Optical Thermography Infrastructure to Assess Thermal Distribution in Critically Ill Children

by

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Infrastructure de thermographie optique pour évaluer la distribution thermique des enfants hospitalisés en soins intensifs

Monisha SHCHERBAKOVA

RÉSUMÉ

L'objectif de cette étude était d'explorer et d'évaluer la thermographie infrarouge en tant que méthode d'analyse des profils de température des enfants hospitalisés en soins intensifs. Méthode: Il s'agit d'une étude prospective chez des patients admis aux soins intensifs pédiatriques de l'hôpital Sainte Justine présentant des signes de détresse respiratoire, hémodynamique ou neurologique. Un capteur infrarouge FLIR Lepton 3.5 a été utilisé pour prendre des images infrarouges des patients. La température centrale estimée (mesurée au niveau du thorax ou au niveau du canthus interne de l'oeil) et celle mesurée au niveau de leurs extrémités (doigts ou orteils) ont été extraites. Le gradient et le ratio entre la température centrale estimée et celle des extrémités ont été calculé. Une analyse a été réalisée sur l'ensemble des températures situées le long d'une ligne joignant le point de mesure de la température centrale aux extrémités. Des tests de corrélation de Spearman ont été effectués pour étudier la relation entre le gradient de température et le contexte clinique des patients. Résultats : Au total, 36 patients ont été inclus. La température médiane centrale estimée extraite des images IR des sujets était de 33,88°C [32,74-34,19], et la température médiane des extrémités était de 30,21°C [28,89-33,13]. Il y avait une bonne corrélation entre la température centrale extraite par thermographie et la température axillaire clinique (facteur de corrélation de 0,39, valeur p = 0,016). Il y avait aussi une très bonne corrélation entre la température centrale estimée et celle des extrémités extraites par thermographie (facteur de corrélation de 0,66, valeur p = 1,2 e-05). Les tests de corrélation par rapport à l'état clinique n'ont donné aucun résultat statistiquement significatif. L'analyse des températures extraites le long de la ligne reliant le point de mesure de la température centrale estimée aux membres ont permis de mettre en évidence les artefacts présents sur le corps des patients. Conclusion : La thermographie s'est avérée efficace pour estimer la température centrale et celle des extrémités des patients. Afin de corréler ces mesures avec des conditions cliniques spécifiques tels que le choc ou le sepsis, il est nécessaire de réaliser une étude avec un plus grand effectif.

Mots-clés : soins intensifs, stress hémodynamique, thermographie infrarouge, caméras IR, gradients thermiques

Optical Thermography Infrastructure To Assess Thermal Distribution In Critically Ill Children

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ABSTRACT

Goal: The aim of this study is to explore and assess infrared thermography as a method to analyze temperature profiles of critically ill children. *Methods:* Critically ill patients admitted to the pediatric intensive care unit of Saint Justine Hospital with features of respiratory, hemodynamic or neurological failure were included prospectively in this study. A FLIR Lepton 3.5 infrared sensor was used to take images of the patients in real clinical condition, after obtaining informed consent. The temperatures of their core (either thorax or inner eye) and of their extremities (fingers or toes) were extracted. The gradient between the central and extremities temperature of the patients was calculated by taking their difference and the ratio was calculated by dividing the two values. Continuous temperature analysis along the body was also performed by taking the temperatures along a line joining the core to the extremities. Spearman correlation tests were performed to study any relation between the gradient and the clinical background of the patients. *Results:* In total, 36 patients were included. The median central temperature [interquartile range] extracted from the IR images of the subjects was 33.88°C [32.74-34.19], and the median temperature of the extremities was 30.21°C [28.89-33.13]. There was a good correlation between the central temperature extracted via thermography and the clinical axillary temperature (correlation factor of 0.39, p value= 0.016). There was also a very good correlation between the central and extremities temperature extracted via thermography (correlation factor of 0.66, p value = 1.2 e-05). The correlation tests with clinical markers did not give any statistically significant results. The temperatures extracted along the line joining the core to the limbs were plotted on a graph and gave insightful results into the artefacts present on the body. *Conclusion:* Thermography was found to be effective to estimate the temperature of the core and limbs of the patients included in this study. Correlation with specific clinical conditions such as shock or sepsis needs further study with a larger sample size.

Keywords: critical care, hemodynamic stress, infrared thermography, IR cameras, thermal gradients

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LIST OF ABREVIATIONS

CHUSJ	Centre hospitalier universitaire Sainte-Justine
CWI	Cold Water Immersion
EMR	Electronic Medical Records
FLIR	Forward Looking Infrared (Company)
ICU	Intensive Care Unit
IR	Infrared
IRT	Infrared Thermography
ISO	International Standards Organization
LWIR	Long Wave Infrared
NCIT	Non-Contact Infrared Thermometer
PICU	Pediatric Intensive Care unit
RGB	Red Green Blue

INTRODUCTION

The internal temperature of the human body remains at a constant level of about 36.5 – 37.5° C on average, during normal conditions. In addition, the temperature of the surface of the skin remains stable in the range of 33 to 36 °C (Bierman, 1936; Chan et al., 2013). There are many internal and external factors that influence both the core and skin temperature, including blood flow, presence of fever, ambient temperature, and sweating. Because the temperature of the skin is a function of the internal blood flow, the temperature of various regions on the body can give us an insight into the changes in vascularization at any given time (Lima et al., 2011).

This study explores how infrared (IR) cameras can be used as a method of estimating the core body temperature. IR cameras work on a different principle compared to RGB (red, green, blue) cameras. Standard RGB cameras work on the principle of capturing visible light, which exists in the spectrum of 400 to 750 nanometers in wavelength. Infrared rays, on the other hand, have a wavelength larger than 750 nanometers, and this is the region of the light spectrum that is the basis of infrared thermometry. Infrared sensors capture these rays and convert them into visual images. In visible light cameras, the sensors capture the light that reflects off various surfaces and strikes the camera sensor. On the contrary, IR sensors capture IR heat that is radiated from the surfaces of objects. All objects above 0 K (-273 °C) emit these infrared rays. The thermal camera contains a lens that directs the IR rays onto a sensor element, and the internal electronics of the camera convert this heat signature into a visible thermal image. IR cameras tend to have a much lower resolution as compared to traditional visible light cameras. This is because the wavelength that IR sensors capture is much larger, and hence the sensors must be bigger in size, which limits the number of sensors that can be used without making the camera bulky. (*How Do Thermal Cameras Work? | Teledyne FLIR*, 2020)

The non-contact nature of IR is its biggest strength for its potential in the clinical setting. Current methods of core temperature measurement in pediatrics include rectal thermometry, tympanic membrane IR thermometers, and axillary temperature measurement in the armpit. Some of these methods, especially rectal thermometry, are known to cause discomfort to the patients, and most of them require cooperation from the patient, which is hard to achieve from infants (Dew, 2006). In addition, these measurement methods require a nurse or clinician to perform them manually and cannot be automated. With the introduction of IRT, there is an opportunity to set up a continuous automatic monitoring system that will not require human intervention and can provide real time insights into the physiology of the patient. Temperature screening can be performed by placing the sensor or the camera 1-2 meters away from the patient, depending on the resolution of the device. This allows for passive screening that does not interfere with the work of the clinicians. In addition, IRT gives the opportunity to estimate the temperature of the extremities of the patient. Presently, clinicians touch the hands and feet of the patient to determine if the blood flow to the limbs is compromised, in addition to checking for visual abnormalities such as skin discoloration (Saxena & Willital, 2008). These qualitative measures can be subjective, and results will vary between individuals. This makes the current methods unreliable, and there is a need to develop a uniform and consistent quantitative method of peripheral temperature estimation. IRT is a non-invasive and easy to use method that will give clinicians the opportunity not only to monitor the temperature of the limbs, but to do so passively without intervention.

Although IR thermography (IRT) has a lot of appeal in the clinical setting, its use in the pediatric critical care setting is still very limited. Their efficacy is yet to be validated for widespread standardized use. Several researchers have attempted to create a standardized method of using IR cameras for medicine (E. F. J. Ring & Ammer, 2012), and the International Standards Organization has published a protocol for the use of IRT for fever screening (ISO, 2008). In the protocol it is stated that the inner canthus region of the eye is the best and most accurate region of core temperature estimation in humans.

The camera setup for this study comprised of two cameras - the Kinect Azure and the FLIR Lepton 3.5 sensor. The Azure is a high-definition RGB camera that was used to record RGB, and 3D videos of the patients recruited in this study.

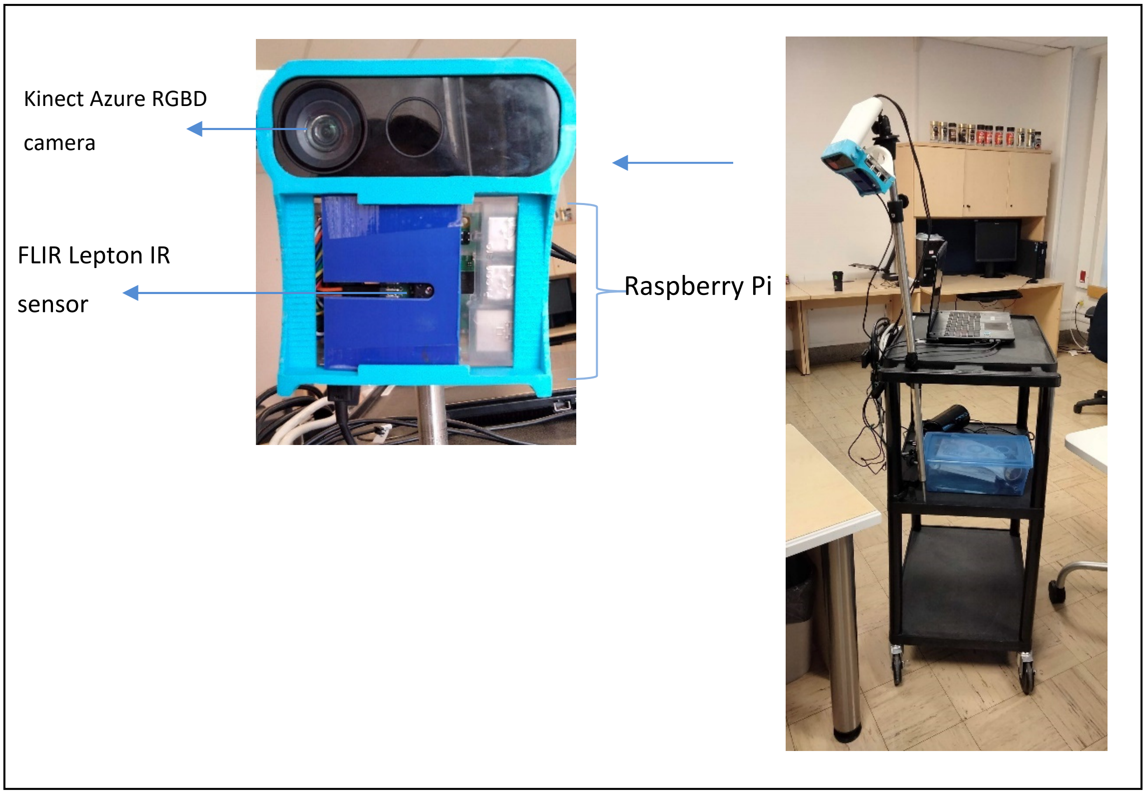

Figure I.1: Setup of cameras that is used at the hospital for acquisitions. The camera support on the pole is affixed to the edge of the ICU beds. The camera setup is comprised of the Kinct Azure camera and the FLIR Lepton IR sensor that is embedded in a Raspberry Pi.

The IR sensor was embedded with the Azure in a support and the IR and RGB images were taken simultaneously. The full setup can be seen in Figure I.1. The idea was to calibrate and register these two cameras. Image registration is the procedure of combining two image feeds of the same scene taken from two different camera locations (or cameras), into one image. Registration methods rely on the idea of locating points in one image and locating the corresponding points in the second, and then using these locations to superpose the images over one another and align the coordinate systems of both cameras. The main benefit and motivation behind registering the image feeds of the two cameras is combining both modalities – the thermal information provided by the IR camera is more useful when superimposed over an RGB image. This way we can reference the temperature of various regions of the body by interpreting this compound image. In addition, the skeleton tracking feature available with the Kinect can allow us to extract the temperature of specific areas of the body from this superimposed image automatically, thus reducing human intervention and error. An algorithm for combining the two image feeds was developed as part of this study.

This study aims to expand the current knowledge base on the use of IR cameras in the critical care setting, especially in pediatrics. The use of IR cameras in the pediatric critical care environment is still a relatively new field. Several studies have been performed to examine how IRT can be used to evaluate the thermic gradient present in the limbs of pediatric patients (Coats et al., 2018; Ortiz-Dosal et al., 2014; Sadr et al., 2019), but the number of such studies remains low. The potential for IR sensors and cameras in the PICU remains promising, and it is of high importance and value to conduct more experiments under various settings to fully evaluate the robustness of an IR setup in an ICU. This work serves as a preliminary step towards setting up a system of continuous thermographic monitoring of patients in the PICU. The idea is to install IR sensors and a Kinect Azure RGBD camera above each bed to perform temperature screenings regularly, without requiring human intervention. This continuous monitoring will act as an additional source of information on the patient's hemodynamic state.

The following work collected IR images of a sample of patients in the critical care unit and estimated the body temperature and temperature of the extremities. Both the gradient and the ratio between these two values was measured. In addition, the modulation of temperature from the core along the body to the limbs was studied. This analysis is a first step towards potentially using IR images to identify medical equipment and artefacts on the patient's body, which will serve in improving future temperature extraction procedures. If the RGB and the IR feed are superimposed over each other using a successful image registration algorithm, and the artefacts on the body can be detected, then the temperature extraction can be automated. This will reduce the amount of human intervention required and streamline the work of the clinicians.

In summary, the main objective was to explore whether IR sensors can be a useful tool to estimate the central and extremities temperature of patients admitted to the pediatric intensive care unit. In addition, an image registration algorithm was developed to try and calibrate and combine image feeds from the Azure and the Lepton IR sensor.

An overview of the thesis and the topics covered is as follows:

1. **Introduction**

   An introduction to the project and its motivations
2. **Literature Review**

   A coverage of some of the papers reviewed as part of the literature for this project. Topics covered incude
   a. Image acquisition with IR cameras
   b. Infrared imaging in fever screening
   c. Current standards for temperature measurement in pediatrics
   d. IRT in medicine
   e. IRT in Pediatrics
   f. IRT as a method of non -invasive body temperatre measurement
   g. IRT for thermographic analysis of critically ill infants
   h. Hemodynamic assessment by infrared thermography in children after cardiac surgery
   i. Challenges for IRT in the ICU
3. **Article submitted (under review) to IEEE Open Journal for Engineering in Medicine and Biology: Optical Thermography Infrastructure to Assess Thermal Distribution in Critically Ill Children**
   a. Abstract
   b. Introduction
   c. Materaials and methods
   d. Results
   e. Discussion
   f. Conclusion

g. Acknowledgement
h. Supplementary materials

4. **Conclusion**

A summary of the work done in this project and a reflection on all the findings

5. **Recommendations**

Proposals for future work and ideas on how the drawbacks of this project can be rectified.

CHAPTER 1

LITERATURE REVIEW

Infrared thermography has increased in popularity in the field of medicine over the past decade. Its clinical accuracy has been evaluated through several trials and studies over the course of the past few years. Most of the papers describe the use of either infrared cameras or non-contact infrared thermometers. This literature review will focus on the use of infrared cameras.

1.1 Image acquisition with IR cameras

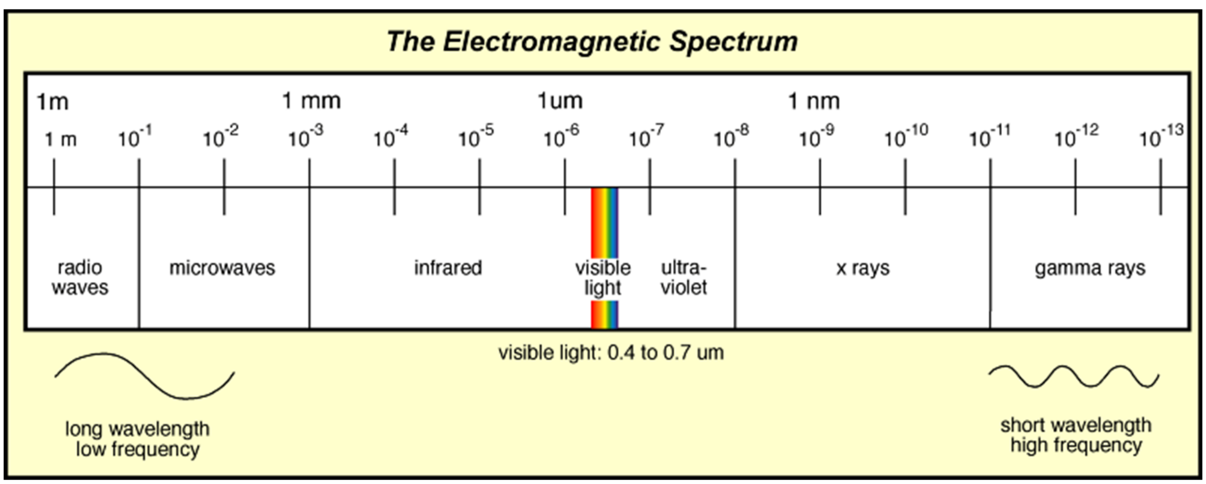

Figure 1.1 A schematic depicting the full range of the electromagnetic spectrum. IR rays have a wavelength larger than visible light and are invisible to the human eye (*The Electromagnetic Spectrum*, n.d.)

Every material in the universe has a certain emissivity associated with it. The emissivity of an object can be described in simple terms as the measure of how well an object radiates thermal energy. An object can, for example, be at a very high temperature, but if it has a low emissivity (such as shiny metals) it will not radiate thermal energy well. Due to this, sometimes metals at very high temperatures show up as being cold on IR images, and it is hard to estimate their actual temperature (*How Does Emissivity Affect Thermal Imaging?| Teledyne FLIR*, 2019).

Figure 1.2 In this image taken from the FLIR website, the ring on the persons finger is the same temperature as the hand but shows up as being much cooler. Taken from "How Do Thermal Cameras Work?", Teledyne FLIR. (2019).

During IR image acquisition, the ambient temperature, and the presence of other objects in the scene play a big role in the quality of the resulting image. For example, if an experiment is being conducted with a thermal camera outdoors, the ambient sunlight present will also strike the target and reflect into the IR sensor. Hence the thermal energy that is received from the target is a combination of the radiation emitted by the object and the heat reflected from the sun. If the target being studied is a very polished metal, due to its low emissivity it will reflect all of the IR rays that strike the surface. So, the temperature reading will represent the reflected heat as opposed to the thermal radiation emitted by the object itself. It is important when conducting experiments with thermal cameras to be mindful of the other objects present in the scene that may cause incorrect measurements from the thermal camera.

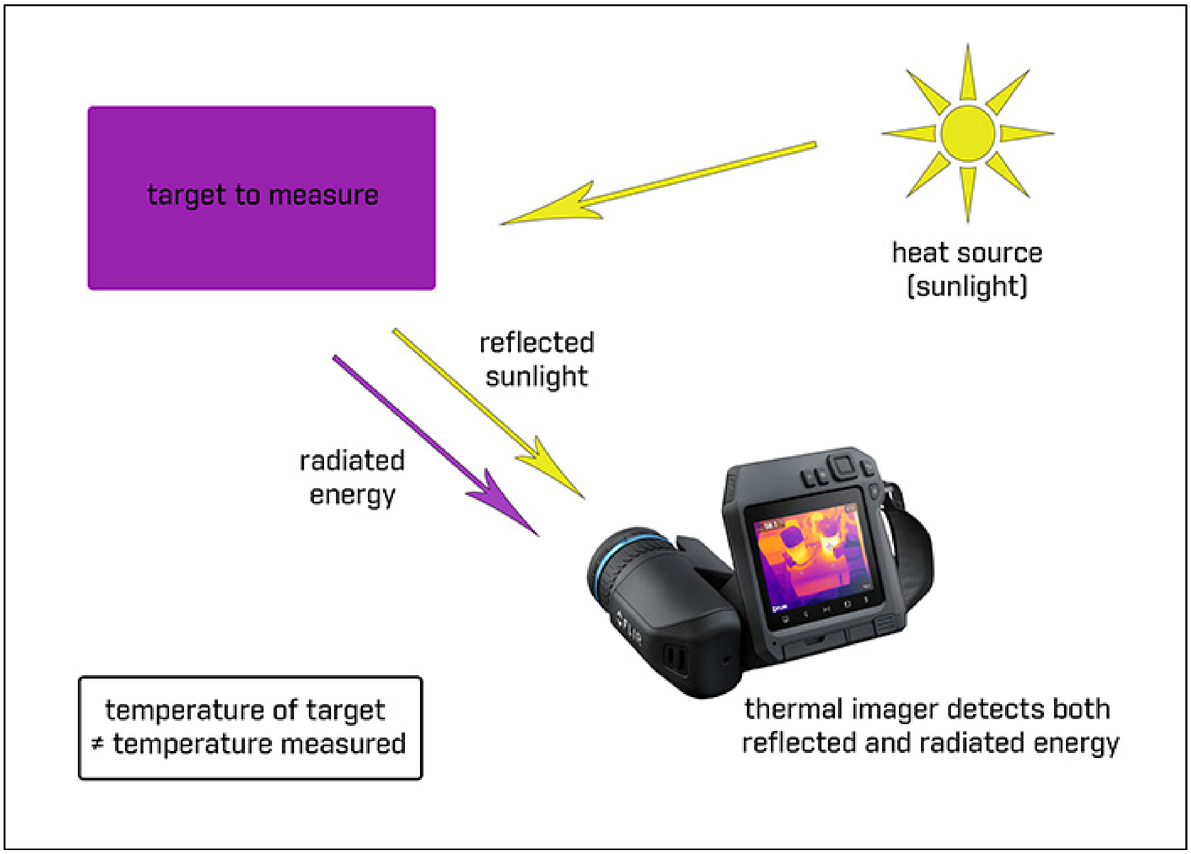

Figure 1.3 Schematic describing a setup to measure the temperature of a target with a thermal camera in the presence of an additional heat source. Taken from "How Does Emissivity Affect Thermal Imaging?", Teledyne FLIR (2019).

1.2 Infrared imaging in fever screening

As mentioned before, infrared cameras have come into the spotlight over the past few years as a non-contact fever screening mechanism in public places during epidemics such as SARS, H1N1, and more recently the SARS-CoV2 pandemic. IR cameras are used in areas like airports and train stations to screen passengers by extracting the temperature of their face (usually the forehead or between the eyes) and provide an alert if it is over a certain stipulated threshold. These methods have come under scrutiny recently as to whether they accurately screen the population (Howell et al., 2020). The International Standards Organization (ISO) published a protocol for the use of IR cameras for fever screening and recommended that the inner canthus region of the eye is the only site on the face that is suitable for non-contact temperature measurement (ISO, 2008). Following the guidelines of the protocol, it is recommended for any studies that use IR cameras for core temperature detection to only use the inner canthus region of the eye to get the most accurate possible measurements.

1.3 Current standards for temperature measurement in pediatrics

The three main methods of core temperature measurement in the PICU are via infrared tympanic membrane thermometer, axillary temperature (armpit) and the rectal thermometer. All these methods have their strengths and drawbacks.

The most popular site for temperature measurement in children is the tympanic membrane, present in the inner ear. This membrane is situated close to the internal carotid artery, and hence the temperature measured here is an estimate of the blood flowing into the hypothalamus of the brain. These IR thermometers measure the thermal radiation and estimate the temperature of the blood in the membrane (Johnson et al., 1991). They are quick and easy to use and cause minimal discomfort to the patient.

Nevertheless, the above method comes with its own set of drawbacks and downsides. The temperature estimated can be affected by several factors. If the patient has been lying on the ear for an extended period of time, it may affect the blood flow to the inner ear, and in turn affect the temperature estimate. It is also affected by hot or cold external temperatures, and the positioning of the thermometer. When a patient is crying, the blood flow to the inner ears increases, and this can sometimes give a false positive for high body temperature. Despite this experience, studies have shown no statistically significant correlation between crying in infants and tympanic membrane temperature readings (Kahyaoglu, et al., 1997). In addition, this method of measurement is not recommended in very young patients (less than 1 month) because the anatomy of the ear canal at this age does not permit the thermometer to be close to the tympanic membrane (Richardson & Lakhanpaul, 2007).

Axillary temperature measurement is a quick and easy procedure to estimate core temperature in children of all ages. It involves the placement of either a mercury thermometer or a digital thermometer in the armpit of the patient, which places the bulb of the thermometer close to the axillary artery. The proximity of this large artery to the thermometer makes this location a good approximation for the core body temperature, and studies have proven this to be true by correlating it to rectal and oral thermometry (Lodha et al., 2000; Wood et al., 2018). Although several studies have shown axillary thermometry to be a reliable indicator of core temperature, there are still studies that disagree on the exact correlation and claim that all axillary measurements must be incremented by a factor to make them equivalent to the ground truth (Singh et al., 2000).

Rectal thermometry is considered to be the gold standard for temperature measurement in children, and there is yet to be a replacement that is as accurate (Greenes & Fleisher, 2001; "Temperature Measurement in Paediatrics," 2000). Rectal temperature readings involve inserting a mercury thermometer around 3 cm into the rectum of the infant, and holding for at least a minute, or until the temperature stabilizes. The invasive nature of the procedure makes it less preferable for many parents, and the discomfort caused to the child often makes them uncooperative. In addition, the added time required for undressing adds to the inconvenience (Kahyaoglu, et al., 1997). Rectal temperature has been shown to not respond quickly to changes in temperature in the body, i.e., it can sometimes be higher than the actual core body temperature (Martin et al., 2004). Lastly, there is also a risk of perforation of the rectum if the thermometer is not inserted correctly.

Hence, there is a need for a reliable method of temperature measurement for children in the ICU. The ideal method would be non-contact and non-invasive, to provide as little discomfort to the patients as possible. Infrared thermography has the potential to fill this gap of requirement, as it is completely non-invasive and gives insight into the temperature distribution across the entire body, not just at certain sites. This can give the clinicians more information into the physiological state of the patient.

1.4 IRT in Medicine

Even though some standards have been defined, IRT still shows inconsistent results because most studies have variations in their implementation of equipment set up, acquisition and temperature extraction procedures. One study aimed to evaluate the clinical effectiveness of IRT and performed an experiment with 596 subjects by extracting facial temperature from thermal images. The Pearson correlation coefficient for IRT vs the reference temperature (taken via oral thermometry for each patient) was found to be highest when the temperatures were extracted from the inner canthi region, as opposed to other regions of the face such as the forehead (Zhou et al., 2020).

IRT has been growing in popularity and use in the medical field over the past few years but remains out of reach for many researchers, mostly due to restrictions in budget (IR cameras can go up to about 2000 USD per unit), access to databases of thermal images and limited financial resources. In addition, there are currently very few publicly available databases of medical thermal images to allow for researchers operating with a lower budget to have the opportunity to explore thermography (Shaikh et al., 2019).

So far, IRT has been successfully used as an adjunctive tool in the evaluation and diagnosis of several medical conditions, including breast cancer, skin diseases and more recently, several vascular disorders including inflammation in the feet of diabetic patients (Ilo et al., 2020). The vasodilation and vasoconstriction of blood vessels and capillaries is a process that regulates temperature and the amount of blood flowing through a particular organ or limb (Kellogg, 2006). Through the analysis of thermal images taken of subject's feet, the authors were able to successfully reveal differences in temperature between areas of the skin, showing abnormal microvasculature caused by diabetes.

1.5 IRT in Pediatrics

The use of IRT for the diagnosis and analysis of physiological disorders in children is an especially new field. There have been several attempts to use IRT to detect and analyse abnormalities. The non-contact nature of IR screening is its biggest appeal in the field of pediatrics, as other forms of temperature measurement such as rectal thermometers are invasive and cause discomfort to the patients. One study performed an experiment where 483 examinations were performed over the course of 10 years on 285 pediatric patients. IRT was found to be a useful tool to follow up and supplement the diagnosis and detection of various ailments such as vascular malformations, burns, and thrombosis among many others (Saxena & Willital, 2008).

Even so the use of IRT in pediatrics is still a new field due to a limited number of relevant studies, but it has been shown to be more accurate in skin temperature estimation in children as compared to adult subjects (Owen & Ramlakhan, 2017).

1.6 IRT as a method of non-invasive body temperature measurement

The inner canthus of the eye has been found to be a dependable region of the face for temperature extraction through non-contact methods such as NCITs and IR cameras (ISO, 2008). Although the inner canthus has found to not be dependable in some situations such as sports and exercise, there is enough evidence in literature to show that if all the required protocols are followed, the temperature extracted from this region of the face is a reliable estimate of the core body temperature (Fernandes et al., 2016).

There have been previous attempts to construct a non-invasive temperature monitoring setup using the FLIR Lepton sensor. In 2019, a study used the Lepton 2.5 sensor to set up a continuous body temperature monitoring system that would take IR images of a subject from 40-80 cm away and extract the forehead temperature (Lin et al., 2019). Face detection and tracking was used to detect the face and then a region of interest was extracted from the forehead. The Lepton 2.5 comes with a radiometry feature that allows the output of the camera to be an image where each pixel is a 14-bit value that corresponds to the scene flux, which can be converted into the temperature value using Planck's equation, which is what the authors chose to do. But something that would have simplified their methodology would have been to use the “TLinear” mode that does the conversion intrinsically and produces pixels that represent the scene temperature values in Kelvin. Another potential drawback of this study is that they used another thermal imager (Keysight U5855A) to measure the subjects’ temperature from the same distance and used this value as the temperature ground truth. So, this paper essentially studied the reliability of the FLIR Lepton 2.5 sensor versus an industrial thermal imager, and did not evaluate its reliability against a gold standard form of measurement, such as rectal thermometry(Greenes & Fleisher, 2001). In addition, the distance between the subjects and the thermal camera was very short, only 40-80 cm, which is not a realistic distance for the clinical environment. The camera must always be placed a comfortable distance from the patient, so as to not intervene in the work of the clinicians.

1.7 IRT for thermographic analysis of critically ill infants

There have been a few studies conducted to explore how IRT can be used to help in the analysis and diagnosis of patients in certain critical conditions, such as septic shock. One study employed the Leicester MII protocol and took images of the arms of patients belonging to three subgroups – control (n=35), fever (n=16) and sepsis (n=5). The thermal gradient present along the arm was measured and any variations within and between the groups were studied. They found a significant gradient between upper arm and the fingers in the control group, but no gradient in fever and sepsis, and concluded that this gradient could be useful in future studies (Coats et al., 2018).

Another paper on early sepsis recognition devised a fully automated system of calculating core vs extremities temperature by taking images of the frontal and lateral view of the face. They used object detection and image classification to localize the inner and outer ear of the subject along with the tip of the nose and the inner corner of the eye. The gradient between the inner/outer ear and the eyes/nose was calculated for the subjects before and after exposing them to a cold stress test, to simulate the effects of sepsis. The subjects' hands were immersed in ice water (cold water immersion or CWI) and the temperatures from the IR images were continuously extracted, and the moving average of the values plotted on a graph. They found that the core temperature also decreases with the extremities temperature, but at a much lower rate. This study shows that IR imaging has a lot of potential in the field of medical thermography, and that with the right methodology and protocol it can be adopted as an assistive tool to monitor body temperature (Sadr et al., 2019).

In a case series on the use of IRT in children with shock, researchers examined 8 pediatric patients admitted to the PICU (Ortiz-Dosal et al., 2014). Patients that were suffering from shock showed a significant gradient between the core and extremities, at least 7°, when compared to critically ill patients without shock. This result is contradictory to the work done by Coats et. al, who found no gradient in patients with shock. Both studies had small sample sizes, 5 patients with shock for one and 8 for the other. It is clear that the current knowledge on the thermographic profiles of patients with shock and sepsis is not refined enough and more work needs to be done to expand the state of the art for IRT.

1.8 Hemodynamic assessment by infrared thermography in children after cardiac surgery

This article was written and submitted to the Journal of Pediatric Critical Care Medicine by co-author Armelle Bridier as part of her PhD Thesis conducted at the University of Montreal (July, 2021).

The aim of the study was to evaluate whether there was any correlation between the thermal gradient obtained via infrared thermography (IRT) and oxygen extraction ratio (O_2ER) in children that have undergone cardiac surgery in the past 24 hours and are at risk of low cardiac output. Thermal images were taken of the patients after the cardiac surgery, and the temperature of the inner canthus region of the eye was extracted along with the temperature of the extremities (toes or fingers). These values were used to calculate the gradient, and this gradient was correlated with the O_2ER. In total, 41 patients were included, and a significant but weak correlation was found between the temperature gradient and O_2ER ($r = 0.25$, $p = 0.016$), and this correlation increased for O_2ER above 30% ($r = 0.32$, $p = 0.016$). Age was an independent factor and did not influence the thermal gradient, and there was no correlation between vasoactive drugs and the gradient.

The main conclusions drawn from this work was that IR imaging seems to be a good non-invasive method of temperature estimation, but the work could be improved by increasing the sample size and using a camera with higher thermal sensitivity.

In addition to this work, several abstracts were submitted and published in journals as part of the work done in this project. All of the submitted abstracts are included in this thesis in Appendix I to IV. Please reference these abstracts for additional insight into some of the statistical and exploratory work done as part of this study.

1.9 Challenges for IRT in the ICU

Implementing IRT in the ICU comes with its own set of unique challenges. The use of IR cameras in the medical field is still a new and developing idea. One of the limitations is that high-quality IR cameras are expensive and usually out of budget. These IR cameras and sensors can also sometimes get damaged easily because the internal mechanisms are sensitive to external changes in temperature. In addition, IR camera manufacturers have yet to build cameras that are specifically geared to use in the medical field. There is a dearth of specific software and libraries that can process and analyze medical infrared thermograms (Tavares & Natal Jorge, 2013).

Thermal images cannot be interpreted as easily as regular RGB images. Therefore, their use and interpretation require trained personnel or some experience. IR images are best taken in a controlled temperature environment, where the camera can be calibrated accurately and there are no disturbances that can disrupt the image. In a medical setting, especially the ICU, there are several kinds of medical equipment around the patient that emit IR rays and disrupt the images, like ventilator screens, pipes and other electronic devices. In addition, the presence of bandages, catheters and casts reduces the exposure of the skin to the camera sensor. The quality of the output is also heavily dependent on the patient's cooperation. Pediatric patients, especially younger children, often struggle to stay still and sometimes move during the IR acquisitions. In addition, the temperatures recorded from IR images typically are from the surface of the skin, a maximum penetration of 2.5 mm. (Tavares & Natal Jorge, 2013) This means that the temperatures recorded are simply an estimate of the true core body temperature. If an IR image is taken of a patient at a particular instant, it only reflects the blood circulation in the body at that particular instant.

There is currently a need for a standardized procedure and protocol for the implementation of IR cameras in medicine, especially in the ICU. A guideline will make IRT results more reliable and reproducible. The protocol drafted by the ISO is a step in the right direction, but there is still more work to be done to standardize the use of IR cameras in hospitals (ISO, 2008).

A gap in knowledge exists in the field of temperature distribution across the surface of the human body. Several projects have been devised to build a database of the way temperature distribution varies across the surface of the skin in humans. This would act as a crucial reference database to validate the results obtained via IRT (F. J. Ring, et al., 2005).

The aim of this work was to continue in line with the above-mentioned studies to contribute to the current knowledge of IRT for critical care.

CHAPTER 2

OPTICAL THERMOGRAPHY INFRASTRUCTURE TO ASSESS THERMAL DISTRIBUTION IN CRITICALLY ILL CHILDREN

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2.1 Abstract

The temperature distribution at the skin surface could be a useful tool to monitor changes in cardiac output. Goal: The aim of this study was to explore infrared thermography as a method to analyze temperature profiles of critically ill children. Methods: Patients admitted to the pediatric intensive care unit (PICU) were included in this study. An infrared sensor was used to take images in clinical conditions. The infrared core and limb temperatures (θ_c & θ_l) were extracted, as well as temperatures along a line drawn between these two regions. Results: The median [interquartile range] θ_c extracted from the images was 33.88°C [32.74-34.19] and the median θ_l was 30.21°C [28.89-33.13]. There was a good correlation between the θ_c and the clinical axillary temperature (rho = 0.39, p-value= 0.016). There was also a good correlation between the θ_c and θ_l (rho = 0.66, p-value = 1.2 e-05). Conclusion: Thermography was found to be effective to estimate the body temperature. Correlation with specific clinical conditions needs further study.

Index Terms— Critical care, hemodynamic stress, infrared thermography, IR cameras, thermal gradients.

Impact Statement— Temperature gradient analysis through IR imaging shows promise for the PICU, and its applicability in various clinical scenarios will be the subject of further study

2.2 Introduction

Humans have the ability to regulate their own body temperature, and keep it at a stable level between 36.5 and 37.5 °C on average. Similarly, the temperature of the surface of the skin remains stable in the range of 33°C to 36 °C under normal conditions (Bierman et al,1936; Cheung et al., 2012). The temperature of the skin and various parts of the body is a direct result of the blood flow, and hence the temperature distribution at the surface of the skin can give us an insight into the changes in vascularization in the body (Lima et al., 2011). This can allow us to understand whether the blood flow is centralized to the vital organs and directed away from the superficial organs and limbs. Studies have shown that patients with fever and shock show abnormal temperature gradient along the limbs (Coats et al., 2018; Ortiz-Dosal et al., 2014). One study also found that the temperature distribution in children follows a similar pattern to adults, but with less variation (Kolosovas-Machuca et al., 2011). This type of hemodynamic analysis of the human body based on temperature is a new and diverse field and is especially novel when applied to children in the pediatric intensive care unit (PICU).

Infrared thermography (IRT) is a non-invasive method of temperature measurement. All objects that have a temperature above absolute 0 K (-273 °C) emit infrared radiation. These infrared rays when detected by a sensor can be used to measure the objects temperature. Over the last decade, the prevalence and use of infrared sensors for body temperature measurement has surged. The efficacy of these sensors in the clinical setting is yet to be studied and validated for widespread use, especially in the case of critical care. The International Standards Organization (ISO) published a protocol for the use of IR cameras for temperature estimation and recommended that the inner canthus region of the eye is the only site on the face that is suitable for non-contact temperature measurement (ISO, 2008). Hence, it is recommended for any studies that use IR cameras for core temperature detection to only use the inner canthus region of the eye to get the most accurate possible measurements.

The non-contact nature of IR screening is its biggest appeal in the field of pediatrics, as other forms of temperature measurement such as rectal thermometers are more invasive and cause discomfort to the patients without giving an insight into the temperature distribution throughout the body (Dew et al., 2006). A study analyzing 483 examinations performed on 285 pediatric patients found that IRT was a useful tool to follow up and supplement the diagnosis and detection of various ailments such as vascular malformations, burns, and thrombosis (Saxena and Willital, 2008). Even though the use of IRT in pediatrics is still a new field due to a limited number of relevant studies, it seems to be more accurate in skin temperature estimation in children as compared to adult subjects (Owen and Ramlakhan, 2017).

Therefore, the aim of this study was to validate IRT as a reliable estimate of core body temperature in critically ill infants and analyze the clinical value of temperature evolution across the body assessed by IRT.

2.3 Materials and methods

2.3.1 Inclusion Criteria

Patients less than 18 years of age, admitted to the PICU of Centre Hospitalier Universitaire Sainte-Justine (CHUSJ) between January 1st, 2021 and May 30th, 2021 with vital distress (respiratory, hemodynamic or neurological), were prospectively included in this study, after obtaining written informed consent.

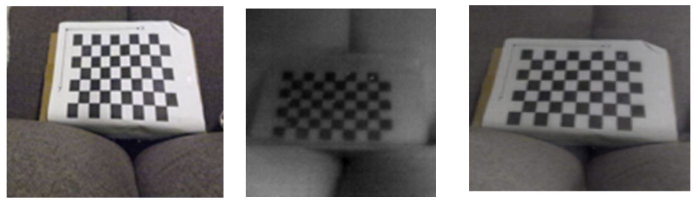
2.3.2 Choice of cameras

Our setup consisted of two cameras – the Kinect Azure and the FLIR Lepton 3.5 LWIR (Long Wave InfraRed) thermal infrared sensor. The sensor had a resolution of 160 x 120 pixels with a thermal sensitivity of < 50 mK. The Azure has several operating modes for its RGB camera, the highest resolution being 4096 x 3072 pixels. The camera was embedded in the FLIR Breakout Board V2, and the board was connected to a Raspberry Pi 3B + that was used to interface with the camera and acquire the images.

The acquisition of RGB videos and images by the Kinect allowed us to get a clear visible light image of the patient to identify any obstructions or artefacts (such as medical equipment) on the patient's body. In addition, the camera was used to extract 3D point cloud videos of the patient, to be used in other projects that assess the respiratory profile conducted at the same institution (Rehouma et al., 2018; Prinsen et al., 2021).

2.3.3 Calibration of cameras

To automate this procedure of temperature estimation, the RGB images from the Kinect were superimposed with the IR image from the Lepton. The procedure of calibrating the two cameras involved taking photos of a calibration marker, whose dimensions are known. The calibration marker used was a checkerboard pattern, provided by MATLAB (Mathworks, 2021). Images of this marker were taken from both cameras, and the checkerboard was detected in each image using object detection. A special marker made of aluminum squares instead of ink was used for the IR sensor, so that the squares show up clearly in the IR image. As aluminum has a low IR emissivity, it shows up dark in the image, while the rest of the marker remains white.



(a) (b) (c)

Figure 2.1 In subfigure (a) is a sample image taken with the Kinect Azure. Subfigure (b) shows a sample image taken with the Lepton IR sensor. The subfigure (c) is the result of superposition of these two images after registration

2.3.4 Image Registration

The process of calibrating the cameras together in MATLAB provides a transformation matrix, that defines how one image must be warped to be superimposed accurately over the other camera image. The checkerboard is detected in the image using the Camera Calibrator App from MATLAB. The points are used to estimate a transformation matrix that is used to warp the IR and RGB images over each other. The result of this superposition is shown in Figure 2.1.

2.3.5 Temperature measurement and extraction

The FLIR Lepton 3.5 sensor has a radiometry feature, which essentially means that the temperature values for each pixel can be extracted from the pixel values of the image. When the TLinear mode is enabled, the image pixel values are converted from representing the scene flux in 14-bit digital counts to representing temperature values in Kelvin. If a pixel value is 30000, that means the pixel is at 300.00 K or 26.85 °C (FLIR, 2021).

In the future, when this process will be automated, one will be able to extract the pixel values, and in turn, the temperature values from a specific region of the image, defined by the skeleton of the patient that will be obtained from the Kinect image. Therefore, the estimation of the core and limb temperature will be possible with little to no human intervention.

2.3.6 Assembly of all parts in the hospital

The setup used at the hospital consisted of a PC and the combined camera (Kinect Azure and IR sensor) embedded in a support. The whole setup of the equipment in the hospital was done on a movable trolley. The support with the Azure camera and the Lepton were connected to a pole that can be fixed onto the edge of the pediatric intensive care unit (PICU) beds, allowing the cameras to be pointed towards the patient at an appropriate distance without interfering with the work of caregivers. The entire setup was reviewed by the IT department at the CHUSJ and approved for use in the PICU unit.

2.3.7 Ethics and legal compliance

This study was observational. The study protocol and the experimental equipment setup was approved by the Research Ethics Board (2016 project number 1242) before being used in the pediatric intensive care unit (PICU).

2.3.8 Performing acquisitions with patients

The equipment set up was brought into the ICU room and the camera placed at the edge of the bed. The chest of the patient was exposed, and any clothing or blankets were removed. The hands and feet were exposed so that temperatures of the extremities can be extracted. During the acquisition of 3D point clouds and RGB videos, in order to avoid disturbance in the field of view obscuring the view of the patient, parents and caregivers were asked to vacate the area for the duration of the acquisition. The required images and videos were recorded, and the entire procedure took about 10 minutes.

2.3.9 Extraction of temperatures from IR images

To determine the core temperature (estimated as temperature of the inner canthus) and the temperature of the extremities (namely either the toes or fingers), the pixel values of the corresponding regions were extracted manually, using a software developed in MATLAB. In some images, the eyes of the patient were not visible or obstructed, in this case the thorax was considered for core temperature. Another point from either the toes or fingers was taken, whichever was more clearly visible. Next the difference between these two values was calculated as the gradient. Figure 2.2 shows the points at which the temperatures were extracted for a sample patient.

Figure 2.2: An IR image taken of a patient as part of the study. Two points marked with a small cross have been selected in the image, one on the inner canthus and one on the hand of the patient to extract temperatures of corresponding locations.

2.3.10 Use of RGBD data to identify obstructions on patient body

Each acquisition per patient comprised of a few IR images and an RGB video. IR images only gave us a thermal heat map of the scene, while RGB images gave us the ability to recognize and identify objects, which can be of use when identifying the exact position of the patient's body, and the presence of any medical equipment that may cause obstructions in temperature extraction. If the temperature extraction procedure is performed while only referencing the IR images, because the artefacts are not visible, the temperature points selected may not be accurate.

2.3.11 Analysis of temperature along the line joining the core to the extremities

A useful insight into the thermal heat map of the patient would be to explore how the temperature varies along a line that joins the core (e.g., the inner canthus) to the end of the limbs, say to the fingertips. This would give us a look into how the body temperature changes as we go from the core of the body towards the extremities. These temperature changes can reflect blood flow distribution and gives clinical information on the patient's hemodynamic status.

The analysis was carried out in MATLAB. A line was manually drawn over the IR image to connect the core to the end of either the hand or the feet (whichever was more visible in the image). A sample of points was extracted from the line, and the corresponding pixel values were converted to temperature. These values were then plotted on a graph to give a visual representation of how the temperature varies along the body.

2.3.12 Clinical data recorded for analysis

The core temperature taken by nurses at the time that is closest to the time of acquisition was recorded. This temperature was either a rectal temperature or an axillary temperature. The axillary temperature taken by the nurse is incremented by 0.5 °C when recorded in the electronic medical records (EMR), to make it equivalent to the rectal core temperature measurement (Singh et al., 2000).

The patients were labeled by two physicians according to their clinical state at the time of the acquisition, using data from their EMR. The clinical states analyzed were the presence of any clinical sign of decrease or increase in cardiac output (diagnosis of shock, tachycardia, vasoconstrictor/vasodilator drugs infused, hypotension, diagnosis of cardiac failure, cardiac surgery). The PICU rooms have a constant ambient temperature of 21 – 22 °C.

2.3.13 Statistical analysis

Data were presented as median and interquartile ranges. Spearman correlation studies were performed using the gradients and ratios based on clinical states, using R software (*R Project for Statistical Computing* , 2021).

2.4 Results

In total, 42 patients were included. Thirty-six patients out of 42 patients had clear and usable IR images. Six of the patients had to be excluded due to distortions in the images (n=3), incorrect temperature calibration (n=1), or because their limbs were not visible (n=2).
Their median age was 8 months old, and the median weight was 7.4 Kg. Of the 36 subjects, 16 were female. The detailed description of the patient sample is shown in Table 2-1.

The reason for admission for these patients were diverse, with 12 admitted for respiratory distress, 10 after a cardiac surgery, while the remaining varied from cardiac failure, arrythmia, pulmonary hypertension, and neurosurgery, among others. Most of them had an underlying chronic disease such as respiratory failure, cardiogenic shock and kidney failure.

Of the 36 patients, 10 were on continuous perfusion of vasoactive drugs. Eighteen of the 36 patients were on respiratory support, and the types of support are described in Table 2.1.

Table 2.1 Table showing the physiological and clinical markers of the subject sample. The subject sample was quite diverse, with varying reasons for admission and signs of distress

		N=36
Age (median month)[interquartile range]		8 [1-64.5]
Weight (median Kgs)[interquartile range]		7,4 [4.5-24.6]
Female sex		16 (44%)
Reason for admission		
	Respiratory distress	12 (33.34%)
	Post-cardiac surgery	10 (27.77%)
	Other	14 (38.89%)
Medical history		
	Chronic underlying diseases	33 (91.67%)
	None	3 (8.33%)
Shock state during recording (Cardiogenic shock treated with milrinone)		2 (6%)
Temperature (median C) [interquartile range]		36,8 [36.3-37]
	Site	
	axilary	34 (94%)
	central	2 (6%)
Hemodynamic support (HS)		10 (28%)
	Type of HS	
	Vasopressors	3/10 (30%)
	Vasodilators	7/10 (70%)
Respiratory support (RS)		18 (50%)
	Type of RS	
	Ventilatory support with endotracheal tube	6/18 (33.34%)
	Ventilatory support with facial or nasal mask	10/18 (55.55%)
	Other ventilatory support	2/18 (11.11%)

2.4.1 IR temperature accuracy and temperature gradient analysis

The median central temperature extracted from the IR images of the subjects was 33.88°C [32.74-34.19 °C], and the median temperature of the extremities was 30.21°C [28.89

-33.13 °C]. There was a good correlation between the central temperature extracted via thermography and the clinical axillary temperature, with a Spearman's correlation factor of 0.40 (p-value of 0.017). There was also a very good correlation between the central and extremities temperature extracted via thermography with a Spearman's correlation factor of 0.66 (p-value = 1.2 e-05). This shows that there is consistency between temperatures extracted from different parts of the body for the same patient (the scatter plots for both analyses are included in the Supplementary Materials section).

The gradient between the central and extremities temperature of the patients was calculated by taking the difference between the two temperature values. The median gradient for the subject sample was 3.19 °C [1.06-4.64] and the maximum gradient was 5.96 °C.

Figure 2.3 depicts the distribution of this gradient for the entire subject sample. As can be seen from the graph, the gradient values were varied, ranging from -1.14 °C to + 5.96 °C.

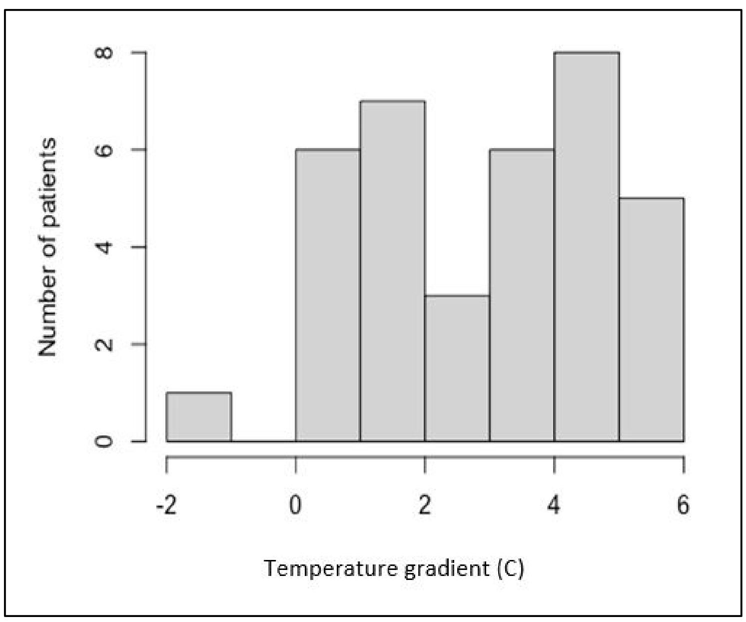


Figure 2.3 Histogram of temperature gradient vs number of subjects. The x axis denotes the temperature gradient in degree C (bins of 2 C), and the y axis is the number of patients that had gradients in that bin

Most of the patients (except one) tended towards positive gradients, meaning that the core was warmer than the extremities, which was the expected result. The median temperature ratio calculated for the subject sample was 0.90 [0.86-0.96], and the maximum ratio was 1.03. Figure 2.4 shows the histogram distribution of the ratios for the entire sample. The ratio is calculated by dividing the temperature of the extremities by the temperature of the core, both extracted from the IR image of the patient. The ratios ranged from 0.8 to 1, with only one patient displaying a ratio > 1. The same patient demonstrated a negative gradient, meaning that the subject's extremities were warmer than the core. The patient's temperature gradient was 1.14 °C and the temperature ratio was 1.03. This subject was receiving milrinone, a vasodilator drug. The gradient for the patients with vasodilators (n=7) was 3.14±2.49 and for the patients with vasoconstrictors (n=3) 3.37±1.94. When data acquisition was done, hemodynamic stability was almost restored in most patients, using vasoactive drugs. This may explain why the gradients were not different between the groups.

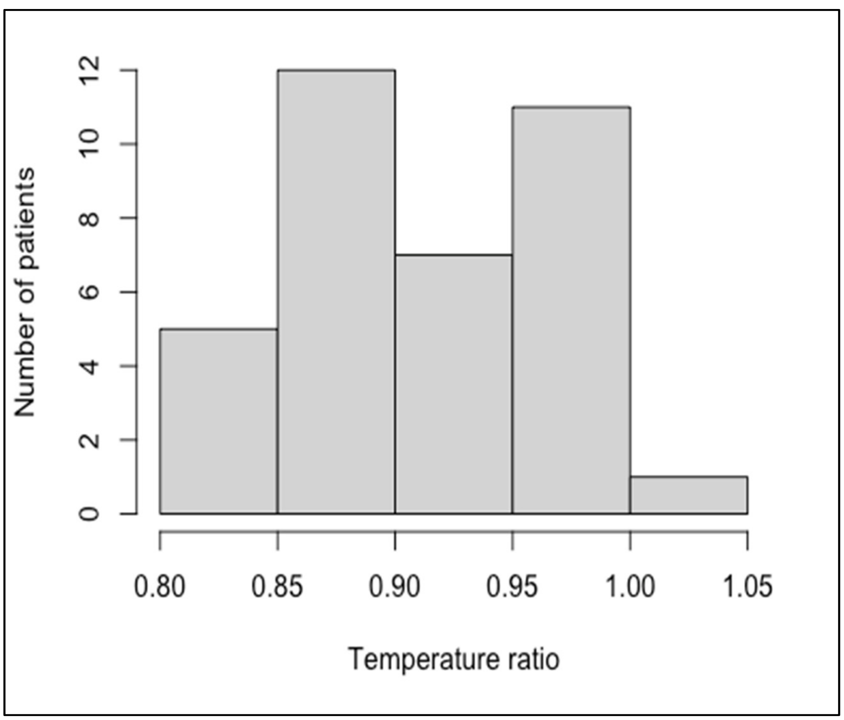


Figure 2.4 Histogram of temperature ratio vs number of subjects. The x axis is the temperature ratio binned on 0.05, and the y axis is the number of patients with ratios falling in that bin

2.4.2 Temperature gradient correlation with clinical status

There was no significant correlation between neither thermal gradient and clinical status nor temperature ratio and clinical status. The results for the correlation analysis are shown in Table 2.2. Based on p-values, there are no subgroups that show significant correlation.

Table 2.2 Results of the correlation analysis done on the basis of temperature gradient. The first and second columns of mean and SD values correspond to the respective subject groups

	Mean 1	SD 1	Mean 2	SD 2	p value
Admitted Post cardiac surgery vs No	2.73	2.08	2.96	1.91	0.76
Admitted For cardiac failure vs No	2.68	2.76	2.92	1.86	1
History of Congenital heart disease vs No	2.54	2.09	3.15	1.81	0.37
Shock vs No	3.54	2.33	2.85	1.94	0.57
Hypotension vs No	3.92	1.98	2.80	1.93	0.26
Tachycardia vs No	3.55	2.44	2.76	1.83	0.33
Hemodynamic support vs No	3.05	2.01	2.83	1.94	0.64
Vasodilator support (milrinone) vs No	3.44	2.65	2.81	1.83	0.35

2.4.3 Temperature analysis along the line joining the core to the extremities

Figure 2.5 depicts the line that was drawn on the IR image of a patient, from the eyes down through the thorax to the toes. This line was used to create the resulting graph depicted in Figure 2.6. The temperatures of each pixel along the line were extracted and their values plotted. The graph goes from a high peak that represents the temperature of the eyes, as the line moves over the cheek, which is visibly cooler in the IR image, we can see a drop in the graph line. As the line moves over the neck the temperature increases again, but as the line moves over the chest artefact, which was a bandage, there is a sharp downward drop in the graph. Similarly, there is a large trough that corresponds to the temperature as the line moves over the diaper region of the patient.

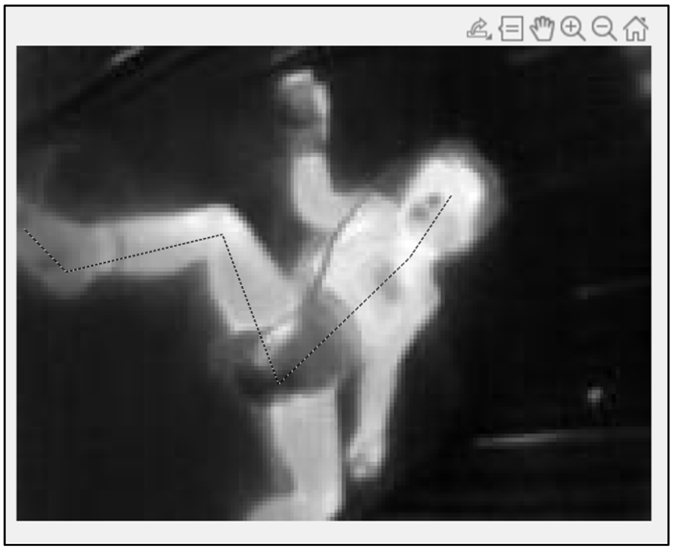


Figure 2.5 IR image taken of another patient as part of the study. A line is drawn starting from the inner canthus region of the eye, down to the chest and along the leg to the toes

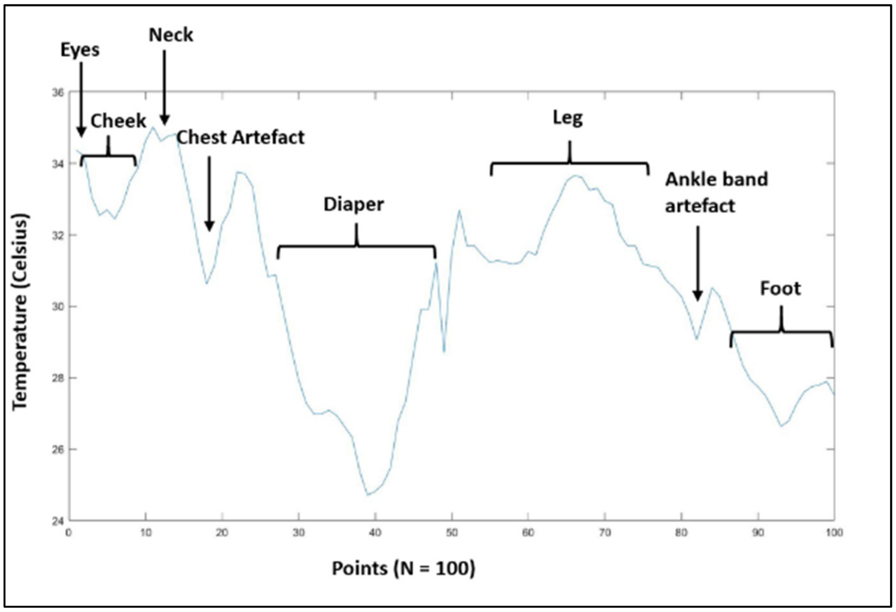


Figure 2.6 Resulting graph for the line drawn in the above image. The temperature goes from a peak at the eye region and gradually decreases while having several drops and highs as it goes over low temperature regions caused by artefacts on the patient's body

2.5 Discussion

Despite the absence of significant results from the hemodynamic assessment using IRT in our cohort study, we believe that IRT can be a useful tool in evaluating the thermal profile of critically ill patients, especially to monitor the impact of the vasoactive support on this gradient with time (not assessed due to study design). Our results show promise in terms of IRT being a useful tool in evaluating the thermal profile of critically ill patients. The graph drawn using the temperatures extracted along the line in Figure 2.5 and 2.6 demonstrates an opportunity to evaluate the continuous gradient present throughout the limbs. For example, the section of the graph line that corresponds to the leg can be used to calculate the slope of the temperature gradient from the thorax to the toes. This slope can then be correlated with clinical vital sign markers such as oxygen extraction ratio to study if it is correlated with this marker of cardiac output. A threshold can be used to eliminate temperature values outside a certain range, and this could be used to automatically detect artefacts present on the patient's body.

The statistical correlation analysis done demonstrates potential to quantify the gradient that exists between different parts of the body of critically ill children. The temperatures recorded from the IR images are in line with the literature on the temperature of skin in children, but previous work focused mostly on healthy subjects (Kolosovas-Machuca et al., 2011). The temperatures recorded from the IR images are in line with the literature on the temperature of human skin. Although the patients recruited were from a diverse clinical background, they were all stabilized at the time of acquisition. In addition, the sample was unbalanced, for example only 10 patients were on hemodynamic support, while the rest 26 were not. In our sample, the one patient with higher temperature in the extremities was a patient under vasodilating medication. However, we could not draw any conclusion due to our small sample size and the absence of evolution of temperatures over time for a given patient.

One of the main limitations experienced was the low resolution of the IR sensor. For the checkerboard to be clearly visible in the IR image, it must be placed close to the sensor, roughly 1 meter away from the camera. If the checkerboard is placed far away, it becomes difficult for the checkerboard detection algorithm to detect the squares. Registering the image views of cameras that have an extreme difference in resolution is challenging. This limitation will have to be addressed in the future, either by using a different marker or upgrading the IR sensor to one with a higher resolution.

2.6 Conclusion

In conclusion, the study explored several pathways for which IRT could be useful for temperature screening of critically ill children. More work needs to be done to improve the registration algorithm and perform analyses on a more diverse subject sample with patients demonstrating vital distress.

2.7 Acknowledgement

We would like to acknowledge the support of the Fonds de Recherche en Santé du Québec, Quebec Ministry of Health and CHU Ste-Justine, along with the Natural Sciences and Engineering Research Council of Canada for supporting this work. There are no conflicts of interest to disclose.

2.8 Supplementary materials

The below supplementary material includes some figures that were not included in the main body of the article. The following graphs depict some of the correlation analyses performed as part of this work. The first graph (Figure 2.7) depicts the scatter plot of the clinically measured axillary temperature versus the core temperature extracted via thermography. The p value is 0.017 and the Spearman's correlation factor of 0.40.

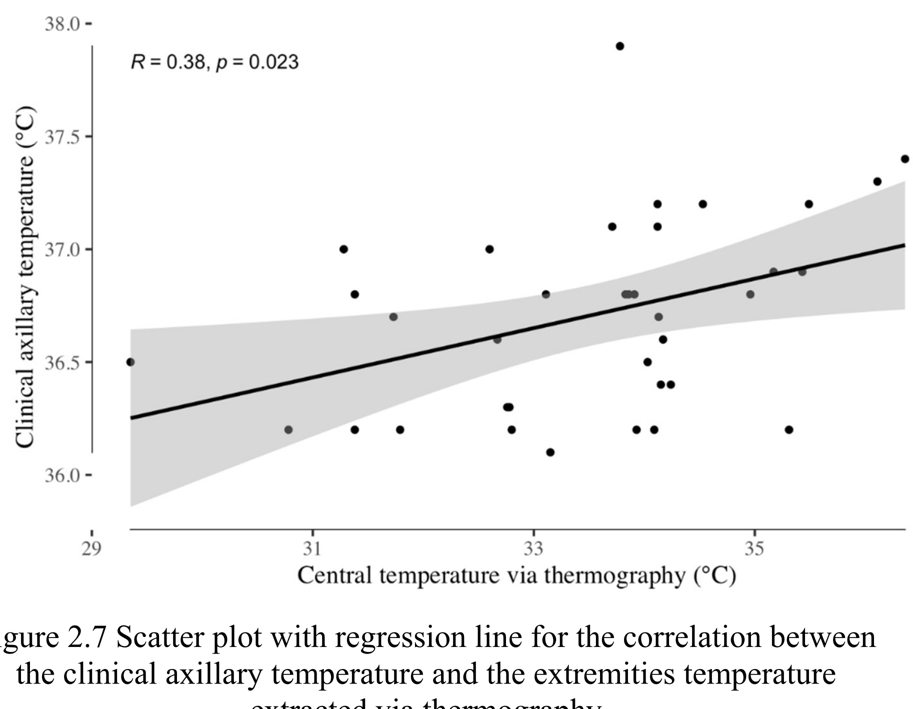


Figure 2.7 Scatter plot with regression line for the correlation between the clinical axillary temperature and the extremities temperature extracted via thermography

The next graph (Figure 2.8) depicts the correlation between the temperature extracted from the extremities of the patient, versus the temperature extracted from their core, via thermography. There is a good strong correlation between the two values, which shows that the method shows consistency within the same patient (Spearman's correlation coefficient of 0.66, and a p value of 1.2 e-05).

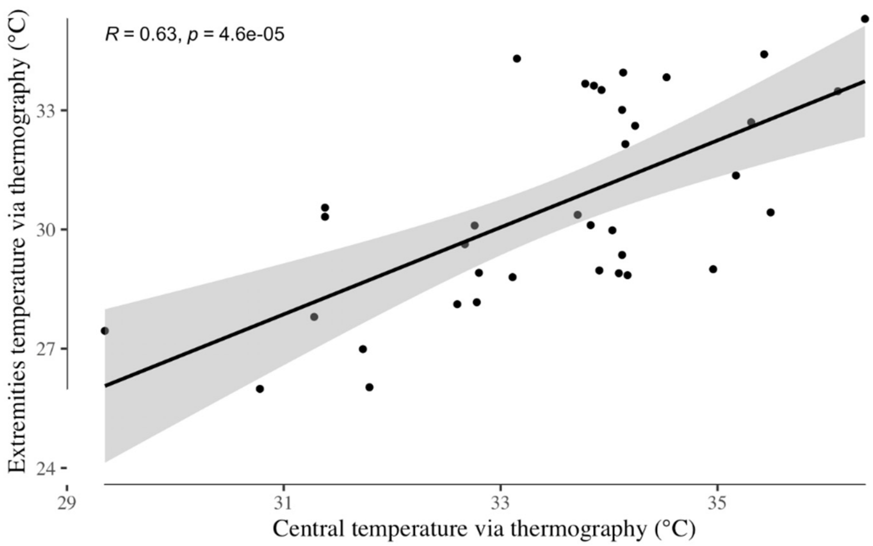


Figure 2.8 Scatter plot with regression line for the correlation between the clinical axillary temperature and the core temperature extracted via thermography

CONCLUSION

The main objectives of this study were as follows:

1. Evaluate IR thermography as a potential tool for non-contact temperature screening in the pediatric intensive care unit;
2. Explore if temperatures extracted via thermography can give us an insight into the temperature distribution that exists between the core and the limbs of critically ill patients;
3. Analyze the correlation between temperature gradients between the core and extremities versus the clinical background of the patient;
4. Set up an image registration algorithm to combine the image feeds of the Kinect Azure and the Lepton Infrared sensor;
5. Perform continuous analysis by studying how the temperature varies along a line joining the core to the limbs, and using the resulting graphs to detect artefacts on the patient's body.

Infrared thermography shows a lot of promise and future in the PICU and some of its potential was explored in this study. The results of the core and extremities temperature estimation show promise for IRT as a potential tool to approximate the body temperature of patients in a critical care environment. The use of IR sensors in the ICU environment can serve as a method of continuous passive monitoring of the body temperature that does not interfere with the work of the clinicians.

The linear temperature analysis performed from the core to the ends of the limbs can be refined in the future and developed into a standardized method of gradient measurement along the limbs. The gradient present between the core and the limbs provides a lot of useful insight into the state of blood flow in the body and can be used as a marker to detect fever, sepsis, and shock in the future. An algorithm can be developed that will combine the skeleton tracking functionalities of the Kinect Azure with the IR images and automate the procedure of extracting the temperatures along the limbs of the patient. This will require a more refined image registration procedure between the two devices.

Even though the patients recruited were admitted to the critical care unit, they were all clinically stable at the time of the image acquisitions. They had varied medical backgrounds but at the time of acquisition they did not actively display any signs of hemodynamic distress, and none of the patients had fever or septic shock at the time the IR photos were taken. Hence it was not possible to discern how the IR temperature profiles would differ if the patients had compromised blood flow in their limbs. This study must be expanded in the future by performing the IR image acquisitions with patients that are presently experiencing fever or other forms of hemodynamic distress, to explore whether IRT can be a useful tool to diagnose these conditions.

Through the course of this project there were several obstacles and constraints that had to be mitigated in order to continue the smooth progression of the work. A significant constraint that limited our work in the initial stages of the project was the tradeoff between the cost of IR equipment versus the resolution of the sensors. The current state of the art with IR imaging has come a long way, but high-resolution IR cameras (greater than 1 megapixel) still remain out of budget for several researchers. Because the end goal for this work was to equip all of the PICU beds in the hospital with a camera, the IR sensors would have to be purchased in bulk. Hence, we required a more affordable alternative, but the market currently does not have high resolution IR sensors at an affordable rate. So, the sensors we chose to settle for were on the lower range of pixel resolution. This limitation to a lower resolution camera meant that there was a large difference in resolution between the IR sensor and the Kinect Azure.

Due to the low resolution of the IR sensor, the calibration marker had to be placed close to the camera setup during the calibration procedure, for it to be visible in the resulting image. In the real clinical setting, the camera setup can be anywhere between 1 to 2 meters away from the patient, depending on the size of the bed. This means that the registration parameters calculated during the calibration procedure are not accurate to superimpose the resulting patient images, as they are at varying distances.

The IR sensor chosen for this study was the FLIR Lepton 3.5 LWIR sensor that needs to be embedded in a compatible breakout board, such as the FLIR BreakoutBoard V2 used in this project. The breakout board contains a socket in which the sensor module is embedded. Even though the sensor is meant to click into place, throughout the course of performing acquisitions at the hospital sometimes the sensor would come loose from the board, causing errors, and rendering the software unable to generate images. The sensor would have to be inserted back into place. In addition, there were times when the IR image captured was simply a grey blank image. Typically, this occurs if there is an issue with the pins of the sensor and the connection with the pins on the breakout board. The problem can be fixed by "power cycling" the sensor, i.e., disconnecting it from the board and leaving it for about 10-15 seconds for the residual power in the pins to dissipate before inserting it back into the board. This resets the sensor and allows for a clear image to be generated.

The image registration procedure involves taking images of a calibration marker with both cameras, and then using these images to superimpose the two image feeds together. For the Kinect RGBD camera a standard marker make of ink on paper can be used, because it will show up clearly in the RGB image. IR cameras do not work on the same principle as standard RGB cameras, and hence require a special setup. Initially the images of the marker were taken by placing the calibration marker in direct sunlight. The black squares of ink absorb more heat and get warmer when placed in the sun and hence show up brighter on the IR images. This method is limited to the positioning and intensity of sunlight available at any given point in time, so a better method needed to be constructed. An IR lamp was directed towards a calibration marker made from aluminum. The IR rays from the lamp reflect off the marker and are captured by the sensor, generating a clear image of the marker. Because aluminum is a poor radiator of IR heat (due to low emissivity), the aluminum squares show up as dark in the image, while the rest of the marker is white. This creates a clear image of the marker allowing it to be detected easily by the detection algorithm.

The sensors used for this project were purchased online from DigiKey.ca. If there was an issue with a sensor and we needed a replacement, sometimes the specific sensor would be out of stock. A lower version of the same range of sensors (FLIR Lepton 2.5) would have to be purchased, and the existing hardware and software adapted to be compatible with the new sensor. The Lepton 2.5 has a pin setup that is different from the Lepton 3 and 3.5. When using the Lepton 2.5, the wiring of the setup had to be modified, and the software code had to be adjusted to interface with the correct pins.

The Lepton sensor used for taking IR images in this study was embedded in a Breakout board that was connected to the Raspberry Pi with jumper wires. The Raspberry Pi was initially connected to the PC using an ethernet cable. This created a network between the PC and the Pi, which allowed us to connect to the Pi Desktop via the network, and work with the IR acquisition software. Unfortunately, this setup was prone to errors, and the connection procedure didn't always succeed. In addition, the presence of an extra wire between the two devices complicated the setup. To mitigate these issues, a Wi-Fi router was introduced to the setup, and the Raspberry Pi was configured to connect to the router automatically on startup. This way the Wi-Fi connection between the two devices makes the interface smoother, and reduces the wiring required.

In conclusion, the study explored some of IRT's potential in the field of critical care. It expands some of the existing knowledge base on the use of IRT in pediatrics but still has some room for improvement, especially in the area of image registration and camera calibration. With a more diverse subject sample, it could be possible to explore how hemodynamic stress and abnormal blood flow manifest in IR images.

RECOMMENDATIONS

Some of the main recommendations for the future of this study are as follows:

1. Attempt to recruit patients that have a history of either fever, septic shock or other forms of hemodynamic stress and are also manifesting symptoms of compromised blood flow during the time of acquisition. Including patients that are clinically unstable will give us more of an insight into how the temperature gradient changes with different clinical states;
2. Use IR camera with higher image resolution, in order to improve quality of IR image. The higher resolution image will allow us to calibrate the camera by taking images of the calibration marker from further away, to better mimic the actual distance between the camera setup and the patients during the acquisitions. This will improve the registration results of the setup, allowing us to superimpose the Azure and the IR camera images;
3. Once the registration algorithm is improved and the Kinect and IR feeds are combined, it will allow us to program a system that uses the skeleton tracking capabilities of the Azure to detect the limbs and core of the patient, which in turn when superimposed over the IR images will enable us to automatically extract the temperatures from various parts of the patient's body. This will eliminate the manual temperature extraction procedure, thus creating a streamlined system with less human intervention and error;
4. Migrate the current setup that exists on a trolley with a PC, to a more portable system that can be embedded in each ICU room. Currently there is work being done to implement the system on a Jetson Xavier portable computer. The idea is to connect the Lepton sensor and the Azure directly to the Jetson and embed the entire setup into a support that holds all the cameras together and points them towards the same scene. The setup will be affixed onto the ceiling above the patient bed and programmed remotely to take both RGB 3D videos and IR images of the patient. This will eliminate the need to have technicians manually bring the setup to the room for every acquisition and take the photos and videos. There are certain security and privacy

constraints that will come into play with the installation of cameras in the unit, and these need to be seriously addressed before this setup is implemented;

5. The temperature graph analysis has a lot of scope, and temperature thresholding can be used to automatically detect an artefact if the temperature drops below a certain value. This way the graphs drawn from lines joining the core to the extremities can be used to analyze various medical equipment on the body of the patient such as bandages, pipes and catheters, and their effect on the IR images can be studied. Once the RGB and IR images are superimposed over each other, these artefacts can be used to exclude these regions from the temperature analyses and automate the overall procedure of temperature extraction. The RGB images and videos can also serve as a form of validation for the presence of artefacts, as they are easily detectable in the color images.

APPENDIX I

ABSTRACT I: HEMODYNAMIC ASSESSMENT BY OPTICAL THERMOGRAPHY IN INFANTS WITH CARDIAC SURGERY

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Abstract presented at the Critical Care Canada Forum, October 2020

Introduction: Assessment of hemodynamic status of critically ill children is a challenging situation that usually requires the combination of several biomarkers including clinical signs and blood tests(Wernovsky et al., 1995). Those signs include the assessment of peripheral temperature.

In postoperative cardiac surgery in children, a high thermal gradient between core and peripheral temperature was correlated with increased systemic vascular resistance and decreased cardiac output(Murdoch et al., 1993; Schey et al., 2010).

Objectives: The aim of the study is to assess the efficacy of thermographic profiles to detect a cardiogenic shock in post-cardiac surgery infants.

Methods: Children admitted in a single pediatric intensive care unit after a cardiac surgery were included, after obtaining parental consent. Exclusion criteria included extracorporeal membrane oxygenation support, continuous hemofiltration or peritoneal dialysis supports, any extensive skin disease, and children with an external active heating or cooling system. Infrared images of the patients were taken using the FLIR OnePro camera and the core temperatures (extracted from the internal epicanthus) and toes temperatures were extracted. The temperature gradient between core and extremities (ΔCET) was calculated and compared to the oxygen extraction coefficient (O2ER, difference between arterial and mixed venous oxygen saturations) measured at the same time. Data are expressed as mean ± standard deviation. The samples were divided into 4 groups based on the values of ΔCET (< or >5°C) and O2ER (< or >50%), and the McNemar test was used to compare classifications.

Results: 22 patients (from age 10 years to 0.3 months old) were included in the study. The ΔCET was 3.11° C± 1.84 and the O2ER was 39.7% ± 19.9. As illustrated in the Figure, no clear correlation was observed between ΔCET and O2ER. The McNemar significance probability between the two variables was 0.51.

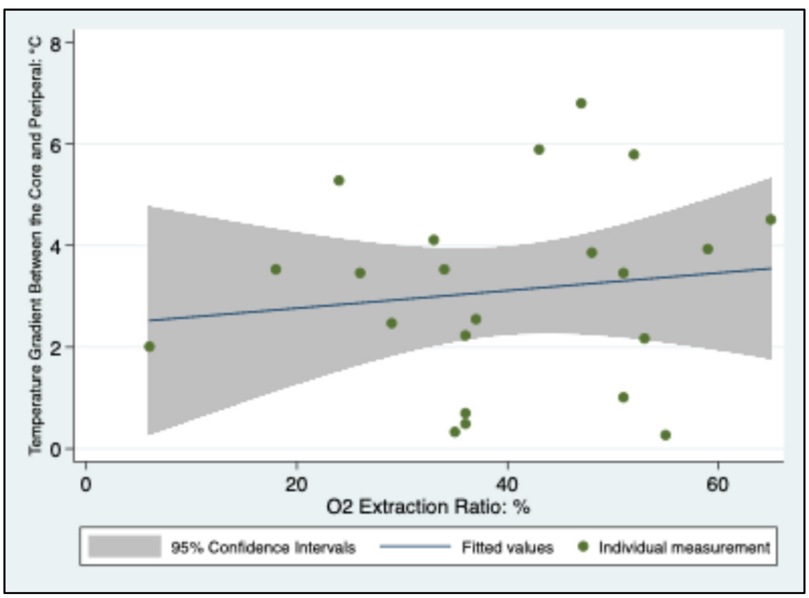

Figure-A 0-1 Scatter plot for correlation between temperature gradient and oxygen extraction ratio

Discussion and conclusion: The absence of correlation between the two variables could be due to many factors, one of which is a small dataset. The influence of factors modifying the peripheral circulation should be analysed, such as vasoactive amines (Milrinone, epinephrine) which are frequently used after cardiac surgery. In conclusion, thermography could be an additional tool in multimodal monitoring after cardiac surgery, and more patients will be included in the study to improve the reliability of the results, and to explore the impact of contributing factors, like age, central temperature, and vasoactive treatments.

APPENDIX II

ABSTRACT II: COMPARISON OF INNER EPICANTHUS AND FOREHEAD TEMPERATURE MEASUREMENTS VIA IR THERMOGRAPHY

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Introduction: Human body temperature is a very crucial biomarker that can denote various physiological changes including inflammation and cardiac failure. Infra-Red thermography (IRT) has been used for fever screening and has great potential for temperature measurement, but currently its role in clinical practice is not clear. Studies have shown that the inner canthus of the eye is the most reliable temperature marker in the adult face. There is currently not enough clinical data to demonstrate the effectiveness of IRT when used to screen infants. The aim of this study was to examine if the canthus temperature (CaT) and forehead temperature (FHT) correlate with the body core temperature (BCT) in critically ill children.

Methods: Children from 0 to 18 years old admitted in a single pediatric intensive care unit (PICU) that had undergone cardiac surgery were included in the study, after obtaining parental consent. Exclusion criteria included extracorporeal membrane oxygenation support,

continuous hemofiltration or peritoneal dialysis supports, any extensive skin disease, and children with an external active heating or cooling system. Infrared images of the patients were taken using the FLIR OnePro camera and the temperatures from the internal epicanthus and forehead were extracted every few hours. Simultaneously, the rectal, and in some cases axillary temperatures (augmented by + 0.5 C) were extracted to serve as a reference. We examined if the BCT correlated with the temperatures simultaneously measured at forehead and canthus by applying Spearman's rank correlation coefficients.

Results: 67 independent measurements in 22 children were included. Their age ranged from 0.3 months to 10 years old. The data extracted demonstrated a strong correlation between the canthus and forehead temperatures (Correlation coefficient= 0.85, $p<0.001$); while we could only find a correlation between CaT and BCT and FHT and BCT (Correlation coefficient: -0.02 and -0.11 respectively).

Conclusions: From the sample, there are no conclusive findings about the relation between the core and facial skin surface temperatures recorded. The relationship will need to be further investigated by incorporating more samples, examining any potential confounding variables, and working to improve the efficiency of thermographic acquisition.

APPENDIX III

ABSTRACT III: HEMODYNAMIC ASSESSMENT BY OPTICAL THERMOGRAPHY IN INFANTS WITH CARDIAC SURGERY

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Abstract published in the *Journal of Critical Care Medicine*, January 2021, Volume 49 - Issue 1 - p 197 doi: 10.1097/01.ccm.0000727548.27303.72

Introduction: Assessment of hemodynamic status of critically ill children is a challenging situation that usually requires the combination of several biomarkers including clinical signs and blood tests. Those signs include the assessment of peripheral temperature. In postoperative cardiac surgery in children, a high thermal gradient between core and peripheral temperature was correlated with increased systemic vascular resistance and decreased cardiac output. The aim of the study is to assess the efficacy of thermographic profiles to detect a cardiogenic shock in post-cardiac surgery infants.

Methods: Children admitted in a single pediatric intensive care unit after a cardiac surgery were included, after obtaining parental consent. Exclusion criteria included extracorporeal membrane oxygenation support, continuous hemofiltration or peritoneal dialysis supports, any extensive skin disease, and children with an external active heating or cooling system. Infrared images of the patients were taken using the FLIR OnePro camera and the core temperatures (extracted from the internal epicanthus) and toes temperatures were extracted. The temperature gradient between core and extremities (ΔCET) was calculated and compared to the oxygen extraction coefficient (O2ER, difference between arterial and mixed venous oxygen saturation) measured at the same time. Data are expressed as mean ± standard

deviation. The samples were divided into 4 groups based on values of ΔCET (< or >5°C) and O2ER (< or > 50%), and the McNemar test was used to compare classifications.

Results: 22 patients (from age 10 years to 0.3 months old) were included in the study. The ΔCET was 3.11° C $\pm$ 1.84 and the O2ER was 39.7% $\pm$ 19.9. No clear correlation was observed between ΔCET and O2ER. The McNemar significance probability between the two variables was 0.51.

Conclusions: The absence of correlation between the two variables could be due to the small dataset size. The influence of factors modifying the peripheral circulation should be analysed, such as vasoactive amines which are frequently used after cardiac surgery. In conclusion, thermography could be an additional tool in multimodal monitoring after cardiac surgery, and more patients will be included in the study to improve the reliability of the results.

APPENDIX IV

ABSTRACT IV: HEMODYNAMIC ASSESSMENT BY INFRARED THERMOGRAPHY IN CHILDREN WITH CARDIAC SURGERY

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Abstract presented at the Congres De Reanimation De La Societe De Reanimation De Langue Francaise 2021

Rational

The postoperative period of cardiac surgery is a crucial moment during which low cardiac output can occur. The assessment of hemodynamic status of critically ill children is challenging and the clinician's estimate of cardiac output is often unreliable. Extremity heat is often used to evaluate peripheral perfusion but remains a very subjective sign.

A high thermal gradient between core and peripheral temperature has been correlated with increased systemic vascular resistance and decreased cardiac output, but the results are controversial. The aim of this study is to assess the relationship between thermal gradient, obtained by thermography pictures, and oxygen extraction levels in children in post-operative cardiac surgery.

Patients and Methods / Materials and Methods

Children admitted in a single pediatric intensive care unit after a cardiac surgery were included, after obtaining parental consent. Photos of patients with external cooling system, extensive skin disease and extracorporeal support were excluded as this could change the thermal gradient. Infrared images of the patients were taken using the FLIR OnePro camera within 24 hours after surgery. The core temperatures (extracted from the internal epicanthus) and toes temperatures were extracted. Temperature gradient between core and extremities (thermal gradient) was calculated and compared to the simultaneous oxygen extraction ratio (O_2ER: the ratio between arterial and mixed venous oxygen saturations). The correlation was established by the Spearman correlation coefficient.

Results

29 patients of 5 (0-15) months-old were included in the study. One to three thermal images per patient were analyzed for a total of 66 photos. Our patients had cardiopathies that are frequently described in pediatrics. The thermal gradient median was 3,34 °C (1,6-4,3). The O_2ER median was 35,5% (39-43). A low correlation was observed between thermal gradient and O_2ER. The Spearman's rho was 0,24 p=0,049.

Discussion

The weak correlation between the two variables could be due to many factors, one of which is a small dataset. The frequent use of vasoactive amines (Epinephrin, Milrinone) in post-operative cardiac surgery can modify the peripheral circulation and influence on the thermal gradient. The central temperature should also influence the thermal gradient.

This weak correlation can also be due to the infra-red technology itself like the FLIR one camera lack of performance or other technical aspects.

Conclusion

Thermography is potentially an additional tool in multimodal monitoring after cardiac surgery. A more significant correlation would probably observe with a larger dataset, after taking confounding factors into account and with a more reliable technique of thermal image acquisition.

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