

Original Research Article

Evaluation of a replanted finger and measuring its perfusion changes to predict its viability by laser speckle contrast imaging

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ABSTRACT

Background: This research aims to monitor the microcirculation of the replanted finger, which was entirely severed by using laser speckle contrast imaging (LSCI) for early detection and revision of vascular compromise for successful finger replantation.

Methods: These six months of research was taken for a survey of 40 cases of replanted fingers of patients of distinct ages and sex. Scrutinizing was done postoperatively by LSCI, every hourly for seven days, to assess changes in blood perfusion both in replanted fingers and healthy ones and analyzed graphically.

Results: Initially, from postoperative d=0 to d=2, the perfusion value was at baseline, which ranged 40 ± 15 perfusion unit (PU), showing a wave-like curve, then gradually increased up to 350 ± 50 PU or above in case of those which survived successfully, showing continuous peak slope. However, a gradual drop in perfusion, <35 PU from d=2 or d=3, was seen in those despite undergoing heparinized finger pin-prick bleeding therapy and failed to thrive, showing a downslope curve. Whereas some were under meticulous observation, which flourished lately. Concurrently, a comparison was made with the healthy fingers' of the same patient, ranging from 200 ± 50 to as high as 400 ± 50 or above. Clinical correlation, as well as perfusion readings of LCSI, were done simultaneously.

Conclusions: LSCI provides sensitive and reproducible finger microcirculation measurements and is reliable in predicting reductions in blood perfusion induced by venous or arterial occlusion. It is, therefore, an informative device to detect microvascular compromise during and after replantation surgery.

Keywords: Replanted finger, Replantation, Laser speckle contrast imaging, Perfusion evaluation, Microcirculation, Predictability

INTRODUCTION

While evaluating the viability of a tissue clinically, numerous sophisticated techniques, such as laser Doppler flowmetry (LDF) and laser Doppler perfusion imaging (LDPI), have appeared to quantify and qualify this method for further objectivity. However, unlike laser speckle contrast imaging (LSCI), these have been least used in recent decades to evaluate local blood flow in stressed tissues, such as flap surgery, burns, dermal

perfusion in deep tissue imbrication and wound undermining for wound closure, and also to assess retinal blood flow, liver microcirculation after hepatic transplantation, in laparoscopic surgeries, gastric tube reconstructions following esophagectomy, neurosurgery to analyze cerebral blood flow, assess oral mucosal blood flow following periodontal plastic surgery and so on.¹⁻¹⁴ Despite this, clinical judgment by the surgeon remains the golden standard for postoperative evaluation of the tissue. However, clinical assessment is always subjective,

and tissue perfusion, also its viability cannot rely only on clinical experience.

Laser speckle contrast analysis (LASCA), also recognized as LSCI, is a technique based on the appraisal of the imaged speckle pattern that evolves from random interference of coherent light dispersed by a media comprised of light scattering particles and visualizes blood perfusion of microcirculatory tissue instantly.^{15,16} It is a camera-based method that illuminates a tissue area with 785-nm divergent laser light and analyzes the light interference pattern dispersed from the tissue composed of dark and bright fields, called a speckle pattern, which is equal to the proportion between the standard intensity deviation and the intensity mean.¹⁷ This pattern will alter over time when there is motion in the object, such as red blood cells in a tissue. A charge-coupled device (CCD) camera with a preset exposure time will record these changes as motion blurring in the speckle pattern in this PeriCam PSI System. The amount of blurring will vary depending on the degree of motion in the picture region. The more movement in an image, the more it appears blurred, the average intensity deviation will reduce, resulting in reduced speckle contrast, and vice versa. However, this relation is independent of frame rate, number of images, and tissue perfusion.¹⁸ PeriCam PSI system uses arbitrary units, perfusion units (PU), to record blood perfusion.

Fercher and Briers initially proposed the biomedical use of LSCI using analog techniques in 1981.⁷⁻⁹ It has developed into a non-invasive, non-contact, and rapid method for measuring microvascular blood perfusion with the growth of digital cameras and quicker computers.



Figure 1: Post-operative LSCI assessment of a replanted middle finger (rt.) of a patient in the general ward at a working distance within 8-10 cm, at room temperature $26\pm 2^{\circ}\text{C}$.

LSCI is currently used primarily in microvascular research, where it is used as a skin perfusion measurement technique during microvascular function

testing and can be easily handled and used on the bedside (Figure 1) or during operations (Figure 2) due to its technological simplicity; and elevated spatial and temporal resolution, making it appropriate for dynamic functionality. Blood flow (volume of blood per unit time in the vasculature) and perfusion (quantity of blood per amount of tissue per unit time) are vital clinical microcirculation parameters.¹⁹ The blood flow speed strongly relates to the morphology of the vasculature itself (e.g., local vessel diameters and vessel density).^{19,20}



Figure 2: Immediate intra-operative monitoring of a replanted lt. index finger by LSCI in an operating room, keeping the working distance (distance between the laser lens and the skin to be measured) between 8-10 cm.

Many reconstructions and replantation surgeries are practiced in today's plastic and reconstructive world. These have, however, so far been the least evaluated by the above techniques.²¹ Hence, the purpose of this research is to assess a replanted finger by LSCI, every hour or so for seven consecutive days after surgery, and to monitor the vascularity of the replanted finger for the early detection and review of vascular compromise for successful finger replantation.

METHODS

Patients

The research was authorized by the Institutional Review Board of the Provincial Hospital affiliated with Shandong University, People's Republic of China, and under all local rules and regulations, informed consent acquired from each patient. From March 2019 to August 2019, forty cases of patients with severed fingers, whether transphalangeal amputation (proximal phalanx or middle phalanx or distal phalanx or through proximal interphalangeal joint (PIPJ) or distal interphalangeal joint (DIPJ)) or fingertip amputation (Tamai Zone I or II) of distinct ages and sexes, were taken for this 6-month pilot study. They were hospitalized and operated as an emergency basis with the history of accidental or machine crush injuries, or guillotine injury by knife or slamming by a door, etcetera.

Table 1: The number of replantation cases and their perfusion data of patients of different age groups and sexes, the levels of amputation of fingers, injury types, neurovascular structures and tendons repaired, and the number of cases where vein grafts were required.

Replantation category	Total no. of fingers	Average perfusion	Mean age and sex (total no.)	Levels of amputations (total no.)	Injury types (total no.)	Neurovascular structures anastomosed (total no.)	Palmar cutaneous vein graft (total no.)	Bone fixation by Kirschner wire (total no.)	Flexor and extensor tendons repaired (total no.)
Survived	Uncompromised	22	350±50 PU (p<0.05)	Tamai Zone I (6)	Machinery crush (14)	Nerves [0.5mm-0.7mm diam.] (32)	(18)	Single axial/ Double axial/ Arthrodesis	Flexor tendons (34)
	Compromised or under special Observation	3	100±50 PU (p<0.0005)						
	Heparinised finger Pin-prick bleeding therapy	9	200±50 PU (p<0.001)	M: F (30:10)	Accidental Crush (13)	Veins [0.6mm-0.9mm diam.] (38)	(34)	Extensor tendons (30)	
	Exploratory surgery	1	300±50 PU (p<0.00005)	Transphalangeal [PP or DP or MP or PIPJ or MPJ or DIPJ] (24)	Guillotine (9)				
Necrosed	5	<35 PU (p<0.00003)							

PU= Perfusion unit, M= Male, F= Female, PP = Proximal phalanx, DP= Distal phalanx, MP= Middle phalanx, PIPJ= Proximal interphalangeal joint, DIPJ= Distal interphalangeal joint, MPJ= Metacarpophalangeal Joint, diam.= diameter, p= p value, mm= millimeter.

Equipment

Laser speckle contrast imager (PeriCam PSI system, Perimed AB, Jarfalla, Sweden) LSCI has been used to evaluate the replanted finger's skin perfusion.^{15,22-24} The working distance, that is, the space between the LSCI camera and the skin to be monitored, placed precisely 8-10 cm above the patient's finger. Depending on the central axis of the fingers replanted, the region of interest (ROIs) was taken as 2-5 mm², average 5 mm², and marked. The perfusion evaluated by illuminating the tissue with a divergent laser beam (invisible near infrared) of 785-nm-wavelength, generating a pattern of speckle over the illuminated region. An advanced CCD camera recorded the speckle image, while another captured a standard color picture of the measured area. The camera exposure time for all measurements was kept constant at 30 sec. By using a frame grabber, the acquisition rate was set to 10 images/s and was procured at 50 Hz mains frequency frame rates and saved on a post-processing computer using custom software. The images transformed into pseudo-color images during this process, where the flow indicated from red (high flow) to blue (low flow).

Surgical procedure

After immediate hospitalization, emergency surgery was performed. The severed fingers were preserved at 4°C for 5-7 hours before the operation. A thorough history and necessary investigations have been done to exclude any major diseases such as cardiac, pulmonary disease, or peripheral vascular disease, so on, and precautions were taken accordingly. Replantation surgery performed by thoroughly washing the wound by hydrogen peroxide, chlorhexidine, 0.9% normal saline, and povidone-iodine. Thorough debridement of contaminated and necrotic tissues done, fixed the stump and the proximal part of the fingers with single or double axial Kirschner wires, arthrodesis done in some cases, flexor and extensor tendons were repaired respectively, digital nerves, and vessels (diameter ranging 0.6-0.9 mm) with or without palmar vein graft, anastomosis done (Table 1).²³⁻²⁵ The room temperature and the patients' vital parameters like blood pressure, heart rates, and other vital signs continuously monitored both intraoperatively and postoperatively.

Subsequently, the postoperative assessments were performed by LSCI for 24 hours for seven consecutive days to monitor the perfusion. All measurements performed at approximately 26±2°C room temperature. During this period, the patients laid supine, comfortable, and warm, and the operated hands immobilized by external plaster in a neutral position. Parenteral medications like injectable anticoagulants, antispasmodic, vasodilator, antibiotic, and analgesics set accordingly. At times, finger pin-prick bleeding therapy and heparin soaked gauze was also provided, to those nearly to fail replanted fingers.^{26,27}

Data analysis

LSCI images were processed using the system analysis software program. The perfusion values represented as PU (perfusion units) defined as an arbitrary unit calculated from the speckle contrast analysis.²⁸ It can be rapidly processed to generate a full-field map of the perfusion index proportional to the concentration and mean velocity of red blood cells in the tissue to be measured.²⁹ A circular region of interest (ROIs) ranging from 2 to 5 mm², an average 5 mm², was selected in each image. The frame rate set to 10 images per 30 sec. For each image, the average perfusion in each ROI calculated. The perfusion data of the replanted finger and that of the normal healthy finger were measured and obtained every hourly after operation for seven days; statistically analyzed and graphically represented in Microsoft Excel Worksheet.

RESULTS

Forty cases of replanted fingers (which were entirely severed) whether transphalangeal amputations (PIPJ or DIPJ or proximal or middle or distal phalanges) or fingertip amputations (Tamai zone I or II) and of distinct ages and genders are included in this six-month pilot study. Despite other general health issues, surgery performed as an emergency basis under controlled observation and care. The perfusion of these replanted fingers was compared with that of the healthy fingers of the same patient and monitored every hourly for the whole day consecutively for 7 days, both clinically and by LSCI (Figure 3). LSCI images were also captured instantly after surgery. Replanted finger microcirculation measurements were successfully made in all patients, resulting in analyzable speckle contrast images and assumption of a mean threshold value by which we can predict the viability.

The recorded perfusion values were analyzed in the Excel worksheet, and a graph was obtained. Amongst forty replanted fingers, twenty-two revived effectively. On postoperative d=0 to d=1, the average perfusion, in these uncompromised replanted digits, was found to be at baseline, from as low as 40±10 PU or 100±50 or above, depending on patients' body built (Figure 4). From d=3 to d=5, there was a gradual increase in perfusions each day, rising to 350±50 PU or more, forming a steady wave-like curve. Nine, however, survived after enduring supervision owing to the heparinized finger pin-prick bleeding therapy, creating a sustained peak from d=2 or d=3 onwards; perfusion value rising to 200±50PU or above (Figure 5). However, five failed to survive even after the therapy, as mentioned earlier, building a stable downslope perfusion curve of <35 PU at d=2 or d=3, which later resulted in amputation (Figure 6). Three were seemingly morbid due to visible color change of skin; however, they endured after removing a few stitches, showing saw-tooth like curve, varying from as low as 35±5 PU to as high as 100±50 PU (Figure 7). One had to

undergo immediate exploratory surgery when perfusion dropped below the threshold level; however, it rose to 300 ± 60 PU after the revision surgery (Figure 8). By this

study, we believe that when the perfusion of the replanted finger falls below the threshold level, it fails to thrive.

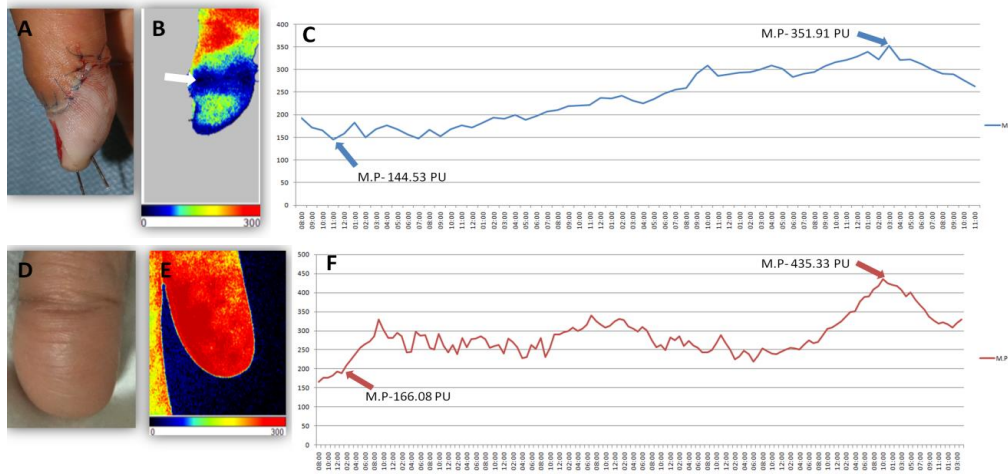


Figure 3: Respective photographs and LSCI images (A and B) showing a replanted right thumb of a 25-year-old male and that of his healthy left thumb (D and E), respectively; arrow in (B) showing minimum perfusion when ROI - 3.7×4.2 cm; the color bar below shows high blood perfusion (red) and low perfusion (blue); (C) show crinkly changes in perfusion curve of 7 postoperative days; arrows indicating low perfusion of 144.53 PU (lt.) at 0 post-operative day and highest perfusion of 351.91 PU (rt.) on 7th post-operative day and later gaining stability in an uncompromised replanted thumb. Note the perfusion values in the graph of a healthy thumb (F), the lowest perfusion of 166.08 PU (lt. arrow) at 0 post-operative day, and the highest 435.33 PU (rt. arrow) at 7th post-operative day.

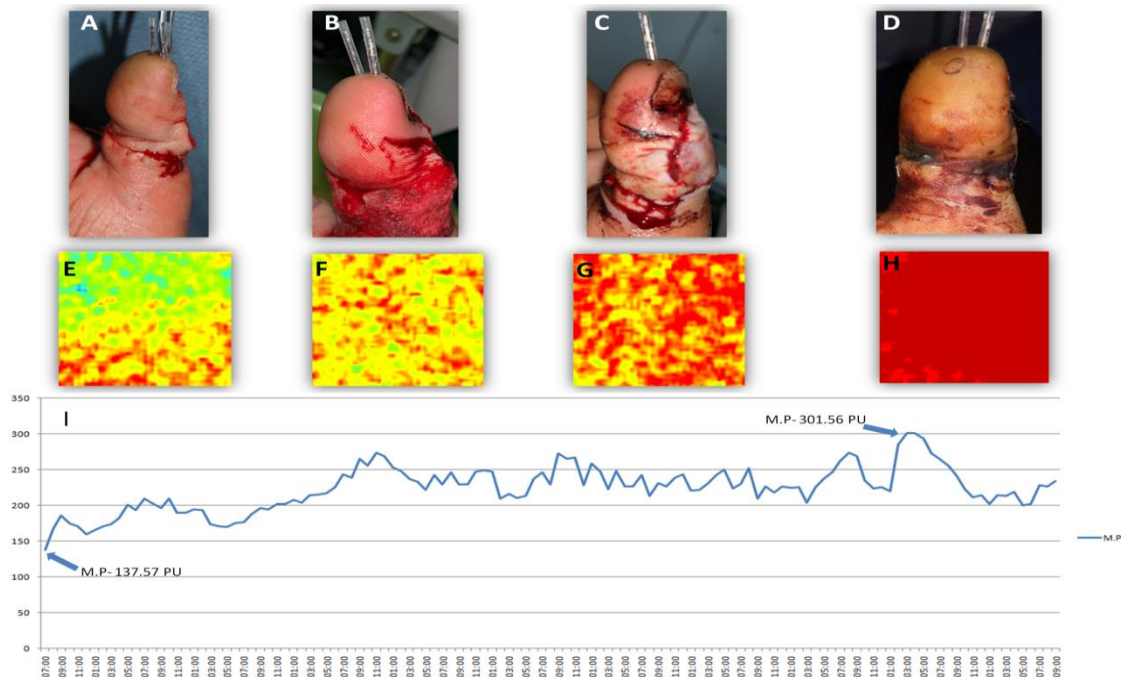


Figure 4: (A-D) No or mild changes in skin color and perfusion in an otherwise typically healed replanted digit of a 32-year-old male, rt. thumb (saw machine crush injury, transphalangeal amputation of proximal phalanx) on 1st, 3rd, 5th, and 10th post-operative days, respectively; (E-H) LSCI images illustrating changes in skin perfusion of 5 mm^2 ROI; (I) showing corresponding seven postoperative days' steady wave-like perfusion curve; arrows showing lowest perfusion - 137.57 PU (lt.) on 0 post-operative day and highest - 301.56 PU (rt.) on 7th post-operative day, getting stable subsequently ($p < 0.05$).

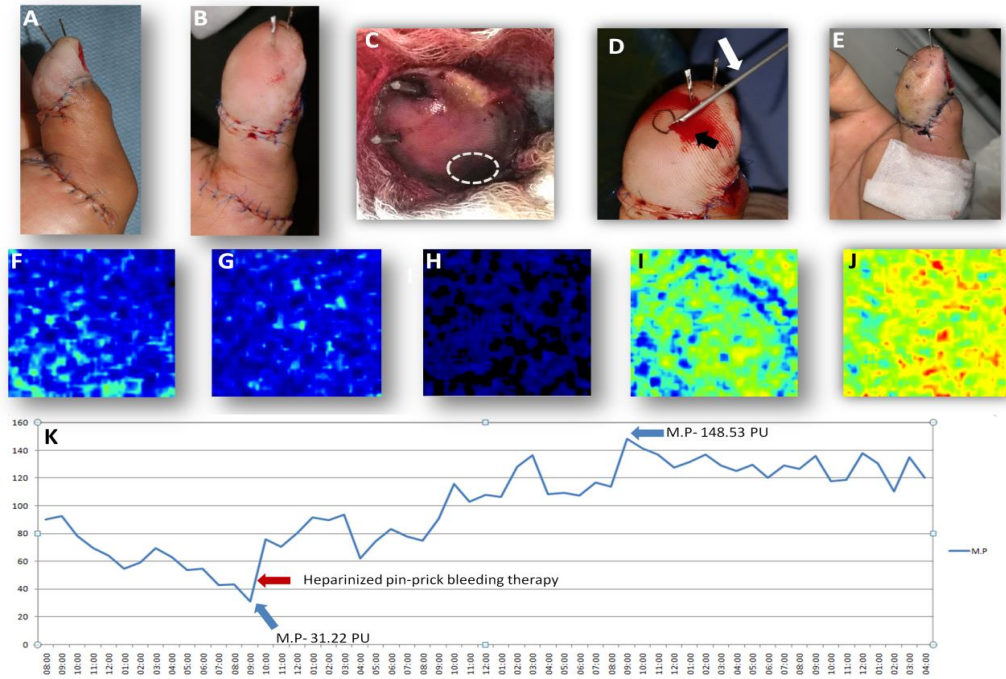


Figure 5: (A-E) Visual appearance changes of a 50-year-old male, replanted rt. thumb (machine crush injury, Tamai zone II amputation) on 0, 1st, 3rd, 5th, and 8th post-operative days, respectively, along with their corresponding LSCI images (F- J); white dash area in (C; arrow) shows skin color change due to less perfusion in ROI of 5 mm² on 3rd post-operative day, perfusion falling to 31.22 PU (K; lt. blue arrow). Henceforth, pin-prick bleeding therapy [by a syringe needle, white arrow (D)], and adding heparin-soaked gauzes executed. Note the fresh blood exsanguinating from the pricked area (D; black arrow), thus increasing perfusion gradually (K; red arrow), forming a sudden peak-like curve rising to 148.53 PU on 5th post-operative day, subsequently becoming steady; (E and J) its survival on the 7th post-operative day (p<0.001).

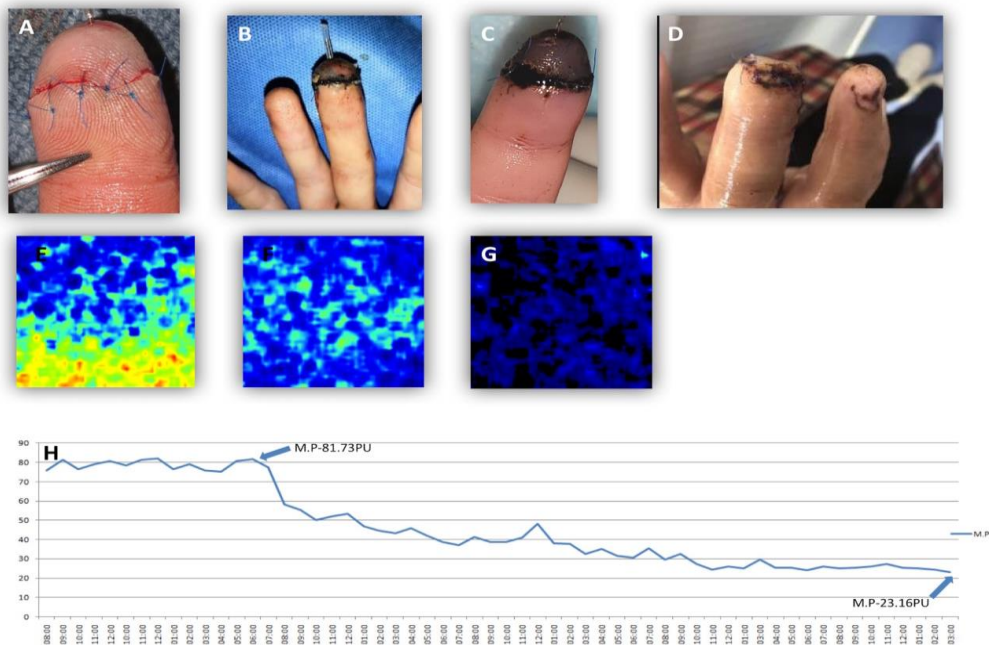


Figure 6: (A-C) Gradual changes in the skin color of a necrosed replanted rt. middle fingertip (accidental crush injury, Tamai zone I) of a 14-year-old female on 0, 1st, 3rd post-operative day, respectively; the corresponding perfusion changes of speckle images (E-G) from moderate to very low perfusion, well illustrated in (H), with high perfusion of 81.73PU on 1st post-operative day steadily falling to 23.16 PU on 3rd post-operative day; (D) the necrosed stump was amputated later (p<0.00003).

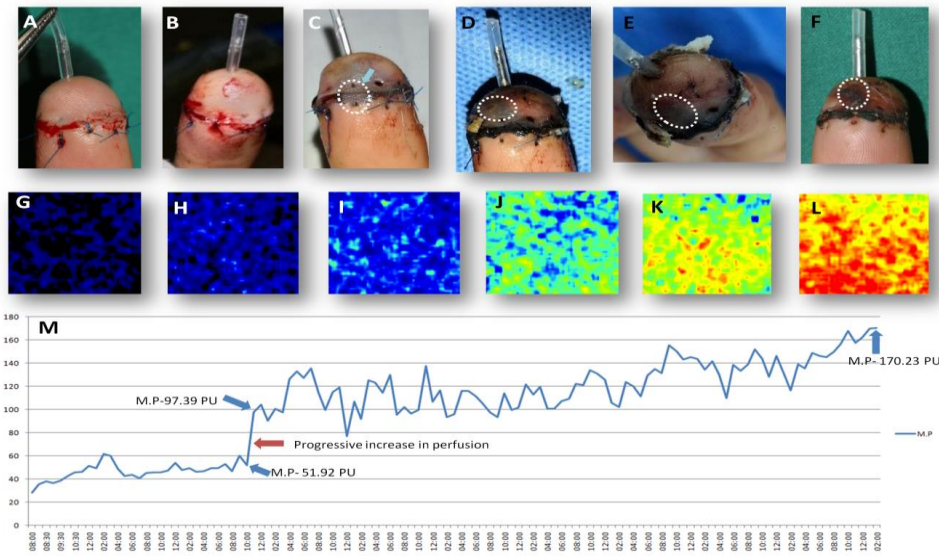


Figure 7: (A-F) Typical visual images of an 18-year-old female replanted rt. middle fingertip (guillotine type, door crush injury, Tamai zone I amputation); despite the usual appearances of (A and B) on postoperative and 1st post-operative day respectively, however, their corresponding contrast images (G and H) show low perfusion ROI; cautious observation without any intervention was taken; hereafter, few stitches were removed on 2nd post-operative day (C; white dotted area), the tension was decreased, showing noticeable improvement in perfusion (I), rising to 97.39 PU from as low as 51.92 PU (M) forming a saw-tooth like graph of the perfusion curve; however, the dark tint of the skin (D-F, white dotted circles) lingered, yet, the corresponding contrast images (J-L) show tremendous improvement in perfusion, and is evident in (M) with maximum perfusion of 170.23 PU on 7th post-operative day [p<0.0005].

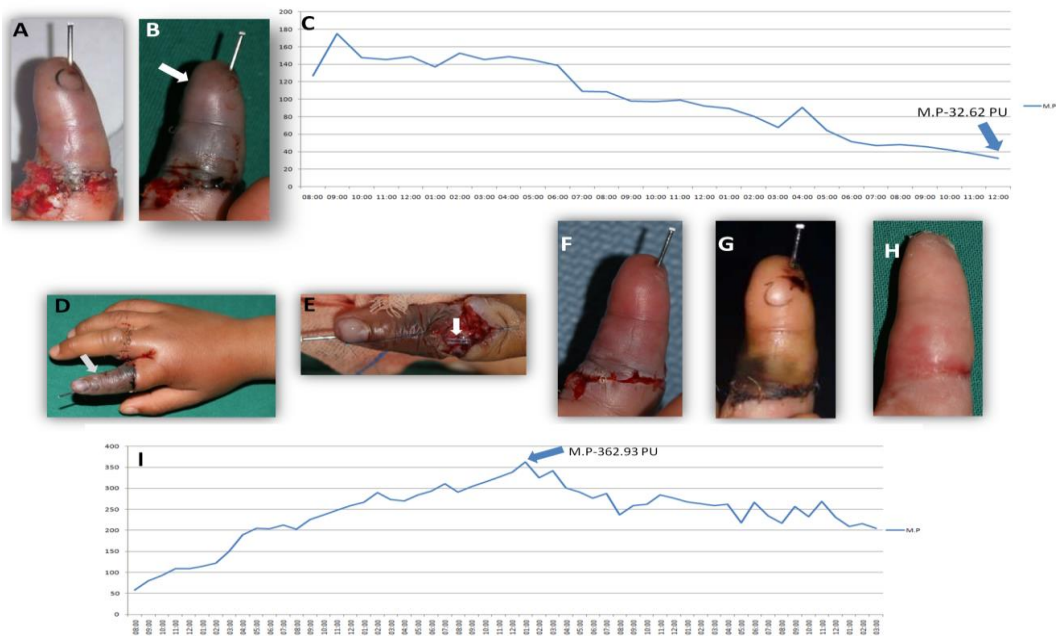


Figure 8: (A) The visual appearance of a replanted rt. index finger of a 3-year-old boy (Guillotine type, knife-cut injury, transphalangeal amputation; PP) on 1st post-operative day. Note the skin color changes in (B and D; arrows) due to venous congestion on the 2nd post-operative day; corresponding perfusion graphical representation (C) gradual downslope from 2nd post-operative day, falling to 32.62 PU; subsequently, exploratory surgery was performed immediately, excising the thrombosed segment of dorsal digital veins up to 0.01mm and reanastomosing them (E, arrow); henceforth, gradual improvement in vascularisation is seen F and G on 0 and 3rd post-operative day, respectively, rising to 362.93 PU (I, blue arrow) on 3rd post-operative day and getting continuous afterward. (H) Shows effectively healed replanted finger after one month [p<0.00005].

DISCUSSION

Finger amputations, whether complete or partial, are one of the significant common injuries faced in emergency departments worldwide.^{24,26} Despite advanced and sophisticated microsurgical surgeries, like replantation, doubts about the outcome have not yet solved.²⁴ These situations prevailed over by using devices like LDF and LDPI, which are being used for decades to evaluate local blood flow in stressed tissues. However, these have not been implemented much for assessing tissue perfusion in replanted fingers.^{4,20,22}

LASCA, also known as LSCI, is a dynamic, non-invasive, camera-based technique, that is readily applied and performed anywhere close to the bedside or operating theatre, and visualizes blood perfusion of microcirculatory tissue instantly due to its high spatial and temporal resolution.^{1-4,6-9}

There are principal benefits of postoperative screening using LSCI. First, this camera-based method allows surveillance of microcirculation without touching the patient or the finger replanted. Second, tissue perfusion is measured in real-time within few seconds and can obtain a complete perfusion image which, is continually documented and makes it particularly suitable for use in restless patients who are not able to lie still for a long time. Third, it enables observation of the rapid response to arterial or venous occlusion. Fourth, skin perfusion can be quantitatively evaluated using LSCI, although it will require further clinical investigations to verify its effectiveness.

A significant drawback, however, is the technique's sensitivity to the tissue motion to be measured. It is particularly grueling in the evaluation of unsedated kids and uncooperating patients after surgery where, despite the brief procurement moment, artifacts are prevalent owing to patient motion, and breathing which can lead to diagnostic errors if clinical choices are to be made using the method. Another study limitation is, it is arduous to evaluate very tiny regions (ROIs), such as the fingertips, as most of the finger length is covered by gauze bandages and dressing pads, the possible impact on the measured perfusion of the measuring range, and tissue curvature.

There are many previous studies in which LSCI was used to assess the ability to detect microcirculation in stressed tissues, such as flap surgeries, burns, poorly healing wounds, to evaluate retinal blood flow in optic or ocular surgery, in liver transplantation, in laparoscopic surgeries, in gastric tube reconstructions following esophagectomy, neurosurgery to assess cerebral blood flow, etcetera.¹⁻¹³ However, there have been only articles about case studies published so far regarding the evaluation of replanted fingers by LSCI.²¹

To our best knowledge, this pilot study is used for the very first time for the assessment of replanted finger

microcirculation. The primary ruling in this study is that LSCI is a robust and secure method that can reliably measure changes in the perfusion of replanted fingers postoperatively, every hour, for the first week. Initially, the perfusion value curve was at baseline, from as low as 40 ± 10 PU or 100 ± 50 or above (depending on patients' body built), for the early two or three postoperative days, gradually increased to 350 ± 50 PU for those fingers which persevered successfully within ten days ($p < 0.05$). In other cases, it remained stable for the first few days ranging 35 ± 15 , then owing to special care and observation like heparinized finger pin-prick bleeding therapy, the perfusion curve had a gradual steep and raised to 200 ± 50 PU or more from $d=2$ or $d=3$ onwards, indicating its survival ($p < 0.001$). However, few were under meticulous observation without any intervention, perfusion ranging 100 ± 50 PU ($p < 0.0005$). Some needed exploratory surgery when perfusion had a sudden fall below the threshold ($p < 0.00005$); whereas some failed, despite careful observation and care ($p < 0.00003$).

Shortly, there are plans to study and evaluate the post-operative changes in perfusion patterns on random pattern flaps by LSCI.

CONCLUSION

In conclusion, we have found that the mean perfusion values initially during $d=0$ to $d=2$ were nearly stable and low, forming a threshold of 40 ± 10 PU, however, when gradually increased to 350 ± 50 PU at $d=3$ to $d=5$, the curve had a steady peak, showing the viability of an uncompromised replanted finger. When compared with a healthy finger, the perfusion values were nearly or higher than the replanted finger that thrived, about 400 ± 50 PU or more. However, a gradual drop in perfusion, < 35 PU, seen on $d=2$ or $d=3$ in those despite undergoing heparinized finger pin-prick bleeding therapy, failing to survive, had a gradual, continuous downslope. Some were undertaken particular observation in those which were seemingly congested; the perfusion values ranging from 35 ± 5 PU to as high as 100 ± 50 PU. Hence, LSCI is a promising predictor for the foreseeable tissue necrosis and a reliable, easily implemented technique to assess replanted finger microcirculation in real-time and lessen unavoidable complications.

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