



# Evaluating physiological progression of chronic tibial osteomyelitis using infrared thermography

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## Abstract

**Purpose** Medical infrared thermography (IRT) was used as a complementary means for the clinical evaluation of musculo-skeletal trauma and progression of chronic tibial osteomyelitis.

**Methods** Twenty-two adult patients with a medical diagnosis of chronic tibial osteomyelitis were followed up by IRT performed along with standard radiography. Thermal data of the affected limb were compared with those of the healthy contralateral limb based on the thermal profile of the lower limbs as per the medical thermography guideline (32 °C). Data were acquired in the following regions of the lower limb: proximal tibia, diaphysis, and distal tibia, using a FLIR infrared camera, and data were processed using MATLAB®.

**Results** For patients with active infections, an increase in the average temperature of the affected limb above + 1.0 °C was observed when compared with the temperature of the contralateral. The wound region of the patients showed an increased temperature (32.3 °C) compared with the temperature of the contralateral (31.4 °C). In contrast, in latent infections, the thermal differences were small, generally below 0.3 °C, and thus were within the threshold of normality. In contrast, in areas diagnosed with reduced blood supply, the affected limb showed an average temperature up to – 5.7 °C below normal. Additionally, the initial temperature range (26.5 to 34.5 °C) decreased during the treatment to 29.8 to 34.1 °C, indicating a convergence toward normality.

**Conclusion** IRT has significant potential as a complementary imaging modality in the follow-up of patients with bone lesions with a diagnosis of osteomyelitis as it does not use ionizing radiation, thus allowing repetitive use as desired. Thermal images show important physiological information related to vascularization necessary for bone repair, as well as provide a good indication of the boundary of the infected area, adjacent to the trauma, which is useful for positioning the radiography equipment. However, it should be noted that IRT cannot replace other medical imaging techniques, as it provides information about the skin and cannot directly evaluate the interior of the body.

**Keywords** Chronic osteomyelitis · Infrared imaging · Prosthetic infections · Tibia fracture · Medical diagnostic

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## Introduction

Chronic tibial osteomyelitis (CO) is an infectious disease that leads to progressive bone destruction and necrosis, resulting in bone sequestration and apparent fistula. It is a disease with a significant morbidity, of up to 50% of the patients with open infected fractures (Heitzmann et al. 2019). CO presents with important clinical symptoms such as edema and an increased temperature of the affected limb, localized heat in the adjacent areas of the fistula, painful sensitivity, serous secretion, and foul odor. In patients with compromised vascular supply, the temperature of the affected limb decreases at the bone wound and adjacent regions (Lewandowski et al. 2019), which leads to ischemia, limiting the concentration and effectiveness of antibiotics (Spellberg and Lipsky 2012).

The recurrent diagnosis of osteomyelitis may originate from a vascular shortage (Hong et al. 2017) which slows down the bone-healing process. Indeed, a good vascular network, rich in blood supply, contributes to the treatment of CO (Lou et al. 2019) (Tu and Yen 2007) by increasing the action of bone reconstruction (osteoblastic) and bacterial inoculation (Gosain et al. 1990). However, a compromised vascular network prevents the action of broad-spectrum antibiotics on the infected bone limiting their action. Problems include low concentrations of antibiotics due to inadequate perfusion to the bone and the surrounding soft tissue environment (Romanò et al. 2014); (van Vugt et al. 2019) and the administration of strong antibacterial therapy to quell antibiotic resistance and biofilm formation on bone implants (Lindfors et al. 2017). Thus, the infectious process advances to adjacent areas, spreading to the upper and lower portions of the bone lesion and affecting newly regenerated areas. The infection results in sequestration of bone tissue and debilitates the tibial structure, increasing the possibility of refractoriness at the trauma site. In patients who are tobacco consumers, complications are even greater because smoking impedes the process of bone healing (Siegel et al. 2000). Although the use of an external fixation system, such as the Ilizarov apparatus, provides satisfactory bone stabilization, allowing for bone transport and elongation, prolonged use of this device is also related to complications, such as infection in bone insertion pins and Kirschner wires (Khan et al. 2015).

To improve vascularization and create a viable environment, the first step in CO treatment is the appropriate cleaning of the bone cavity affected by the severe infection, with a surgical procedure of radical debridement, requiring excision of all portions of the infected bone and the surrounding soft tissue and skin damaged by necrosis (Cierny Iii et al. 2003).

The reconstruction of a limb affected by osteomyelitis comprises three main phases: restoration of the bone

structure, filling of the dead space, and restoration of the soft tissue by covering with grafts and muscle flaps through reconstructive plastic surgeries (Ong and Levin 2010). Muscle flaps improve blood flow, contributing to effective access to antibiotic drugs and allowing increased necrotic phagocytic activity, thus facilitating bacterial cleansing of the bone wound (Russell et al. 1988). The tibial anatomical region is considered the most recurrent site of infection, as the blood supply to the tibia is relatively poor compared to that to other long bones (Pincher et al. 2019).

In the treatment of osteomyelitis, the lack of widely accepted standard diagnostic criteria stands out, as there is no non-invasive diagnostic biomarker (Lipsky and Berendt 2010). Imaging tests are often negative in acute diseases and often nonspecific in chronic diseases, requiring the collection of a bone sample to obtain optimal cultures (Lipsky and Berendt 2010). Diagnostic imaging techniques, such as computed tomography (CT) or magnetic resonance imaging (MRI), are often used as additional diagnostic tools. However, these cross-sectional imaging modalities have limited sensitivity and specificity in the presence of metallic implants, which may result in artifacts (Verberne et al. 2016), and do not demonstrate signs of bone infection (Loessel et al. 2021; Verberne et al. 2016). Occasionally, suspected osteomyelitis is detected by imaging in the absence of an open wound or soft tissue infection, and may also be asymptomatic in patients with spinal cord or other neurological impairments (Lipsky and Berendt 2010). Radiographic changes are not often seen when bone loss is less than 50% (manifested as osteopenia), and a bone loss of more than 50% takes typically a minimum of 1 to 3 weeks. Therefore, radiography is insensitive to the detection of osteomyelitis (Lipsky and Berendt 2010) in these situations. One method to overcome the lack of sensitivity of X-rays is to perform serial examinations. Initially, negative test results from patients with acute osteomyelitis tend to become positive after repeating the tests for a few weeks. In successfully treated osteomyelitis, radiography may show new bone formation that suggests inactivity when consolidated or corked (Lipsky and Berendt 2010). MRI tests are generally more reliable for acute infections than for chronic infections. Medical infrared thermography (IRT) has been presented as a diagnostic test that is complementary to radiological imaging to locate bone infections due to the thermal changes in bone and soft tissues that precede the changes perceptible in the radiological examination. Medical thermography is useful for the diagnosis of acute fractures; for the treatment of bone pseudarthrosis with severe segmental loss and the use of an external circular fixator (ECF) (Morasiewicz et al. 2008); after drug treatment of osteoporosis in the spine (auf der Strasse et al. 2020); and diagnosis of septic arthritis (Spalding et al. 2008) and venous thrombosis

(Deng et al. 2015). In the diagnosis of osteomyelitis, important results have been observed in clinical follow-up to detect decreased vascular activity in bone lesions in 20 pediatric patients diagnosed with chronic nonbacterial osteomyelitis (Zhao et al. 2019). These results show the effectiveness of infrared thermography in the assessment of thermal changes in lesions, emphasizing the potential of this technology for allowing immediate notification in an outpatient setting. Although IRT has been used to assess the inflammatory activity of CO in children, there is no reference regarding the follow-up of clinical treatments in adult patients in a hospital environment.

Thermal monitoring of the evolution of the inflammatory process, with analysis of the lesion and the areas adjacent to the bone wound, makes it possible to add additional information to the clinical follow-up and to improve the treatment and antibiotic therapy, which can be administered for a long period of time, between 4 and 12 weeks. The occurrence of infection is due to the high probability of microorganisms remaining alive in necrotic tissue, leading to proliferation of bacteria and fungi in the bone tissue. Therefore, the objective of this experimental study was to evaluate the contribution of medical IRT examination in a hospital clinical environment as a complement to radiographic imaging for the diagnosis and monitoring of adult patients with CO.

## Materials and methods

### Sample

The sample for this study consisted of 22 adult patients, 14 men aged between 25 and 71 years and eight women aged between 30 and 67 years, during outpatient clinical treatment. The inclusion criteria were adult patients (over 18 years old, both sexes) with a medical diagnosis of CO in the tibial bone, without other orthopedic trauma. Images were obtained from the Trauma and Bone Reconstruction Department of the Paraná Federal University Hospital in Curitiba, Brazil, from June 2020 to June 2021.

The thermal reference values of the thermographic profile of the lower limbs (32 °C) were used, according to the medical thermography guideline, for comparison of the thermal images of the affected tibial segment and healthy contralateral limb.

### Methodology

Diagnostic images were acquired using a professional thermographic camera (FLIR model T530, Professional Scientific, FLIR® Systems Inc., Wilsonville, Oregon, USA) with thermal sensitivity/NETD < 30 mK at 30 °C, 42° lens, sensor focal plane array resolution of 320 × 240, and minimum

focusing distance 0.15 m. The camera emissivity was set to 0.98, as indicated by the manufacturer.

Thermographic images were obtained in accordance with Singapore Standard SS582:2020 for biomedical and health images, as defined in the literature by (Ring and Ammer 2012). The images were taken after the necessary acclimatization period of 15 min, while the outpatient room with a 10-m<sup>2</sup> area was kept in comfortable conditions (21 to 24 °C and 50% RH, windows closed to minimize external disturbance, and ventilation off). The thermal images were pre-processed using FLIR Tools 6.4 software (FLIR® Systems Inc.) to extract the regions of interest (ROIs); the data were processed by MATLAB® 2021 (MathWorks, MA, USA), and boxplot plots of the temperature medians were manually created by a thermography specialist. The bone lesion was evaluated by analyzing the temperature in the ROIs centered on the lesion area, encompassing adjacent edges and tissues close to the bone lesions, and compared to the thermal data of the same tibial portion of the healthy contralateral leg.

Thermal images were acquired in the anteroposterior view on the same day and in the same orientation as the X-ray images. Patients were evaluated by default in the supine position. However, in patients who required wheelchairs, images were acquired under the same conditions but in the seated position. The camera was positioned perpendicular to the tibia, at 0.40 m, to allow correlation between thermal and radiological images.

The study met the ethical recommendations of Resolution 466/12 and was approved by the Research Ethics Committee of the Federal Technological University of Paraná (UTFPR) number 3,014,748 on November 12, 2018, and by the Research Ethics Committee of the Hospital das Clínicas of the Federal Paraná University (UFPR) number 3,067,005 on December 8, 2018.

### Statistical analysis

Thermal images were segmented into rectangular ROIs of the same size and location in both the affected and contralateral legs. The size of the ROIs was limited to not include metallic components of the external fixator if it was used. The thermal data were processed using MATLAB® 2021 software. Outliers were first removed, and then the median temperature of the corresponding segment was calculated for each ROI. Temperature differences were determined between the ROI median temperature of the affected limb and that of the corresponding contralateral region. The results were analyzed over the specific clinical follow-up time of each patient (considering day zero as the date of the first thermal image acquisition).

To analyze the temperature differences between the ROIs of the affected leg and contralateral side of each patient, the Wilcoxon paired test was applied. Regarding the possibility

of significant thermal differences between the temperatures of the first and last thermal images evaluated, the Mann–Whitney  $U$  test was performed: first, for independent samples of the temperature data and then for the temperature differences.

## Results

All patients had implant-related infection after open fractures, and one of them, patient 22, relapsed after 20 years of treatment. This pathology presents a challenge from the perspective of understanding the pathogenesis and choosing the most adequate treatment strategy. Unfortunately, due to the worsening of COVID-19 cases in southern Brazil, hospitals were forced to suspend all but urgent patient care, which interrupted the data collection of the first nine patients.

Six patients underwent only one clinical follow-up, showing a bone lesion with the presence of serous secretion and diagnosis of infection in the tibial diaphysis (patients 1, 3, 5, and 8), proximal tibia (patients 2, 6, and 9), and distal tibia (patients 4 and 7). In these cases, higher temperatures were observed in the affected limb than in the contralateral limb. Patient 3, who suffered severe bone trauma 30 years ago, and presents a controlled infection, has a similar temperature in both lower limbs. Patients 1 and 7 presented a lower temperature in the affected limb than in the collateral limb, due to the presence of phleboliths (diagnosed by X-ray), which are calcifications within small veins that promote bone sclerosis and reduce the vascular supply necessary for scar repair. The average temperature and thermal differences of the evaluated patients are shown in Fig. 1.

Figure 2 shows examples of visible, X-ray, and thermographic images of patients under treatment. Panels d, e, and f show the patient with an external fixator.

Thermal images were obtained from the next six patients, 10–15, who attended three to six clinical follow-ups during

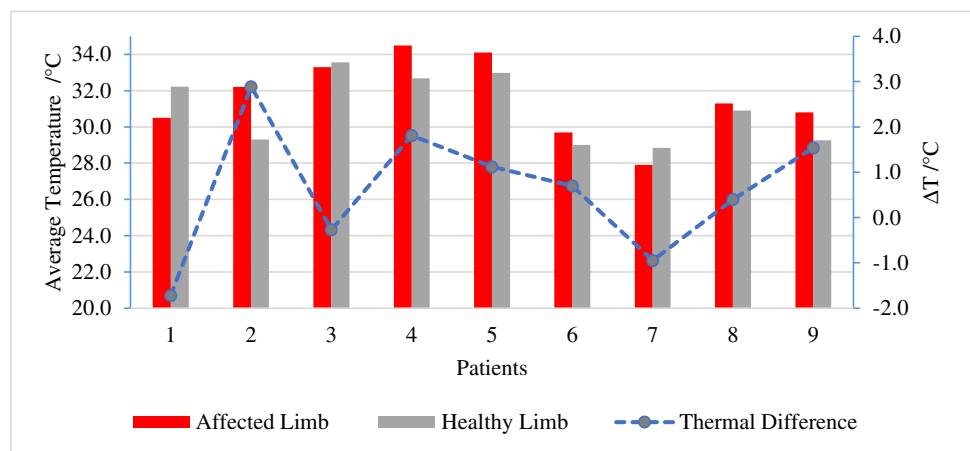
return medical appointments. In the first and second clinical assessments, patient 10 presented with a very low average temperature in the tibial shaft portion of the affected leg, indicating poor vascularization in the region of the bone lesion, although a significant improvement was observed. However, in subsequent evaluations, the thermal data showed no improvement after the treatment, indicating a recurrent infectious process. Patient 11 underwent six clinical follow-ups and had non-purulent bone secretion in the proximal tibial portion. Conversely, patient 14 attended only three medical follow-up consultations and showed an infectious process with secretion in the proximal portion of the tibia.

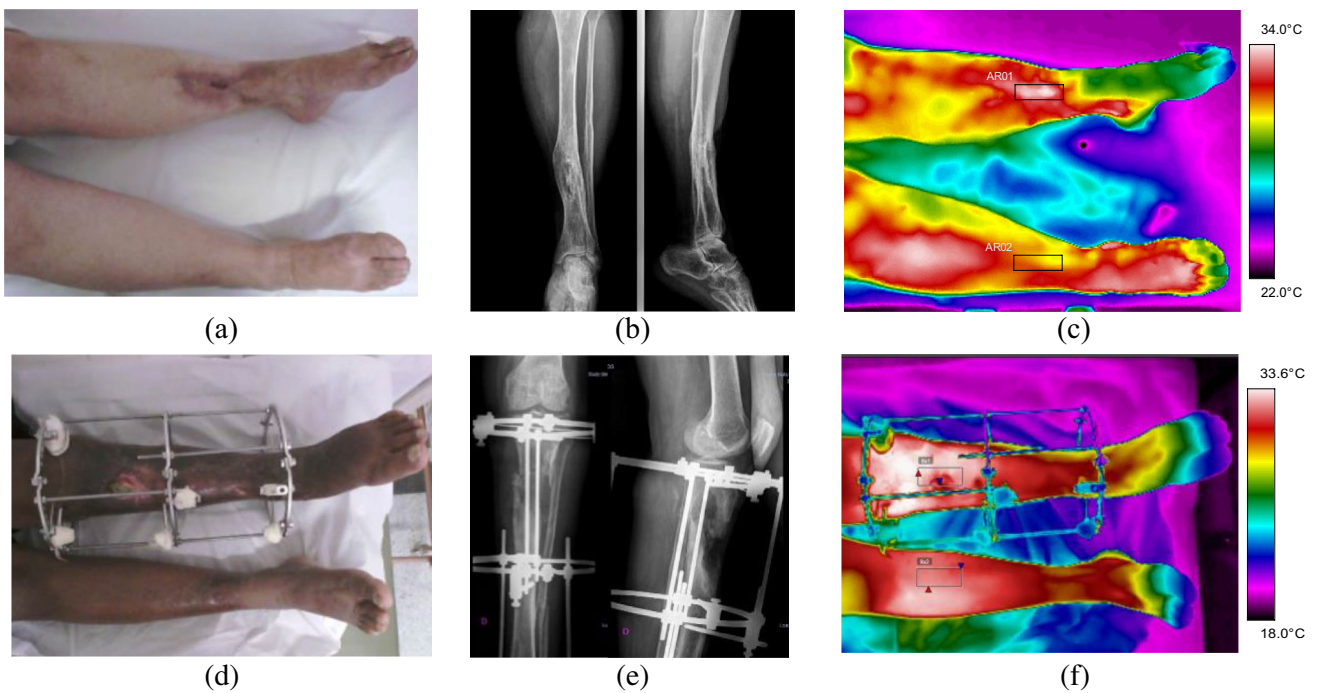
Patient 14, in the first thermographic examination, presented a medical diagnosis of latency of the infectious process following outpatient treatment for 2 years in the trauma and bone reconstruction department. In the first thermal analysis, poor vascularization was observed in the bone wound with a reduced healing process. However, in the second evaluation by thermal imaging examination and radiography, there was a recurrence of the infectious process in the bone tissue, denoting a difference of  $+2\text{ }^{\circ}\text{C}$  compared to the healthy contralateral limb.

Over four visits, patients 12 and 13 showed a difference in the temperature of the affected limb in the tibial shaft portion due to active bone infection. However, patient 12 started with temperature equilibrium between both limbs and then, in the three sequential segments, showed a decrease due to reduced vascularization of the bone and soft tissues adjacent to the lesion. For patient 13, in the two initial clinical follow-ups, the infection was controlled, but in assessments 3 and 4, a bone infection was found again.

Patient 15 underwent three follow-ups: the first assessment showed a very high temperature in the affected limb, and a diagnosis of biofilms in the blocked plate in the distal tibia was made, which resulted in a bacterial infectious process that was difficult to control. Two different types of

**Fig. 1** Average region of interest temperatures for patients 1 to 9 for the affected limb and the corresponding difference in the temperature of the contralateral (healthy) limb. This group underwent a single clinical follow-up





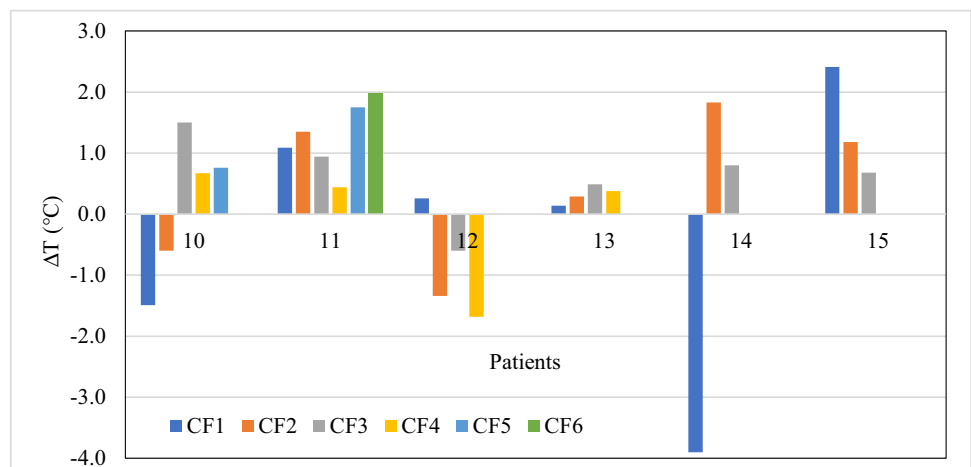
**Fig. 2** Picture of the lower limbs (a, d). Anteroposterior and oblique radiography (b, e). Infrared image and defined regions of interest (c, f)

antibiotics were prescribed (sulfametoazol trimetropin and ciprofloxacin), which showed efficacy through radiographic and thermographic examinations in the second and third clinical follow-ups, indicating a decrease in the average temperature. The thermal difference data for the evaluated patients are shown in Fig. 3.

Only six patients attended the hospital for two sequential appointments. The findings corroborate the diagnosis, demonstrating active infection with minimal bone secretion. The affected limb presented thermal difference greater than +1.0 °C for patients 16, 18, and 19 in the distal tibia portion, for patients 17 and 21 in the proximal tibia portion, and for volunteer 20 in the tibial shaft portion.

In the most severe cases, with symptoms of pain and increased serous secretion and presence of a characteristic odor of necrosis, the thermal difference was greater than +2.8 °C, as in the second evaluation of patients 16, 18, and 21. Patient 19 presented thermal symmetry due to good clinical evolution 30 days after surgical bone debridement and resection of the infectious process. The thermal values denoted thermal similarity: the affected limb had a median temperature of 31.10 °C, and the healthy limb had a temperature of 31.11 °C. The thermal values showed temperatures close to the normal values for the evaluated segment (32 °C), according to the reference data of the thermal profile for lower limbs, presented in the

**Fig. 3** Temperature difference in the region of interest between the affected limb and the healthy one, for patients 10–15. This group underwent three to six clinical follow-ups (CF)



medical thermography guideline (Brioschi et al. 2012). In the second thermographic evaluation, the patient reported painful symptoms in the portion affected by the bone wound and not being able to properly support the foot of the affected limb on the ground, and a lower temperature was observed in comparison with that of the contralateral limb, as corroborated by radiographic images. The radiological and thermal imaging data indicated a suspicion of reduced blood flow to the bone wound, with a reduction of  $-1.0\text{ }^{\circ}\text{C}$ , which is considered an important thermal difference, indicating the possibility of a medical decision of a surgical procedure for wound revascularization with graft of fibula (Fig. 4).

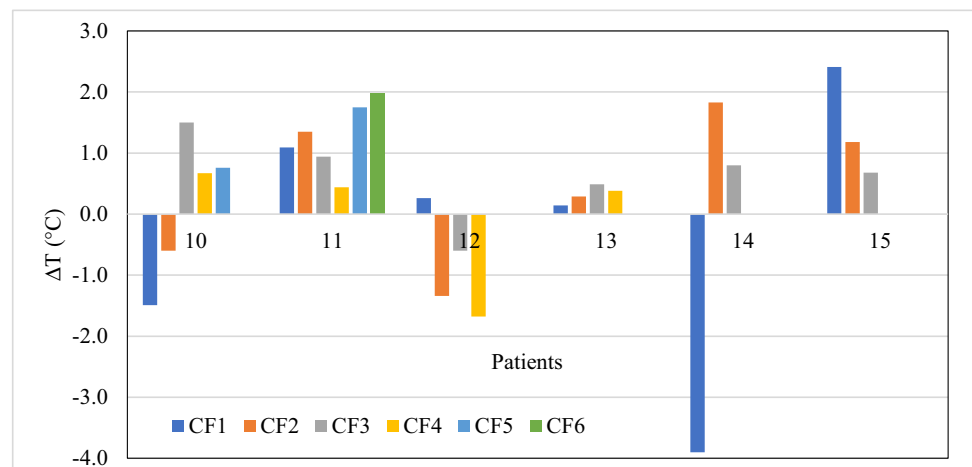
Patient 22 (male, 59 years old) underwent nine follow-up evaluations. The images were analyzed from the beginning of the patient's follow-up: four ROIs were determined by thermal analysis due to the fragility of the bone sequestration process and the possibility of fracture in the medial tibial region, and external bone fixation was required. In the first follow-up, the patient was diagnosed with reinfection; thus, the bone cavity was filled with surgical polymethyl methacrylate (PMMA) cement mixed with antibiotics. Comparative thermal images were obtained for a healthy contralateral limb of the same bone portion. The data showed a decrease in the temperature of the ROI, compatible with a decrease in local vascularization, averaging  $26.6\text{ }^{\circ}\text{C}$ . At the second clinical follow-up, the bone wound remained at the same temperature as that obtained in the previous diagnostic measurement.

In the third clinical follow-up, there was an increase in temperature to  $31.9\text{ }^{\circ}\text{C}$  in the limb affected by the bone lesion, caused by worsening of the infection, with increased purulent secretion and foul odor. The results of the pathological examination showed resistance to 40 different types of bacteria, highlighting a difficult-to-treat diagnostic picture; furthermore, the patient had been diabetic and a smoker for many years, which hindered bone consolidation.

In the fourth clinical follow-up, the PMMA was found to be loose in the bone cavity, showing resistant infection with the possibility of spreading to the proximal portion of the tibia, presenting a strong odor of necrosis and symptoms of intense pain in the affected limb, and an increase in local temperature to  $33.0\text{ }^{\circ}\text{C}$  was observed. At the fifth clinical follow-up, the patient was admitted for surgery, with suspicion of posterior proximal tibial fracture due to bone fragility caused by the progress of bone sequestration and multiple reinfections. The patient was unable to walk, experienced severe pain, and the wound had a temperature of  $32.8\text{ }^{\circ}\text{C}$  ( $+0.7\text{ }^{\circ}\text{C}$  higher than the expected). In the sixth clinical follow-up, the patient experienced a stroke after hospital discharge in the home environment. When performing bone debridement and wound cleaning surgery, it was necessary to place an ECF for greater support of the affected leg. The bone wound subsequently improved, without serous secretion and a temperature of  $32.1\text{ }^{\circ}\text{C}$ . For this patient, median temperatures were compared between both limbs in the four regions, corresponding to the proximal, medial, and distal tibial portions, and in the bone lesion. To obtain the temperature in the portion of the bone adjacent to the wound area, the medial portion was removed; in the same way, to obtain the temperature of the medial portion, the portion of the bone wound was removed, resulting in four median temperatures used for the analysis of the clinical evolution of the patient during follow-up.

In the seventh clinical follow-up, which occurred 1 month after the last medical evaluation, the infectious condition worsened, with edema in the regions adjacent to the fistula (bone cavity). The patient was undergoing special dressings with weekly changes in the hospital environment and was at risk of amputation of the affected limb. Therefore, amikacin, a strong antibiotic, was prescribed. The measured temperature rose again in the ROI, reaching  $33.8\text{ }^{\circ}\text{C}$ . In the eighth clinical follow-up, the patient presented with a decrease in edema in the leg under treatment and a decrease in bone

**Fig. 4** The temperature difference in the regions of interest of the affected limb and the healthy one, for patients 16–21. This group underwent two clinical follow-ups (CF)



secretion. The temperature also decreased to 32.7 °C at the ROI. In the ninth clinical follow-up, the patient still showed no improvement in his clinical condition, with no changes in the temperature measured in the investigated bone cavity; the outpatient care protocols were continued for special dressings and the antibiotic prescription was replaced with sulfametoxazol trimetropin and ciprofloxacin. A comparison of the thermal measurements of the affected limb under clinical treatment with those of the healthy limb (contralateral) showed that they are compatible with a diagnosis of bone injury and decreased local vascularization, with active bone infection in the eight sequential CF, as shown in Fig. 5. Only CF 4 and 9 showed thermal symmetry; however, the patient was still undergoing clinical treatment until complete healing of the cavity and control of CO, which presents cyclic recurrences. Although the clinical follow-up thermal assessments were more frequent, combined with the administration of a powerful antibiotic with a wide spectrum, the thermal fluctuations were lower than those in the healthy contralateral limb.

Thermography enabled the observation of the vascular function of the tibia and adjacent upper and lower soft tissue regions related to the bone wound in this severe clinical case of osteomyelitis. Temperature is a good indicator of scarring or relapse of bone infection. Figure 6 a shows an infrared image with four ROIs defined for patient 22, corresponding to the proximal tibia (a), diaphysis (b), and distal tibia (c), and around the wound. For the median temperature calculation, the wound area was excluded, as it was filled with cement. Figure 6 d shows an infrared image with the ECF, and Fig. 6 b and e show the visible images of the lower limbs and Fig. 6c and 6f the X-ray images.

Figure 7 shows the median temperatures of the four ROIs and the baseline of the population (according to the guidelines, 32 °C). Notably, the cement filled the wound

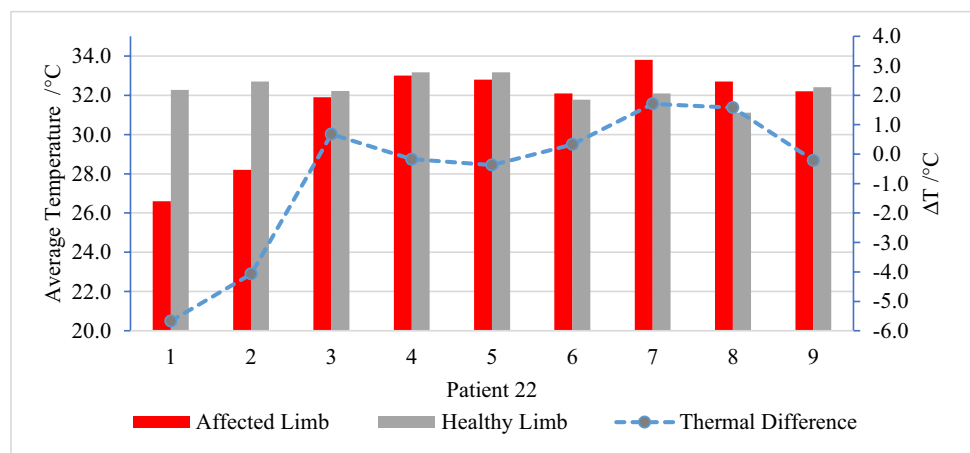
during follow-ups 1 to 3 (0–112 days); thus, the respective temperature (black line) was significantly lower than the normal temperature during this period.

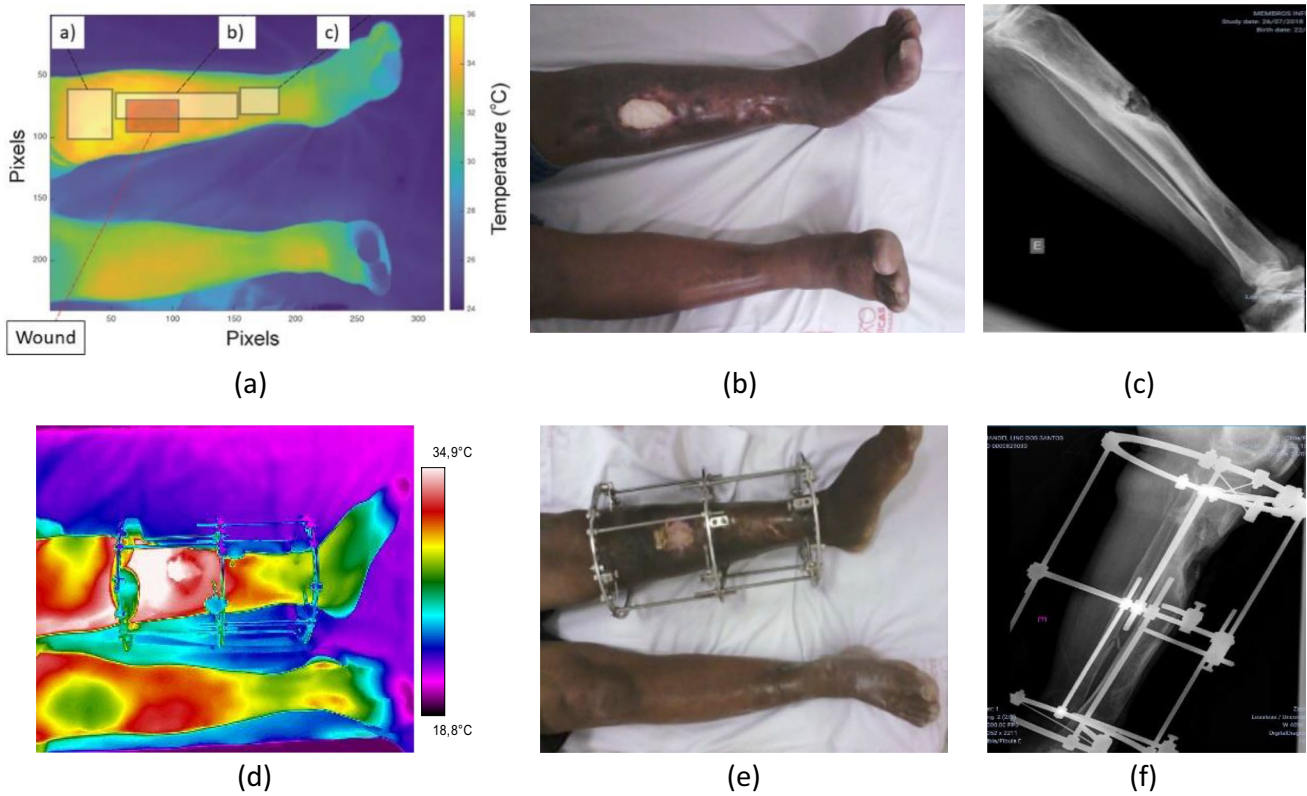
As shown in the wound in detail in Fig. 8, the thermal image (b), with 40 × 70 pixels, presents a blue color in the middle, which highlights the coldest temperature corresponding to the bone loss cavity filled by PMMA with antibiotics to treat CO.

Comparing all the patients evaluated with the mean temperature of the reference thermal profile for the lower limbs (Brioschi et al. 2012), the results showed temperature variations depending on the clinical follow-up and the evolution of the infectious process. Only two patients showed temperatures close to the mean thermal reference line, in accordance with the established standards of medical thermography normality for the tibial body segment. Patient 19 showed equivalent temperatures in the fourth assessment, with a median of 31.0 °C in the affected leg and 31.1 °C in the contralateral. Patient 22, the only patient who was followed during the entire period (300 days), presented in the ninth thermal evaluation a median temperature of 32.5 °C in the affected limb and 32.4 °C in the contralateral (Fig. 9).

For all patients at all follow-ups, as illustrated in Fig. 10a, mostly, the temperature of the wound was higher than that of the contralateral leg. In fact, abnormalities in the median temperatures between the ROIs of the affected leg were found to be correlated with those of the contralateral leg, indicating a significant difference ( $p < 0.01$ ). Figure 10 b shows the initial measurements for all patients (day 0) and the subsequent measurements (day > 0). It should be noted that patients did not complete treatment during the evaluation period. However, the initial temperature range (26.5 to 34.5 °C) decreased to (29.8 to 34.1 °C), indicating a convergence toward the normal values.

**Fig. 5** The average temperature (left axis) of the regions of interest, and the temperature difference in the ROIs of the affected limb and the healthy one (right axis), for patient 22. This patient underwent 9 clinical follow-ups

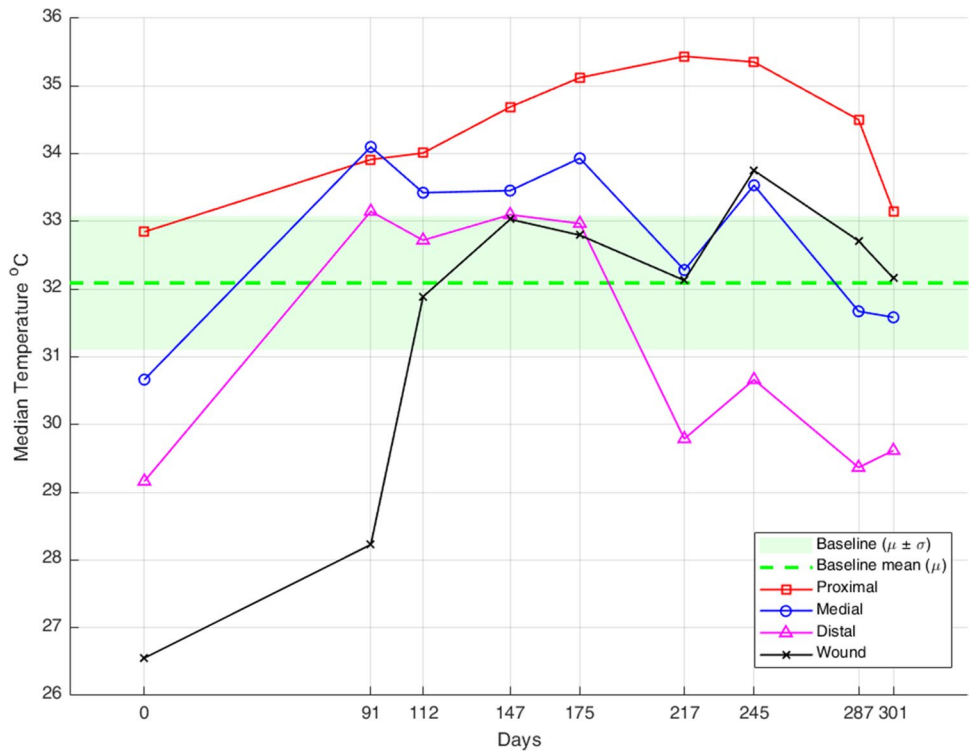




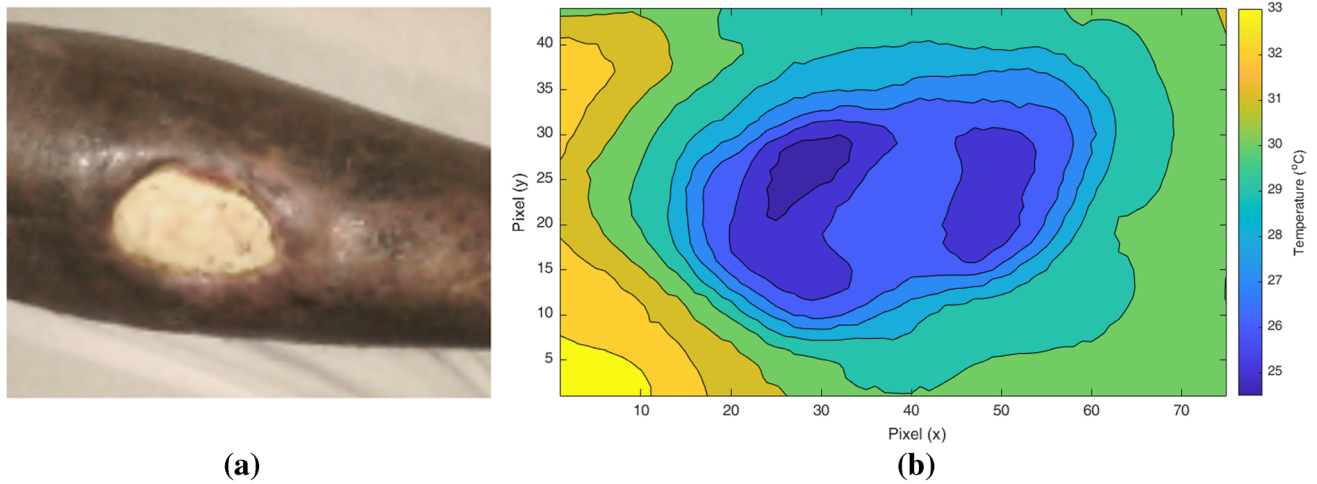
**Fig. 6** Infrared image of the patient’s lower limbs with the delimitation of the regions of interest (a, d); image at the beginning of the clinical follow-up and after placement of an external circular fixator. The white circular area in middle of the leg is PMMA that was

placed there to treat the tibia chronic osteomyelitis associated with cavity bone loss (b); visible image with the use of an external circular fixator and small size of the bony wound (e); X-ray images in oblique view (c, f)

**Fig. 7** Median temperature of patient 22 in the three regions of the tibial bone and bone wound. The green range and the dashed line refer to the baseline

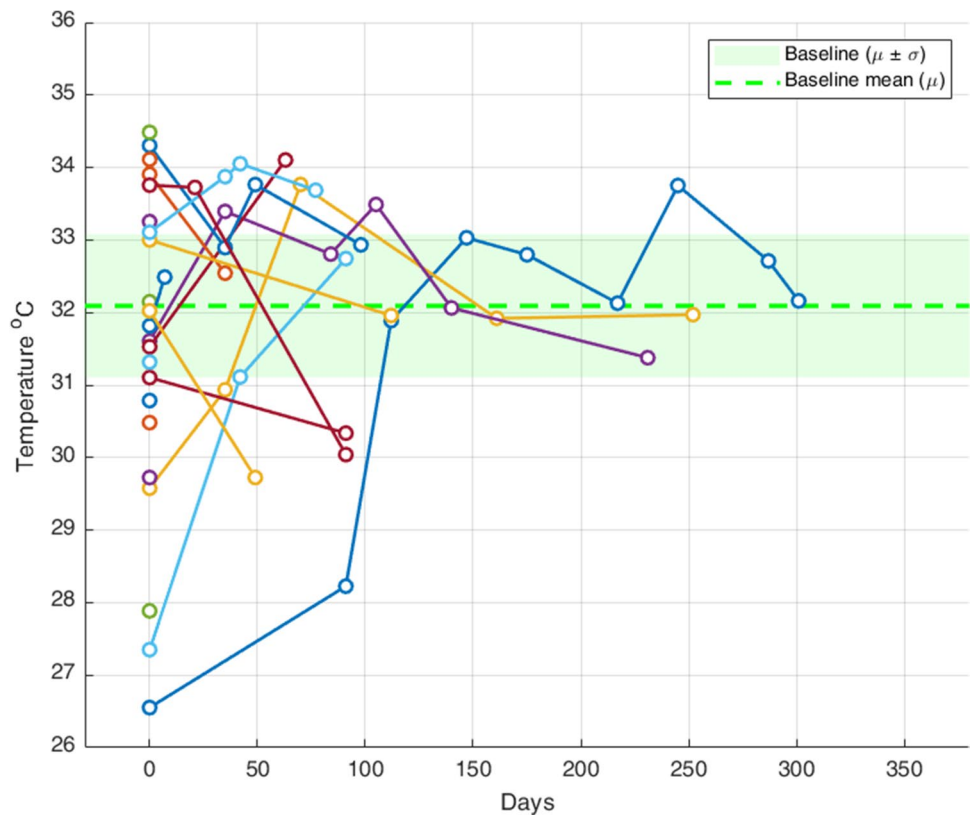






**Fig. 8** Picture of the affected area (a) and thermal image (b) of the bone wound acquired in the first medical appointment (day 0), showing a reduction of local vascularization (marked as blue)

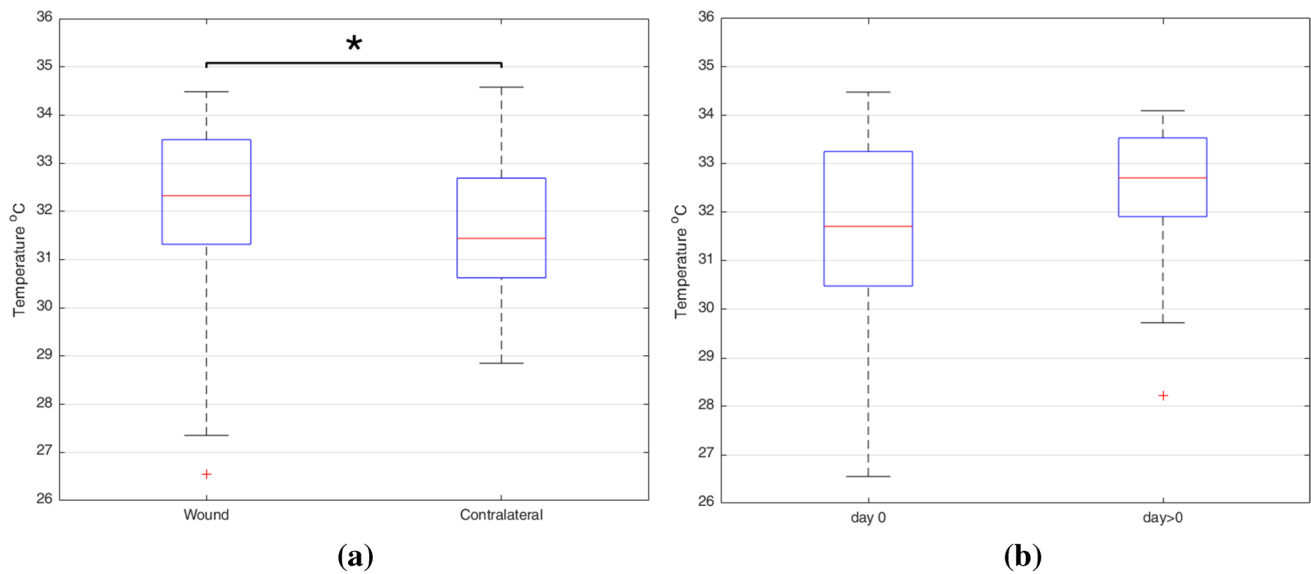
**Fig. 9** Median temperature and clinical follow-up of all patients. The green dashed line represents the mean of the medians of the control group, and the band represents the standard deviation. The blue line represents patient 22



**Discussion**

A patient with CO is considered to have a challenging prognosis for trauma and bone reconstruction due to severe bone tissue infection and possible progression to the bone, causing bone destruction and persistent tissue infection, requiring long-term follow-up and making

definitive treatment difficult (Glaudemans et al. 2019; Rao et al. 2011; Siegel et al. 2000). Serial surgical debridement combined with local and systemic antibiotic administration is considered the most appropriate protocol for successful treatment (Ferguson and Sandu 2012). Monitoring CO in the apparent bone (tibia) using thermography provides additional physiological data to support clinical decisions, especially in cases of recurrent infections or



**Fig. 10** Median temperatures in the regions of interest of the wound compared to the contralateral, for all patients and follow-ups (a). Boxplot of all patients, at day 0, compared to all the thermal acquisitions at the following appointments (b)

vascular deficits. The correlation of multimodal medical images allows for better targeting of surgical and drug treatments.

In a period of 1 year, thermal images of 22 patients in the trauma and bone reconstruction department evaluated during their return visits and CF were acquired. However, only one volunteer was validated for the entire study period.

The bone lesions in the tibial diaphysis and distal tibial portions were more difficult to heal and close. These findings are in agreement with those of Paluvadi et al. (2014) and Schottel et al. (2014), who carried out observations in 50 patients with lesions in the distal tibia. They highlighted that vascularization naturally decreased in this portion of the tibia, as well as soft tissue coverage, which are determining factors that favor a poor healing prognosis.

In the 22 patients investigated, when the tibia was infected, the temperature increased, with differences between the affected and the healthy limb ranging from +1.0 to +4.7 °C. The results showed that these thermal differences are compatible with infection diagnostics of purulent secretion manifestation and with the clinical palpation exam, in the observation of heat and local redness in the skin coverage in the areas close to the lesion. The thermal data were useful in all follow-ups and agreed with the X-ray data.

In patient 22, the administration of broad-spectrum antibiotics reduced the infection and bacterial process, leading to a thermal equilibrium, with differences lower than 0.2 °C in the distal tibia. However, despite the thermal balance, the patient presented with a pathological fracture in the tibia and fibula due to the severity of the lesion in the tibial diaphysis, aggravated by the fact that the patient was a smoker, with

a clinical indication for the placement of external circular equipment for bone fixation. In addition to the support provided by the Ilizarov apparatus, the patient was treated with laser therapy for the bone wound. As the thermal evaluations of clinical follow-up were frequent, and a powerful spectrum antibiotic was administered, the thermal fluctuations were small.

When performing surgical procedures to promote a viable vascular environment for bone healing, with a focal increase in blood circulation, there is an increase in the temperature in the region to be treated. Thus, IRT plays an important role as a complementary imaging method in an outpatient hospital setting, helping monitor osteomyelitis because MRI and CT imaging are usually negative in the diagnosis of osteomyelitis in the acute phase and frequently for image analysis of CO (Lipsky and Berendt 2010). Bimodal analysis of diagnostic medical images with 3D anatomical information of bone structures observed on radiographs and CT scans, associated with data on thermal changes in vascular supply, allows the physiological assessment of bone healing. Muscle flap grafts provide soft tissue, aiming to cover the wound after debridement of necrotic tissues, and also increase the capacity of supplying blood to the dead space created after surgical bone resection; therefore, this technique empowers bone tissue to resist the advancement of infectious processes (Al Kelabi et al. 2009). Thus, thermography provides an evaluation of the success or rejection of the implanted muscle tissue.

A case study carried out by researchers (auf der Strasse et al. 2021), in the assessment of tibial bone consolidation by infrared thermography, reinforces the applicability of

thermographic diagnostics in the analysis of temperature changes during the phases of bone healing and infectious processes in the regions of Kirschner wire insertion, thus contributing to more adequate medical decisions. Clinical follow-up in 20 medical appointments with thermography in the different stages of bone remodeling, including stages of fixation adjustment for bone traction or stretching, as well as infectious and post-surgical processes of bone graft, demonstrated that additional physiological data of bone vascularization were not observed in the X-ray examinations. The influence of metallic streak artifacts is produced by the presence of circular rings of the external fixation system, which makes it difficult to obtain a good diagnostic image because of their proximity to the bone lesion, producing regions with saturation and loss of image information (Sheridan et al. 2018) and making it difficult to view some anatomical structures. The bone graft also provides opportunities for a vascular increase and consequent temperature augmentation of the region under treatment. In these cases, thermal monitoring provides physicians with additional data on real-time patient clinical evolution. During the treatment process, periodic consultations require successive imaging examinations, exposing the patient to constant ionizing radiation and increasing public health costs for antibiotics, X-ray, CT, and MRI examinations (Panteli and Giannoudis 2016). For an immediate analysis of the healing process and the proximal areas affected by recurrent reconstructive surgeries, IRT seems to be beneficial for both patients and surgeons as a complementary imaging method.

The research carried out by Zhao et al. (2019) was a unique study that investigated the diagnosis of tibial CO confirmed by medical radiographic images and evaluated by thermal images, and it also showed changes in the temperatures of the affected regions. Thus, it was possible to demonstrate the applicability of IRT as an indicator of inflammatory changes expressed at the epidermis level, thereby reducing the number of examinations with ionizing radiation. These authors pointed out the potential of IRT for the identification of infected bones in patients with non-bacterial osteomyelitis. However, unlike our study of adult patients, the reproducibility of temperature measurements over several days was not verified because of the difficulty in retaining children and adolescents for repeated assessments in an outpatient hospital setting. The authors also showed that the diagnosis using IRT exhibited higher ROI temperatures compared to the healthy contralateral limb in pediatric patients with CO with inflammatory bone activity in the distal portion of the tibia and fibula.

Thus, IRT can be applied in the assessment of the inflammatory process, both in pediatric and adult patients, where significant temperature differences, higher than 1.0 °C, are observed when compared to the healthy limb. In tibial CO with active bone infection, it was possible to

monitor the advance of the infectious process to nearby regions, indicating the viability of thermal images as a potential aid in medical diagnostics.

The authors (Morasiewicz et al. 2008) included in their research thermographic evaluations of 175 healthy patients without any tibial lesions, which constituted a thermal profile for healthy lower limbs. All portions of the tibia were mapped in correlation to 18 patients with severe trauma and diagnosis of bone nonunion in the process of lengthening the bone using ECF. The results of this investigation showed that mean temperature values in healthy individuals were 30.3 °C for the right leg and 30.5 °C for the left leg. These values are close to those of international medical guidelines for thermography (Ring and Ammer 2012) in the lower limbs, with temperatures evaluated in 130 healthy volunteers averaging 31.5 to 32.3 °C in the right leg, and 31.5 to 32.4 °C in the left leg.

In the comparison of infrared image analysis, differences higher than 0.3 °C are considered suggestive of abnormalities (e.g., infectious processes), thus leading to the prescription of more powerful specific antibiotic therapy to contain the progression of infection to bone regenerated areas. Thermal differences equal to or higher than 1.0 °C indicate significant abnormalities according to international thermography standards (Ring and Ammer 2012).

In our study, all patients with active infection showed a temperature change of + 1.0 °C or more in the ROIs evaluated in the different portions of the tibial bone affected by CO. This information makes thermographic images a good indicator of the patient's clinical evolution, as a method of diagnosis and monitoring in the recording of body thermal patterns, aggregating important data.

Notably, IRT provides information expressed by the epidermis on the temperature of regions with lesions or infections in apparent bones and is not effective for analyzing fractures and diagnosing femoral osteomyelitis. Thermal changes reflect vascular thermal conduction to the epidermis, showing additional functional data of the investigated body regions. However, thermal images do not have the diagnostic potential for viewing internal anatomical structures, as shown by tomography, magnetic resonance, or X-ray examinations.

In short, IRT proved to be an important auxiliary medical imaging technique to be used in trauma, bone reconstruction, and infectious diseases for the bimodal evaluation of medical images during the follow-up for treatment of patients with CD. Furthermore, the characteristics of IRT, such as the absence of ionizing radiation, absence of contact, portability, absence of consumables, and relatively low cost compared to CT or MRI, make this technology interesting as a complementary diagnostic imaging method.

## Limitations

Despite the important results obtained, this study has some limitations regarding the difficulty in maintaining regular intervals for medical return appointments. During this period of the COVID-19 pandemic, no urgent appointments were postponed, which seriously affected the plan for acquiring images of some patients.

The bone remodeling activity decreased for patients over 50 years of age and was more critical among women, which may have also affected the results of this study, as this sample included female patients in this age range.

Not all patients showed equal improvement, as the pathology of CO requires long-term treatment, with latency periods and recurrences of bone infections, which are difficult to treat, due to individual biological responses to surgical and drug procedures.

## Conclusion

The thermographic profile of the tibial regions of 22 patients diagnosed with CO was acquired during medical follow-ups at the hospital. The results showed a difference larger than 1.0 °C in the average temperature of the ROIs corresponding to active bone infection. In contrast, in regions diagnosed with reduced blood supply, the affected limb showed an average temperature reduction of up to 5.67 °C in comparison with that of the healthy limb.

Temperature measurements during the initial diagnosis of a wound on the apparent bone along the different stages of healing, as well as in post-surgical infectious processes and bone grafts, provide surgeons with additional physiological data on bone vascularization. A temperature below normal standards (32 °C) for the tibial diaphysis is usually found in the bone wound with loss of adjacent soft tissues, with a slow increase toward the normal as the regenerative healing process takes place. Thus, IRT contributes to reducing the number of examinations that involve ionizing radiation.

Thermographic images are applicable to superficial bones not covered by significant muscle mass, because in these cases, the temperature will be masked, not reflecting the effective physiological changes of the evaluated limb. Thus, IRT can be an added value, used as a complementary image to gold-standard medical imaging technologies (X-ray, CT, and magnetic resonance), allowing combining the diagnostic exam with temperature data, with exams with ionizing radiation in patients who have undergone bone reconstruction treatment. However, it should be noted that IRT cannot replace other medical diagnostic imaging modalities as it provides functional physiological information expressed by the epidermis and does not portray internal anatomical

structures, thus indicating that it is an effective complementary medical diagnostic imaging exam.

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## Declarations

**Ethics approval** Federal Technological University of Paraná (UTFPR) number 3014748, November 12, 2018, and Hospital das Clínicas of the Federal Paraná University (UFPR) number 3067005 on December 8, 2018.

**Conflict of interest** The authors declare no competing interests.

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