancement in overall quality of life (Pereira et al. 2020) (Figure 3A–C).

FIGURE 2 | Use of a smartphone AR app to project the healthy limb's lymphatic anatomy onto the affected limb.

4 | Discussion

The success of LVAs relies on the preoperative identification of suitable lymphatic vessels to redirect lymphatic flow and alleviate volume excess in the affected limb (Rodriguez and Yamamoto 2022; Hayashi et al. 2018). Although some approaches follow venous anatomical pathways, they often result in variable outcomes due to imprecise lymphatic identification (Shinaoka et al. 2020; Granoff et al. 2022). The symmetrical anatomy of the limbs presents an opportunity to enhance precision by using the healthy limb as a guide for surgical planning (Gentileschi et al. 2017; Yodrabum and Tianrungroj 2022). Previous studies have suggested mirroring the contralateral limb to predict lymphatic pathways; however, to our knowledge, augmented reality (AR) using a smartphone app has not been used to replicate this mirrored anatomy in real time (Gentileschi et al. 2017; Mihara et al. 2014; Yodrabum and Tianrungroj 2022). Our technique introduces a practical and reproducible method that leverages readily available mobile technology to project the lymphatic map of the unaffected limb onto the affected side, allowing for more accurate, minimally invasive incisions (Mihara et al. 2014).

Numerous smartphone apps make image editing easier and allow users to overlay images onto the affected limb. These apps are widely available and enable marking without requiring expensive, sophisticated devices or cameras, thereby enhancing

TABLE 1 | Demographic characteristics and postoperative outcomes.

N	Sex	Age	Affected limb	BMI	Infections pre. op.	Operative time	PEV% pre.	PEV% post.	No. of LVA	Rev% vol post op.	Infection post op
1	F	37	LLL	35	Yes	100	23.9	11.5	3	51	No
2	F	68	LLL	29.7	No	240	29.8	6.8	4	77	No
3	F	51	RLL	17.1	No	140	4.32	1.5	3	65	No
4	F	46	RUL	21.5	No	160	16.9	15.4	3	8.8	No
5	M	78	RLL	34.3	No	240	43.28	20.4	4	52	No
6	F	57	LLL	26.5	No	80	59	15	3	74	No
7	M	44	RLL	30	No	110	20.34	13	3	36	No
8	M	69	RUL	26.4	Yes	100	67	49.5	3	26	No
9	F	39	LLL	23	No	130	2.12	1.77	3	16	No
10	F	53	LLL	24	No	110	27.35	15.63	4	42.87	No
11	M	28	RLL	26	Yes	150	29	21	3	26	No
12	F	67	RUL	30.4	Yes	150	58.8	6.91	3	88.23	No

Abbreviations: BMI, body mass index; LLL, left lower limb; PEV%, percentage of preoperative excess volume; REV%, percentage of reduction in excess volume; RLL, right lower limb; RUL, right upper limb.

FIGURE 3 | (A) Preoperative image of a 78-year-old patient with right lower leg lymphedema secondary to prostate cancer treatment; (B) Three-months follow-up after performing four LVAs guided by the "Mirror the lymph" technique; (C) Posterior view of the three-months follow-up.

accessibility and reproducibility in any setting equipped with smartphones. Meticulous planning and photographic documentation contribute to minimizing the margin of error during surgery.

In patients with unilateral secondary lymphedema, where lymphatic dysfunction impedes the location of the lymphatic vessels in the superficial system, utilizing the healthy limb as a template emerges as a valid alternative, potentially reducing the need for additional imaging studies (Yamamoto et al. 2014). It is important to emphasize that this method should be judiciously applied to carefully selected patients exhibiting no trophic skin changes or significant fibrosis indicating severe lymphatic vessel dysfunction (Hara and Mihara 2021b). Although we have occasionally applied this method in primary lymphedema, further studies are needed to evaluate anatomical symmetry and reproducibility in such cases. Therefore, it should be recognized that its use may be limited in advanced cases (Stage III) or in primary lymphedema. For proper validation of the technique or the alignment, future research is required comparing AR-assisted planning versus standard techniques in a randomized or matched cohort.

5 | Conclusions

"Mirror the lymph" with AR is an accessible, reliable and accurate planning method for predicting the location of lymphatic vessels, reducing costs, planning, and operative time for lymphedema treatment. It offers a low-cost option when no other

imaging methods are available. We propose using AR planning with a smartphone app in unilateral secondary lymphedema when identifying a linear pattern in the affected limb is not feasible.

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The authors have nothing to report.

Ethics Statement

This Study has been approved by the Scientific Ethics Committee (Institutional Review Board, IRB), approval number CEC/02/2024.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Video S1:** Complete surgical planning using "Mirror the Lymph" technique. **Video S2:** How to perform the "Mirror the lymph" technique: practical step-by-step demonstration and correlation with MR-Lymphography.