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Evaluation of the Circulation of Reconstructive Flaps Using Laser-Induced Fluorescence of Indocyanine Green

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A new method for evaluating the circulation in surgical flaps using laser-induced fluorescence of indocyanine green (ICG) images is reported. In clinical trials the authors found that ICG imaging demonstrated good circulation accurately in 16 of 21 flaps with no clinical manifestations of compromised circulation. In 3 patients in whom partial discoloration and cyanosis of the flaps were visible, the dye study indicated poor circulation in the identical areas. In 2 other patients in whom flaps appeared clinically satisfactory, the flaps were shown by ICG imaging to have greatly compromised circulation. In a patient in whom the flap was left in place, slough of almost the entire flap resulted. Another flap with questionable circulation was returned to its original location, where it healed. Thus, while it is a still a new approach and under continual evaluation, the use of ICG fluorescence shows promise as a valuable adjunct to current methods of flap evaluation.

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Evaluation of the viability of skin flaps used in reconstructive surgery depends on adequate circulation, which can be difficult to demonstrate. The most commonly employed methods (such as checking tissue color, capillary blanching and refill, and dermal bleeding) are based on subjective clinical inspection, which can be inaccurate even for experienced practitioners. More objective techniques to evaluate flap viability (such as measurement of skin temperature, blood velocity, fluorescein dye perfusion, transcutaneous oxygen monitoring, and ultrasonic Doppler) have not seen widespread acceptance for a number of reasons, including high cost, added time and complexity, and, most importantly, lack of convincing evidence of efficacy.[1–3]

A promising new method of assessing flap circulation is now available. Similar in principle to fluorescein injection, the technique employs indocyanine green dye (ICG) as a fluorescent marker of cutaneous blood. ICG is well suited for this purpose because it binds strongly to blood proteins, has absorption and emission peaks in the near-infrared wavelengths (800 and 840 nm respectively) where the skin is relatively transparent, and has seen widespread diagnostic use for cardiac output, hepatic function, and ophthalmic angiography with few adverse reactions. After the dye is injected, a timed series of laser-induced fluorescence images of the flap are collected, showing the uptake, steady-state distribution, and clearance of dye-marked blood from the flap. Thus, the technique provides direct visualization of circulation to the flap, and is clinically useful in predicting flap viability, monitoring flap healing and treatments, and evaluating flap delays.

Method and Apparatus

The primary components of the diagnostic method and apparatus are shown in Figure 1A. The alignment of the laser and camera is shown in relation to the skin surface. In the current apparatus, the excitation source is a pulsed infrared diode laser array with a wavelength of 800 nm (to match the absorption peak of ICG), a

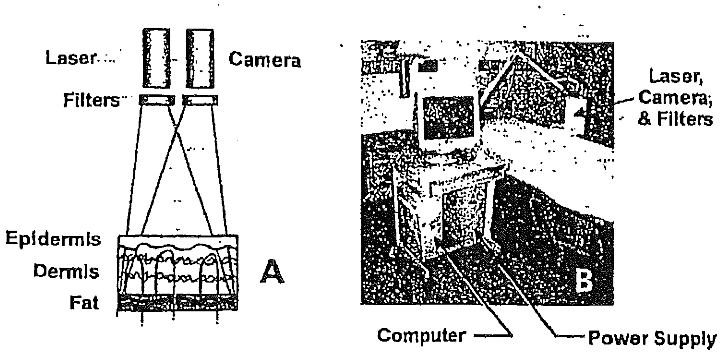

Fig 1. (A) Schematic indicating the diagnostic technique. The filtered laser light induces fluorescence from indocyanine green dye contained in the cutaneous blood, and the resulting fluorescence is collected by a filtered camera. (B) Photograph of the device used in the clinical trials. The device is mobile; the computer, power supply, and monitor are contained on a cart, and the laser, camera, and filters are attached to an articulated arm that is positioned above the patient.

pulse duration of 0.5 to 16 msec, and a pulse energy of as high as 1 J. The output of the diode laser array is imaged onto the skin to illuminate uniformly an area approximately 500 cm^2, and will penetrate to a depth of several millimeters. This level of illumination is far below the skin's damage threshold but provides good signal-to-noise fluorescence images with injection concentrations of 0.1 mg ICG per kilogram of patient weight, which is 10 times lower than the Food and Drug Administration-approved dosage for other applications. The fluorescence is imaged by a nonintensified charge couple device video camera that is filtered optically to block ambient and laser light, and to collect only ICG fluorescence. The images are digitized

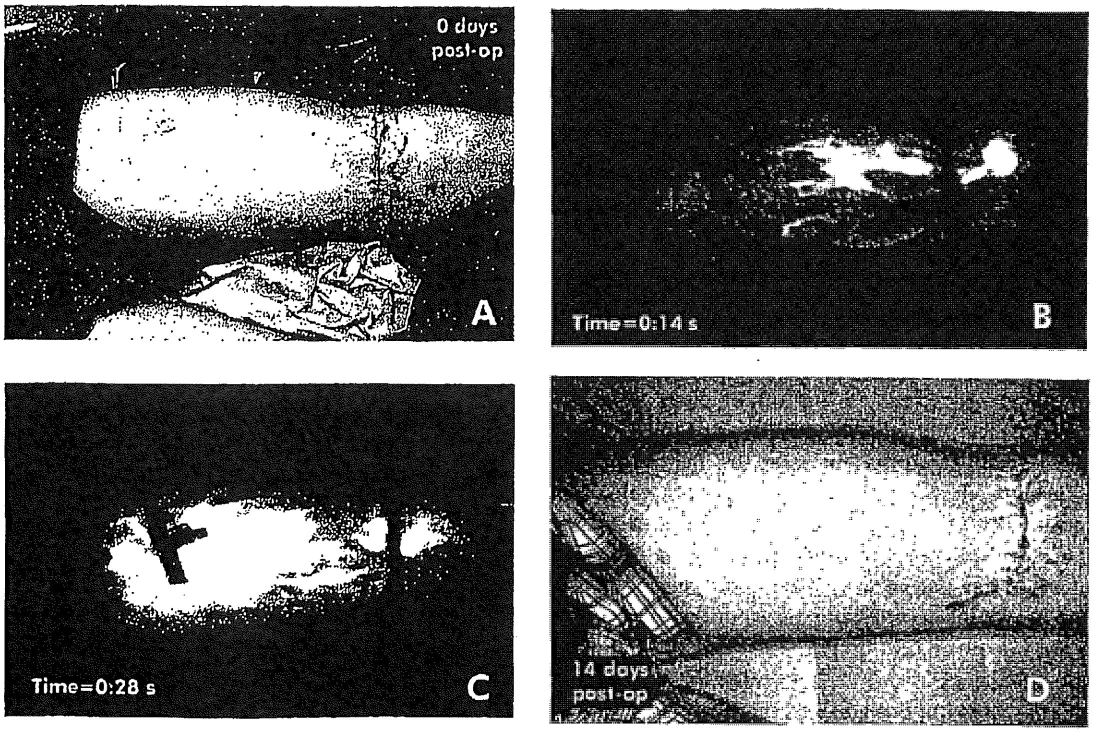

Fig 2. Visible and indocyanine green (ICG) images of a healthy flap. (A) The tissue expander has been removed and the flap elevated and sutured. (B) ICG image at 14 seconds postinjection showing rapid uptake of the ICG dye. (C) ICG image at 28 seconds postinjection. (D) Photograph 14 days postoperatively shows complete healing.

using a computer for real-time display, future analysis, and long-term storage.

The diagnostic system is mounted on a wheeled cart (Fig 1B). It can be moved to the operating room or ward, where it is then readied for imaging. The ICG is then injected in a single bolus, and images are acquired at the rate of approximately six per minute over the next 5 minutes, with a timer recording the postinjection time. Initial images show no fluorescence, even in regions of normal circulation, because the dye requires at least 10 seconds to circulate. Fluorescence typically peaks within approximately 1 minute and then decreases in intensity as the dye is excreted hepatically. The dye concentration, and hence fluorescence intensity, has a decay time (1/e) of approximately 3 minutes. However, if extravascular leaking occurs, the skin may be stained with ICG and the decay in these areas will be significantly longer (hours). The imaging rate of six frames per minute is sufficient to record the dye uptake, steady-state distribution, and gradual decay, although faster framing rates are easily possible with off-the-shelf hardware. Useful clinical information is contained in the uptake and decay times, the steady-state dye distribution, the ratio of normal and flap tissue fluorescence intensity, and the appearance of the fluorescence (e.g., diffuse vs. discrete vessels). Although not performed in the current study, repeat injections can be performed, in principle, after the dye has decayed to approximately 10% of its peak concentration (typically about 9 minutes if no staining has occurred) or immediately after the initial imaging by using higher ICG doses.

ICG imaging may be performed intra- or postoperatively. During surgery the imaging can be conducted immediately after the flap has been elevated, after rotation and temporary suturing, or after the flap has been fully sutured in place. Our experience suggests that the test is most useful after temporary suturing because the flap is stressed but may be relocated easily to the donor position and treated as a delayed flap if the circulation is found to be compromised. Postoperative imaging is useful for monitoring flap healing, assessing the effects of circulation therapies such as vasodilators and hyperbaric oxygen, and for assessing flap viability in borderline cases.

Results

At Columbia–Augusta Medical Center Burn Unit, Augusta, GA, 18 patients with 21 flaps have undergone ICG imaging for the evaluation of surgical flaps. In 1 patient, two flaps were evaluated in the same patient at the time of surgery. In 2 other patients, repeat studies of the same flaps were performed on different days. All flaps were planned for the cosmetic or functional reconstruction of burn scars. Studies were performed in the operating room and/or postoperatively at the patient's bedside, with conventional color photos taken as appropriate. Children less than 10 years of age and pregnant women were excluded from the study.

The majority of flaps (16 of 21) exhibited no clinical manifestations of poor circulation. All tissue regions were viable and showed no significant discoloration. These flaps healed completely within 3 weeks. In all 16 of these flaps, ICG imaging conducted at the time of surgery or within 1 postoperative day also indicated adequate circulation and predicted the viability of the flap.

Figure 2 shows the results of ICG imaging for a typically healthy flap. Here, a flap was extended after tissue expansion to reconstruct a burn scar excised just above the knee. In this patient, fluorescence onset occurred at 16 seconds and the peak signal occurred at approximately 59 seconds, which is indicative of good circulation. Initially the larger, individual vessels are clearly delineated because they are the first to contain ICG-marked blood. Later, the smaller vessels that are below the spatial resolution of the camera system fill, and consequently the image exhibits a more diffuse character. The entire flap in this patient is seen to be well supplied with blood, including the distal end near the suture line. Additionally, the fluorescence intensity of normal and flap tissues are approximately the same intensity. Thus, as was the case for all 16 flaps that healed without complication, ICG imaging shows unambiguously adequate circulation and predicts a fully viable flap.

Conversely, 5 of 21 flaps in the study did exhibit areas of poor circulation, as illustrated by both poor uptake of ICG and clinical appearance. Clinical appearance varied from essentially nor-

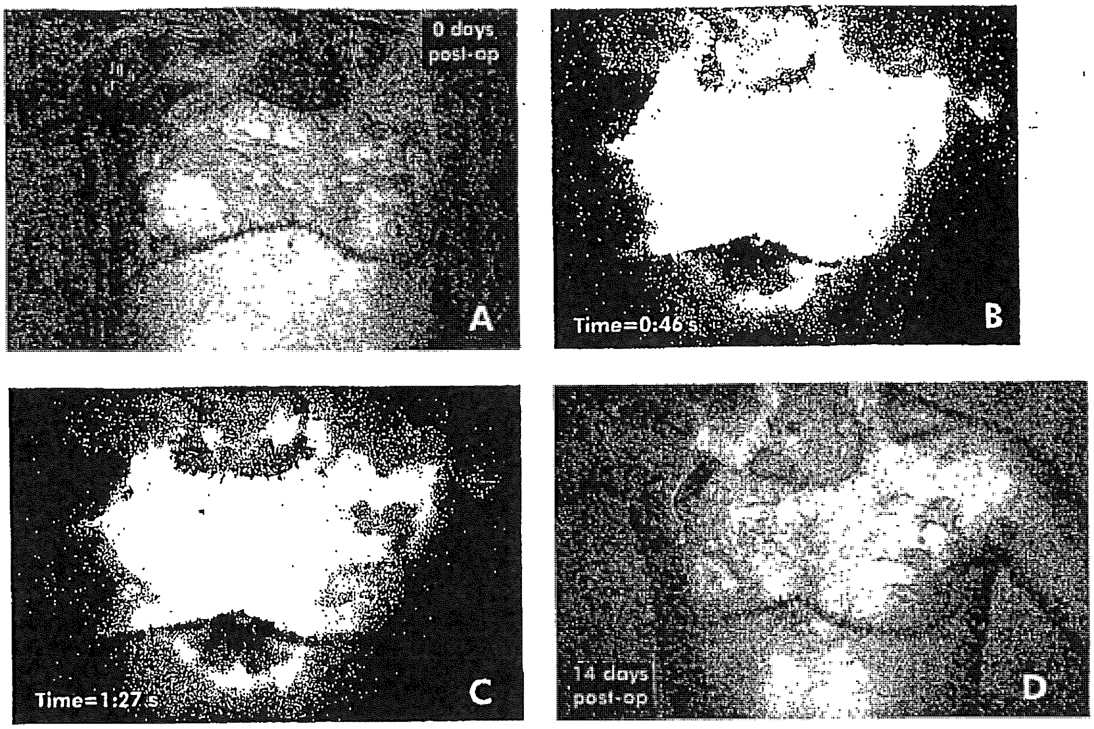

Fig 3. Visible and indocyanine green (ICG) images of a flap with a localized region of poor circulation. (A) Flap on postoperative day 1. The area below the incision has been undermined. (B) ICG image at 46 seconds postinjection showing greater than normal fluorescence in the hypertrophied region and a region of poor circulation directly below the sternum. (C) ICG image at 87 seconds postinjection. (D) On postoperative day 14, tissue discoloration is seen.

mal to slight cyanosis to regions with no apparent blood flow. ICG imaging results and the clinical findings are discussed in the following paragraphs.

In Figure 3, a tissue-expanded flap was extended upward from the patient's abdomen to reduce the area of burn scar on the chest. Visible discoloration was encountered at the distal tip of the flap approximately 3 days after surgery (see Fig 3A). The discoloration encompassed approximately 30 cm^2 directly above the patient's sternum. ICG imaging was performed at the first signs of discoloration, with the results as shown in Figures 3B and C. Most of the flap shows a rapid uptake of well-distributed blood, except for the zone of discoloration. The size and shape of the region of poor circulation shown by ICG matches that of the discoloration. Although the circulation was initially compromised, there was no tissue slough and the area healed without tissue loss, presumably because of the small size of the deficient region and the good blood supply to neighboring tissue. As an aside, the hypertrophied unexcised scar above the incision, which was not undermined, shows additional brightness due to increased local blood supply typical of hypertrophied scar.

Figure 4 shows a pedicled flap raised to cover the dorsum of the hand. Dye uptake in the flap was relatively slow and very minimal at the distal end of the flap. The proximal end of the flap healed well, but at 14 days the distal necrotic corner revealed an area of discoloration and partial slough (see Fig 4D), which eventually healed without further surgery.

In the most dramatic case, a patient experienced destruction of most of the abdominal wall by direct contact with a hot automobile muffler. Skin, fat, muscle, and fascia were necrotic, and were debrided operatively. The wound was cov-

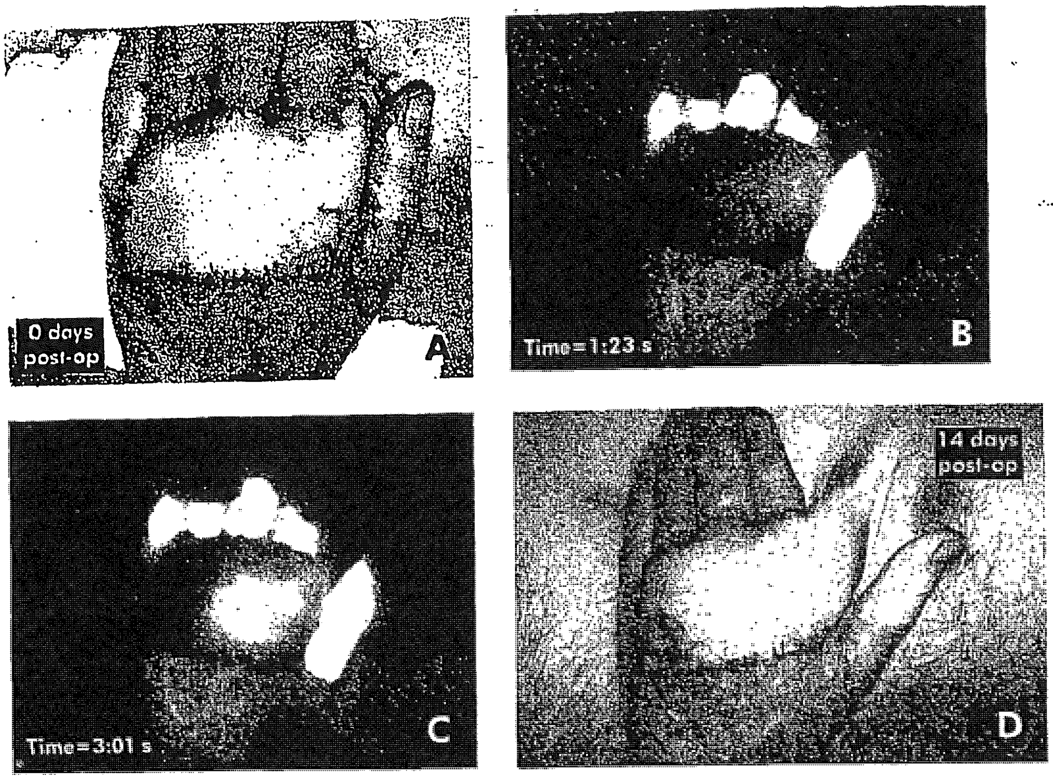

Fig 4. Visible and indocyanine green (ICG) images of a pedicled flap on the dorsum of the hand. (A) First postoperative day. (B) ICG image at 83 seconds postinjection shows relatively slow uptake of dye. (C) ICG image at 181 seconds postinjection shows compromised circulation to the distal end of the flap. (D) Photograph 14 days postoperatively shows partial sloughing at the distal end of the flap.

ered with Gore-Tex, a synthetic tissue replacement. Granulation eventually developed through the Gore-Tex. Over the small bowel, the granulation was covered by split-thickness skin grafts. To provide better coverage of the abdomen, a large flap was raised on the back and swung around over the abdomen after several delaying procedures (Fig 5A). The viability of the flap appeared clinically satisfactory on the operating table and the flap was sutured in place.

After suturing, ICG images (Figs 5B, C) were obtained. In sharp contrast to the ICG sequence seen for normal circulation, the onset of fluorescence in the flap occurred very slowly. Note that although fluorescence was quite evident at 53 seconds in normal tissue, the flap was still devoid of ICG-marked blood 229 seconds after injection. At this point, the laser energy was increased to approximately eight times the typical level, and some ICG was detected in only a small region of the proximal end of the flap. At this energy level, the fluorescence from normal tissue completely saturates the camera, but in this patient the majority of the flap shows no detectable circulation. The flap was left in place, and it gradually demarcated and sloughed (Fig 5D). Removal of the dead flap, regrafting of the abdominal wall, and grafting of the donor site were eventually required and healed well.

In another patient, a flap was raised on the patient's neck with the goal of swinging it around to cover an enucleated eye, the socket of which was now filled with granulation tissue—the result of a severe facial burn. Photographs and selected ICG images are shown in Figure 6. The imaging was conducted after the neck flap was

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