Smartphone-Based Thermal Imaging: A New Modality for Tissue Temperature Measurement in Hand and Upper Extremity Surgeries

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Abstract

Background: Smartphone-based thermal imaging (SBTI) allows noninvasive temperature measurements. Its validity compared with a conventional infrared probe temperature scanner (IPTS) has not been studied. This study compares temperature measurements between the 2 technologies on human participants. **Methods:** Bilateral index finger temperature measurements were obtained on 30 healthy participants using IPTS and SBTI devices. Dominant versus nondominant sides (side-to-side difference) and individual side measurements between the 2 methods were compared for repeatability (precision) and agreement. **Results:** A total of 23 female and 7 male participants were tested. Based on nonoverlapping confidence intervals (CIs), intraclass correlation coefficient of repeatability was higher for SBTI than for IPTS measurements in side-to-side differences: 0.97 (95% CI, 0.96–0.99) versus 0.89 (95% CI, 0.82–0.95). The SBTI method recorded higher side-to-side difference and individual side measurements: 0.56°C (limits of agreement [LOA], –1.09°C to 2.20°C) and 2.64°C (LOA, 0.96°C–4.32°C), respectively. **Conclusions:** In addition to higher precision, SBTI offers added benefits of instantaneous acquisition of the temperature map of the entire hand, allowing quick comparisons of the uninjured and injured fingers. SBTI measurements consistently yielded higher temperature readings in the side-to-side difference as well as individual measurements. This suggested that both devices are not interchangeable for absolute temperature comparisons but are interchangeable in monitoring the changes in temperatures. This study suggests the potential for SBTI devices to be used in the clinical settings and may be of special benefit in telemedicine.

Keywords: Smartphone, thermal imaging, telemedicine, microsurgery, replantation, revascularization, infrared thermometer

Background

Every day, numerous patients are transferred to level I trauma and microvascular replantation centers across the United States. Whenever there is clinical concern for vascular compromise, rapid consultation with a tertiary trauma center to discuss suitability for limb salvage, revascularization, or replantation needs to be obtained and a possible emergent transfer organized. In this scenario, key information including clinical photos, radiographs, and temperature measurements are of great value. Recent studies documented a concerning rate of undertriaging and overtriaging of injuries leading to unnecessary hand microvascular transfers, and possibly excessive costs to the health care system: Up to 62% of transferred patients did not undergo the microvascular procedure they were intended to receive for the initial transfer.^{2,16} The majority of unnecessary transfers appear to be due to telemedicine miscommunication of

the severity of the injured limb between the consulting physician and the upper extremity specialist.

Advancements in mobile phone technology and smartphone application technologies have the prospect of making telemedicine easier and more efficient. Electronic transmission of clinical images for remote consultation has been successfully implemented and tested in dermatology,⁶ otolaryngology,¹ pathology,³ radiology,¹⁹ neurosurgery,¹⁵ orthopedics,^{7,8} and hand surgery.¹⁷ In addition, several studies

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Figure 1. Thermal image of a failing replantation attempt in a small finger showing a temperature view of the whole hand.

Left panel: Clinical photo and corresponding thermal images are interchangeably viewable. Middle panel: Comparative measurements of the replanted small finger to the uninjured control index finger (right panel) are readily possible. The temperature difference is visible as color change and quantitated in degrees Celsius or Fahrenheit at chosen measurement points.

have validated excellent accuracy between photographic versus in-person diagnosis and assessment of replantation potential of hand trauma and burns.^{12,14,17,20}

Recently, smartphone-based thermal imaging was introduced. This noninvasive technology captures a thermal image that will allow the user to assess the temperature anywhere on the thermal image and provide temperature transition zones (Figure 1). In plastic surgery, this technology has already been used to map perforators, identify perforasomes, and monitor free flaps.¹⁰

Along with skin color, capillary refill, and pulp turgor, finger temperature measurement is an important adjunct in assessing digital reperfusion after replantation/revascularization.^{18,21} To our knowledge, there exists no literature analyzing the utility of thermal imaging smartphone devices in hand surgery. The purpose of this study is to examine the precision or repeatability and bias or mean difference (agreement) of the smartphone-based thermal infrared (SBTI) camera temperature measurements relative to temperature measurements obtained from a conventional infrared probe temperature scanner (IPTS).

Materials and Methods

A standard IPTS (Exergen DermaTemp 01001RS; Exergen BSD, LLC, Watertown, Massachusetts) was compared with a SBTI camera (FLIR ONE; FLIR Systems, Inc, Wilsonville, Oregon). The SBTI camera was used in conjunction with an iPhone 7 Plus (Apple, Inc, Cupertino, California). While both devices read temperature by capturing heat radiation emission, the IPTS device only yields a single temperature value, whereas an SBTI camera delivers a thermal

image of the entire hand, allowing temperature reading from every part of the image. The SBTI camera allows temperature readings from -20°C to 120°C , with a sensitivity of $\pm 0.1^{\circ}\text{C}$.

An established method described by Bonett⁵ was used to estimate sample size based on our desired level of precision, set at 0.05. Assuming an intraclass correlation coefficient (ICC) repeatability measurement of 0.96, we determined that 30 participants would provide 80% power to obtain a 95% confidence interval (CI) width at our desired level of precision. This estimate assumes that 3 measurements are obtained from each participant and the participants are randomly sampled.

Institutional internal review board (IRB) approval was obtained prior to study enrollment. Informed consent was obtained from thirty randomly selected volunteers for the study. All participants underwent 3 consecutive temperature measurements with each device from the bilateral palmar aspects of their index finger tips. Information on participant's sex and hand dominance were collected. All measurements were performed by one author (J.C.). The dominant side was always measured first, and 3 measurements from each device were performed by alternating the devices with the first device to measure the temperature being determined by a random number generator. The literature suggests there can be temperature variability between symmetrical limbs of the same individual.^{22,23} Therefore, the purpose of obtaining dominant and nondominant temperature measurements is to calculate the precision or repeatability of each device at detecting the difference in temperatures between the dominant and nondominant sides, as well as assess the amount of agreement between the 2 methods in respect to their abilities

Figure 2. Intraclass correlation coefficient (ICC) of repeatability between the 2 devices.

Note. ICC for smartphone-based thermal infrared measurements is higher compared with conventional infrared probe temperature scanner measurements in the side-to-side differences but is the same in individual side measurements. IPTS = infrared probe temperature scanner; SBTI = smartphone-based thermal imaging.

to detect the disparity in temperatures. The temperature measurements were acquired at the manufacturer's suggested distances of 100 cm for the SBTI and 1 mm for the IPTS.

Linear mixed models were used to estimate ICC representing the repeatability (precision) of the individual side (dominant and nondominant sides) temperature measurements as well as the side-to-side difference (dominant limb – nondominant limb) in temperature measurements obtained by the 2 measurement devices. The 95% confidence intervals were calculated using a normal approximation.

Linear mixed models were also used to estimate agreement between the 2 measurement methods. Bland-Altman⁴ methods were used to estimate bias (mean difference) and limits of agreement. Agreement between systems was modeled as the difference in side-to-side differences between systems: $\Delta_{\text{system}} = (SBTI_{\text{dominant}} - SBTI_{\text{non-dominant}}) - (IPTS_{\text{dominant}} - IPTS_{\text{non-dominant}})$. Agreement was also assessed in the temperature measurements of independent sides between the 2 systems, not accounting for the side-to-side differences between dominant and nondominant fingers. All statistical analyses were performed with SAS 9.4 (SAS Institute Inc, Cary, North Carolina).

Results

Data were collected from 23 (77%) female and 7 (23%) male participants. The majority of participants, 77% (23 of 30), were right hand dominant. Both measurement systems were associated with high levels of repeatability in individual side measurements as well as in the side-to-side

Figure 3. Bland-Altman plot of measurement agreement of the side-to-side differences between the 2 devices.

Note. The solid line represents the mean bias; the dashed lines represent the upper and lower limits of agreement. IPTS = infrared probe temperature scanner; SBTI = smartphone-based thermal imaging.

differences (Figure 2). The individual side ICC repeatability values for the IPTS method were 0.99 (95% CI, 0.99-1.0) for the dominant side and 0.99 (95% CI, 0.99-1.0) for the nondominant side. The individual side ICC values for the SBTI measurements were 0.99 (95% CI, 0.99-1.0) for the dominant limb and 0.99 (95% CI, 0.99-1.0) for the nondominant limb. The side-to-side difference ICC repeatability value for IPTS was 0.89 (95% CI, 0.82-0.95) compared with 0.97 (95% CI, 0.96-0.99) for SBTI measurements.

The bias or mean difference in the side-to-side (dominant to nondominant) temperature measurements between the 2 methods was 0.56°C (limits of agreement, -1.09°C to 2.20°C) with the SBTI measurements being higher (Figure 3). In contrast, when examining agreement between devices based on the individual temperature measurements, not accounting for side-to-side differences, the SBTI had an even higher mean difference or bias, at 2.64°C (limits of agreement, 0.96°C-4.32°C; Figure 4).

Discussion

Temperature monitoring is an important clinical tool, especially when it is used in predicting viability after replantation/revascularization surgery.¹⁸ Absolute temperature measurements have been used as a prognostic indicator of finger viability. Current literature suggests a high probability of vascular complications in replanted/revascularized digits if the temperature is less than 29°C to 32°C.^{11,18,21} We compared the 2 infrared thermal temperature measurement methods with respect to absolute temperature values obtained from

Figure 4. Bland-Altman plot of individual side measurement agreement between the 2 devices.

Note. The solid line represents the mean bias; the dashed lines represent the upper and lower limits of agreement. IPTS = infrared probe temperature scanner; SBTI = smartphone-based thermal imaging.

both dominant and nondominant limbs. Individual temperature measurements from both systems were associated with a high level of repeatability ($ICC = 0.99$) on both the dominant and nondominant sides. However, SBTI measurements consistently were found to be on average 2.64°C higher than the IPTS measurements. This difference suggests that both methods cannot be used interchangeably when comparing absolute temperatures in clinical settings. If absolute temperature measurements are used to monitor perfusion after revascularization/replantation, clinicians must be cognizant of higher temperature readings obtained from SBTI devices relative to the IPTS readers. We recommend consistently monitoring absolute temperatures with a single method.

Besides monitoring absolute temperature, it is also important to document temperature changes of the injured finger compared with a control finger. Literature suggests that a 2.5°C drop in temperature of the replanted/revascularized digit compared with control fingers for greater than 1 hour indicates a probable vascular compromise of the operated finger.²¹ We also compared the 2 measurement systems with respect to side-to-side difference temperature measurements. Side-to-side difference temperature measurements from the SBTI method were more repeatable than side-to-side difference measurements from the IPTS method. The higher level of precision may be attributable to the ability of the SBTI to obtain static images of the entire hand which may permit greater consistency in the location and timing of the temperature measurements. In addition, we observed a high level of agreement (bias, 0.56°C and upper limit of agreement, 2.2°C) between systems with

regard to temperature differences between dominant and nondominant sides. As the upper limit of agreement is less than the clinical meaningful difference of 2.5°C , this suggests that in the clinical setting, the difference measured between the replanted/revascularized digit and the control is interchangeable between the 2 methods, as long as the temperatures taken to calculate the difference were performed with the same device.

SBTI devices are easy to use and noninvasive, and offer greater information capture and ease of data transferability compared with conventional IPTS devices. Besides its higher precision to allow for more sensitivity in monitoring change in replanted/revascularized fingers, the captured thermal image of the entire hand allows for temperature comparison with control fingers on the same hand as well as rapid data transfer to the on-call specialist.

One limitation to the current study was the fact that the measurements were performed on healthy participants rather than on those patients who underwent replantations or revascularizations. However, given the decreasing rate of replantation surgery in the United States to as low as 5 replantations per year,^{9,13} a prospective clinical study with the same statistical power would have taken several years to complete.

Conclusion

This study comparing a new SBTI technology with a conventional IPTS highlights several advantages of the SBTI technology which may prove to be valuable for perioperative microvascular monitoring and improved information transfer in telemedicine. While the SBTI device consistently measured higher temperatures, its measurements were more precise than the conventional IPTS device data. The higher level of precision of the SBTI device would provide for more sensitivity in detecting changes in the vascular status of an injured limb with the added benefit of providing an immediate noninvasive thermal map of the patient's limb allowing for easy comparative measurements. This is a pilot study that has set the stage for future clinical studies to determine the clinical validity of this technology in microvascular surgery as well as telemedicine.

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Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation

(institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

Statement of Informed Consent

Informed consent was obtained from all individual participants included in the study.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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