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ORIGINAL ARTICLE

Early assessment of the efficacy of digital infrared thermal imaging in pediatric extremity trauma

Cicero T. Silva · Nausheen Naveed · Syed Bokhari · Kenneth E. Baker · Lawrence H. Staib · Saad M. Ibrahim · Karl Muchantef · Thomas R. Goodman

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Abstract Young children or those with intellectual disability with trauma to an extremity often undergo radiographs of the whole limb. The objective of the study was to assess the efficacy of digital infrared thermal images (DITI) in pediatric extremity trauma. We hypothesized fractures to be associated with local hyperthermia, detectable with DITI, which could direct focused radiographs. In this exploratory study, patients seen over a 2-month period in a pediatric emergency department for limb trauma were included if an extremity radiograph was taken on the same day. Patients had DITI of symptomatic and contralateral limbs. The warmest area of each image was compared to the site of pain and/or fracture on the radiograph. Fifty-one patients were enrolled. DITI matched 73% of pain sites. Fractures were seen in 11 patients. DITI matched 7 of 11 (64%) fracture sites. DITI performance in pinpointing the site of injury, although suboptimal, is encouraging for further evaluation.

Keywords DITI · Digital infrared thermal imaging · Radiograph · Trauma

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C. T. Silva (✉) · N. Naveed · S. Bokhari · K. E. Baker · L. H. Staib · S. M. Ibrahim · T. R. Goodman
Yale University School of Medicine,
333 Cedar Street, PO Box 208042, New Haven, CT 06520, USA
e-mail: cicero.silva@yale.edu

Present Address:
K. Muchantef
Children's Hospital of Philadelphia,
34th Street and Civic Center Boulevard,
Philadelphia, PA 19104, USA

Introduction

Skeletal trauma is one of the most common reasons for imaging children in the emergency department (ED) [1]. Young children or individuals with a decreased mental status or intellectual disability can pose a challenge to the ED physician in determining the precise site of the injury. The clinical history may not be adequate, and/or the child may be incapable of localizing the site of pain. In the absence of an obvious deformity, the physical examination may be inconclusive. In such cases, the ED physician often needs to order radiographs of a whole limb, hoping imaging will pinpoint the diagnosis.

Healing of pediatric fractures goes through three phases: inflammation, repair, and remodeling [2, 3]. Cellular inflammation peaks within 24 h of injury [4]. Inflammation is associated with hyperemia and can cause a substantial local increase in skin temperature [4]. Digital infrared thermal imaging (DITI) has been used successfully for monitoring the temperature distribution of human skin [5]. Therefore, we hypothesized that fractured bones would be associated with regional skin hyperthermia detectable by DITI. Hence, DITI might direct focused and accurate radiographic examinations in the pediatric population. In addition, DITI might direct attention to areas of hyperthermia, which might correspond to subtle fractures on radiographs.

Thermal imaging has been studied in medicine for decades. It has probably been most investigated for breast cancer [6–13], but growing literature reports its use in a variety of other medical conditions [14–29]. To the best of our knowledge, however, there are only two reports of the use of DITI in skeletal trauma. Cook et al. [30] reported a child with a hyperthermic area on DITI correlating with a fracture site. DiBenedetto et al. [31] evaluated foot injuries in military recruits and found DITI useful in assessing severity and healing. Of note, Garagiola et al. [32] illustrated the findings of

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thermal imaging in the diagnosis and management of sports injury, using older, analog systems.

Our study intended to access the efficacy of DITI in pediatric extremity trauma, aiming to determine the ability of DITI to pinpoint abnormalities in injured limbs—this ability might authorize DITI to guide focused radiographs to smaller limb segments.

Materials and methods

Our institutional review board approved this HIPAA-compliant exploratory study, and informed consents were obtained from patients' guardians.

Sample characteristics

We performed a prospective analysis of radiographs and DITI of patients seen over a 2-month period in the pediatric ED of a tertiary hospital, following limb trauma. Convenience sampling was used with consecutive patients recruited Mondays through Fridays between 8AM and 5PM Patients were eligible if an extremity radiograph was taken on the day of ED visit, but excluded if older than 18 years, if had non-English speaking guardians, or had dressings over the injured area. The ED was encouraged not to apply ice over the injured site prior to DITI, and to remove any ice applied prior to ED arrival.

DITI acquisition

The employed DITI system consisted of a Meditherm med2000 Pro camera coupled with a computer running the following software: Meditherm Iris 7.5 and Meditherm Display (all from Meditherm, Inc., Fort Myers, FL, USA).

The camera measures temperatures in the range of 10–40°C, accurate to 0.01°, with a spatial resolution of 1 mm at a distance of 40 cm from the skin (http://www.meditherm.com/specifications.htm, last accessed on 10/19/2011). The camera was mounted on a tripod, acquiring images vertically, from above. The height of the tripod was adjusted for each patient to have the whole limb to be imaged in the camera field of view. The camera and supplied software were employed on an "out-of-the-box", "plug-and-play" fashion, with no customization made. The system was set up in a radiography room that has controlled temperature, humidity, and air circulation. However, we did not follow a standard pre-imaging patient preparation protocol for skin temperature equilibrium (please see "Discussion" for rationale).

Enrolled patients had one thermal picture taken of the symptomatic limb and another of the contralateral limb by the first and/or second authors (depending on researcher availability). These researchers were blinded to the radiographs. An attempt was made to image the whole limb in extension, with exceptions due to patient pain or modesty. Limbs were imaged on the radiography table or patient stretcher.

When acquired, the DITI images are displayed as actual temperature color maps. Prior to interpretation, these images were windowed by the first author using a standard protocol, as recommended by the DITI system manufacturer: each image had its temperature scale increased until out-of-range, "hot" pixels appeared; the image was then scaled back until the warmest area was reduced to the smallest number of hot pixels. Following such windowing, each image was saved on a grayscale map, with the warmest temperature depicted in red and other temperatures in shades of gray (Fig. 1).

The site of greatest pain, when present and known, was recorded at the time of DITI acquisition. The following was also asked from the patients or guardians and recorded: mechanism of trauma, time since trauma, and, when pertinent, time since ice removal.

Ice packing

Before any DITI image or radiograph was evaluated, the first author reviewed all thermal pictures of patients' symptomatic limbs that had ice applied to the injury sites. The pictures were reviewed on a multicolor map (temperatures

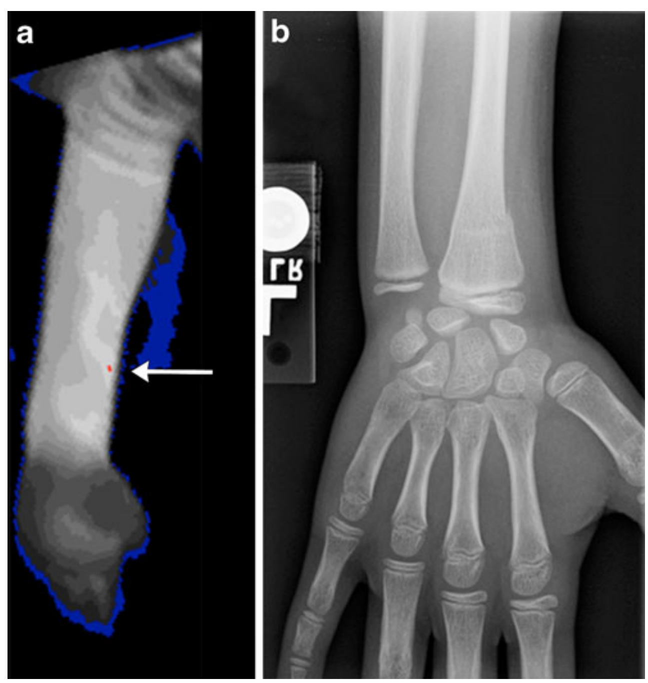


Fig. 1 Ten-year-old girl who fell from self-height. **a** The forearm was considered the warmest segment on DITI (*arrow*), which was obtained 18 h after the trauma. **b** The wrist was considered as positive for fracture on the radiograph. DITI was considered to match the site of injury

depicted by a range of different colors), and patients whose injury site was the coldest section of the limb were excluded from the data analysis. This was done to minimize false-negative results related to prior ice packing.

DITI interpretation

The thermal pictures from both symptomatic and asymptomatic limbs from all patients were anonymized and randomly presented to three readers, attending radiologists with 12, 12, and 5 years of respective post-fellowship experience, but no previous experience with DITI. The readers were blinded to the radiographs. The readers decided, by consensus, the location of the warmest area of each limb. Possible locations were shoulder, arm, elbow, forearm, wrist, hand, hip, thigh, knee, leg, ankle, and foot. The boundaries between each of these limb segments were arbitrarily chosen on each DITI image.

Radiographs

While blinded to the DITI findings, the same readers evaluated by consensus the radiographs obtained from each patient on the day of the ED visit in order to determine the presence and location of fractures. Any available follow-up radiograph, CT, or MRI was also reviewed. These studies constituted the reference standard. Indeterminate cases were resolved by a chart review of the final clinical diagnosis.

Comparison between DITI and radiographs

The warmest segment on DITI was then compared to the injury site on symptomatic limbs. Injury site was defined as the site of fracture and/or pain. DITI was considered to match the injury site when the warmest segment coincided with or bounded the site of injury. We considered boundary segments as matches for two reasons: as stated previously in the article, the borders between each of DITI segments were arbitrarily chosen; moreover, a radiograph will typically cover not only the region of interest but the boundary segments. Therefore, an abnormal wrist on DITI that would lead to a wrist radiograph, for example, would be unlikely to miss a distal forearm fracture (as in Fig. 1).

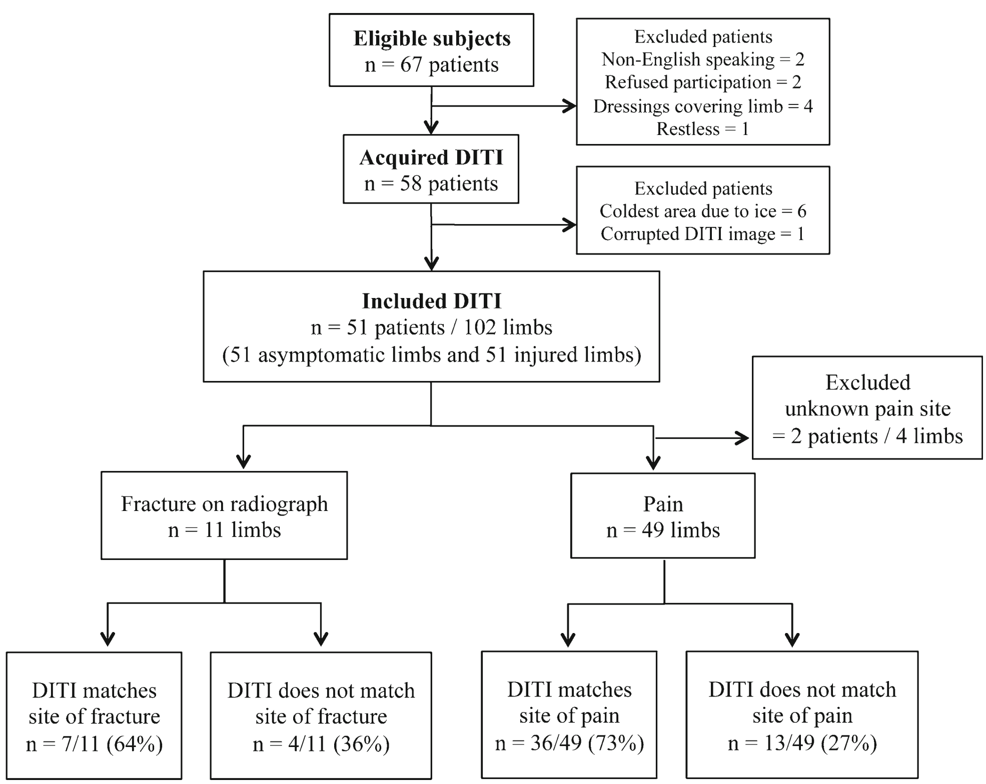
Statistical analyses

Medians were calculated for patients' ages, as well as for the time intervals between trauma and DITI, DITI and radiographs, and ice removal and DITI. The proportion of patients where DITI matched the site of pain and the proportion of patients where DITI matched the site of fracture were calculated.

Results

Figure 2 shows the flow diagram of this study.

Fig. 2 Study flow diagram



Sixty-seven patients were eligible for the study. Sixteen patients were excluded (as detailed in Fig. 2). The remaining 51 patients constitute our cohort: 30 boys and 21 girls, aged 9 months to 17 years 10 months (median 11 years 6 months) (Table 1). A total of 27/51 (53%) patients had trauma to their upper limbs, and 24/51 (47%) to their lower limbs.

The mechanism of trauma was fall from self-height in 17 patients, direct blow in ten, joint twist in five, finger crushing in three, fall from height in three, dog bite in two, gunshot in one, motor vehicle collision in one, and unknown or unwitnessed trauma (limping) in nine.

Time intervals between the trauma and DITI were unknown for 7 patients, but for the remaining 44 patients varied between 23 min and 14 days (median 17 h 30 min), less than 24 h in 31 patients, between 24 and 48 h in four, between 48 and 72 h in five, and more than 72 h in four. DITI images were acquired between 2 h 7 min *prior to* and 2 h 14 min *following* radiographs (median 8 min prior to radiographs), except for one outlier who had a radiograph at an outside hospital and was then sent to our ED, with DITI performed 10 h 14 min following the radiograph. Follow-up radiographs were available in 13 patients. A follow-up MRI was available in 1 patient. No patient had a follow-up CT.

Twenty-eight patients had ice applied to the site of trauma. Of these, 22 were not excluded since the site of injury was not the coldest of the limb on DITI. Time interval between ice removal and DITI on these 22 included patients was 2 min to 23 h (median 55 min).

All but 2 patients (aged 1 year and 1 year 2 months) were able to identify a precise site of pain. Fractures were seen in 11 patients, aged 3 years 2 months to 15 years 3 months (median 11 years 4 months) (Table 1).

All fractures but one were convincingly diagnosed on the initial radiograph; the available follow-up radiographs and MRI did not change the readers' interpretations on any patients. A chart review was needed for 1 patient due to lack of reader consensus on the interpretation of the radiograph (Fig. 3).

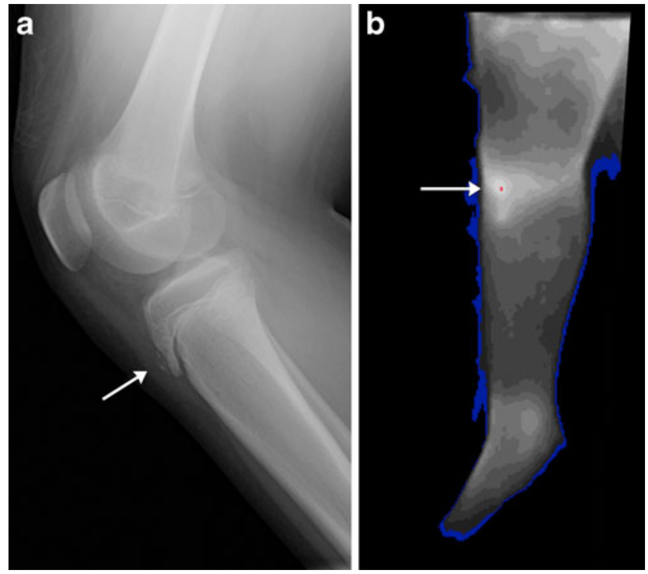


Fig. 3 Eight-year-old girl who fell from height. **a** Lateral view of a knee radiograph reveals fragmentation of the tibial tubercle and soft tissue swelling at the distal insertion of the patellar tendon (*arrow*). **b** The knee was the warmest segment on DITI (*arrow*), obtained 5 h after the trauma. Clinically the patient had anterior knee point tenderness and was diagnosed as having a fracture

DITI coverage

A total of 102 DITI images were acquired, two for each patient (one of the symptomatic limb, one of the asymptomatic limb). Six of the 102 DITI images covered all six segments of a limb (shoulder, arm, elbow, forearm, wrist, and hand on upper limbs images; and hip, thigh, knee, leg, ankle, and foot on lower limbs images). Thirty-three images covered a total of five segments; 35 images covered four segments, and 28 images covered only three segments.

Table 1 Number of patients and fractures by age groups

Patients' age groups	Number of patients	Number of patients with fractures	Number of patients in whom DITI matched the fracture site
0–5 years	11	1	1
5 years 1 day–10 years	8	2	1
10 years 1 day–18 years	32	8	5

DITI performance

The warmest segment matched the pain site in 36 of 49 patients (73%) and matched the fracture site in seven of 11 patients (64%) (Fig. 4) (Table 1).

Discussion

In this pilot study we explored the use of DITI in pediatric extremity trauma. DITI might potentially be employed by a triage nurse on those incapable of localizing a site of pain, to guide focused radiographs to smaller limb segments. In our cohort, DITI did match seven of 11 fractures. However, we found a number of factors that can impact on DITI results and potentially affect the reproducibility of the method. They are listed as follows:

– Standard DITI protocols often ask for about 10–20 min of patient preparation, during which the subject rests with the area to be imaged completely undressed,

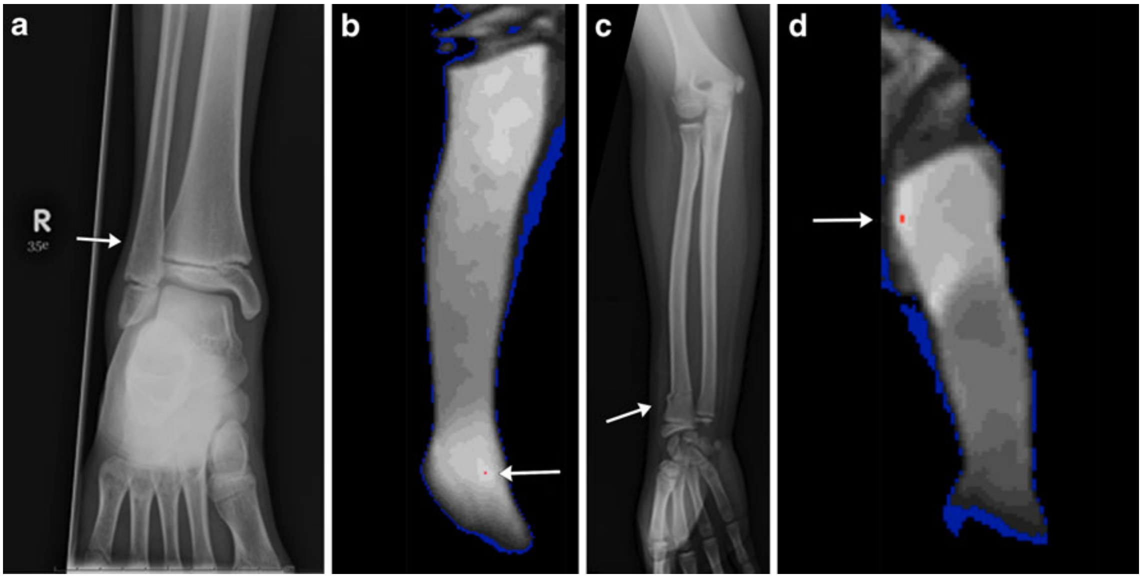


Fig. 4 Examples of fractures on DITI. **a**–**b** Ten-year-old boy who twisted his ankle. Distal fibular fracture site (*arrow* on **a**) matched by DITI (*arrow* on **b**) obtained 2 days after the trauma. **c**–**d** Eight-year-old girl who fell from self-height. Distal radial fracture (*arrow* on **c**) missed by DITI (*arrow* in **d**), obtained 6 h after the trauma

avoiding contact with other parts of the body or with any surfaces [5] (Clark RP, de Calcina-Goff ML, presented at the 1996 conference of the IEEE Engineering in Medicine and Biology Society). This procedure allows for the skin temperature to reach equilibrium, exposing abnormally hot areas. We chose not to follow this preparation as we believed it would be impracticable on young or intellectually disabled children. Further, the time restraints of a busy ED would possibly discourage the use of DITI with such added preparation time. We suspect that spuriously hot areas secondary to insufficient preparation time might have been a major reason for DITI mismatches in our cohort. An alternative and faster approach for skin temperature equilibrium, not evaluated on this study but perhaps worth exploring, would be the use of forced convection cooling directly over the limbs (as in [12]).

– Although we chose to present our evaluation of grayscale DITI maps normalized to the maximum temperature present, the camera used in this study measures actual temperatures, and the software can display their numeric value. The software can also depict temperatures on different color scales. In fact, we had also evaluated the same images on a color scale, with different readers who were also blinded to the radiographs, but the DITI performance was slightly inferior to that of grayscale maps (data not shown). Likewise, following the data analysis the first author plotted the actual temperatures of both fractured and non-fractured limbs from all patients, but there was an overlap between the groups and no identifiable cut-off value (data not shown). Further studies might explore possible correlations requirements between these different image paradigms to increase their accuracy.
– DITI images lack the bony landmarks of radiographs, and we had to arbitrarily choose the borders between DITI segments in this cohort. As an example, the warmest area on DITI seen on Fig. 1, corresponding to a distal radial fracture, might be called “wrist” by some but “forearm” by others. This led us to assign boundary DITI segments as positive matches, although this practice could potentially falsely elevate the sensitivity of the technique. Nevertheless, in this cohort the matching DITI segments *coincided* with a fracture site in six patients and *bounded* the fracture site in only one.
– Ice is often applied to a site of traumatic injury for pain relief. In our emergency department, this practice is the standard of care. If the patient is subsequently imaged by DITI, ice clearly becomes a confounding issue. In our cohort, following the data analysis one of the authors reviewed the charts of the six patients that had been excluded because of ice packing. One of these excluded patients did have a fracture (cold on DITI). If this patient had been included in the data analysis and considered a false-negative, the sensitivity of DITI for fracture would have been seven of 12 (58%).
– Hypothermia has been described in association with muscular strains and contusions by at least one author, thought

to be secondary to vasoconstriction or intramuscular hematomas [32]. However, it is worth noting that the thicker periosteum of the pediatric bone usually walls-off the resultant fracture-related hematoma [4].
– Trauma-related sympathetic nerve damage, although unusual, is known to alter skin temperatures [33].
– The time between trauma and DITI and the use of anti-inflammatory drugs may also play a role in DITI performance. A larger cohort would enable regression analysis to be performed, hopefully elucidating the role of these confounders.

Interestingly, DITI helped distinguish between a normal variant and a fracture in one patient in this series. The patient had fragmentation of the tibial tubercle on the radiograph, which was initially interpreted by one reader as a normal variant but by another as an avulsion fracture, possibly in the context of Osgood–Schlatter disease. The third reader was undecided. The patient had knee pain, and the area was the warmest of the limb on DITI (Fig. 4). Review of her chart revealed that the patient had point tenderness along the anterior knee and had been assigned a final diagnosis of fracture by the ED team.

Our study had a number of limitations, some inherent to a pilot with a small sample size. First, all fractures occurred in distal limb segments, and, therefore, we were not able to evaluate DITI's performance on more proximal fractures. Second, cases in which fewer than six segments were imaged increased the possibility of chance correlations between the warmest area on DITI and pain/fracture sites, perhaps falsely increasing DITI sensitivity. Third, as mentioned previously in the article, we did not follow a standard DITI preparation protocol, and we suspect that the lack of pre-imaging temperature equilibrium was a major contributor to the suboptimal performance of DITI. Nonetheless, we are somewhat skeptical of the feasibility and practicality of a standard pre-imaging preparation for young or intellectually disabled children and for those in a time-constrained ED. Further research would be needed focusing on alternative preparation methods, to make DITI practical for use in a busy emergency department.

Conclusion

The performance of digital infrared thermal imaging in pinpointing a site of injury, although suboptimal, seems to encourage further evaluation with larger cohorts.

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