ORIGINAL ARTICLE

Infrared Thermal Imaging (Thermography) of the Abdomen in Extremely Low Birthweight Infants

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Abstract

Introduction Infrared thermal imaging (thermography) is a non-invasive method to measure skin temperature. The primary aim of this study was to examine the feasibility of thermography for the assessment of abdominal skin temperature in extremely low birthweight (ELBW) infants, with secondary aims to compare abdominal and thoracic skin temperature, and to explore potential relationships between abdominal skin temperature and necrotizing enterocolitis (NEC).

Methods We prospectively examined clinical, radiographic, and thermal imaging data in 13 ELBW infants (< 1000 gm and < 29 weeks gestation) during the first month of life. Thermal imaging was performed using an infrared camera, with skin temperature measured over abdomen and thorax. Abdominal skin temperature was compared to thoracic skin temperature, and these findings further examined in infants with radiographic evidence of NEC as well as those without NEC.

Results We found that thermal imaging in ELBW infants is feasible and can result in accurate measurements of skin temperature over anatomic regions. Overall, the mean abdominal skin temperature was lower than thoracic skin temperature ($p<0.05$ by paired Student's t-test), although this difference appears due to NEC in some infants. Infants with radiographic evidence of NEC had a lower mean abdominal skin temperature compared to infants without NEC ($p<0.05$ by paired Student's t-test).

Conclusions In this study, we found that infrared thermal imaging is feasible in ELBW infants. Thermography may be helpful for the study of thermoregulation in ELBW infants and may provide new insight into the role of regional perfusion in NEC.

Keywords necrotizing enterocolitis, thermography, infrared imaging, thermoregulation

Introduction

Extremely low birth weight (ELBW) infants have abnormal regulation of body temperature (thermoregulation) during the first week of life due to delayed maturation of neurologic control of central and peripheral perfusion.[1-4] Immature control of perfusion is associated with abnormal control of body temperature, and may contribute to adverse outcomes in ELBW infants, including necrotizing enterocolitis (NEC).[3,5-7] Improved understanding of the relationships between skin temperature and perfusion may provide insight into the pathophysiology of NEC and control of regional blood flow in ELBW infants.

Infrared thermal imaging (thermography) is a non-invasive technique which allows the temperature to be measured accurately and continuously over the entire visible body surface. Thermography measures the passive infrared radiation emitted by the target surface and converts

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this radiation into a two-dimensional image relating to the temperature at the target. Thermography imaging has recently been shown to be useful for the assessment of skin temperature in adults in a variety of clinical and research settings, but only one single paper from 30 years ago has examined the early use of technology in ELBW infants.[8-11] In this study, we hypothesized that thermography can be used in ELBW infants to accurately assess regional skin temperature.

The primary aim of this study was to examine the feasibility of infrared thermal imaging for assessment of regional skin temperature in ELBW infants. Our secondary aims were to assess potential differences between abdominal and thoracic skin temperature, and to explore a potential association between abdominal skin temperature and NEC.

Materials and Methods

We performed a prospective non-randomized study of ELBW infants to examine the feasibility of infrared thermal imaging in ELBW infants with secondary aims to identify differences between abdominal and thoracic skin temperature; and to explore potential associations between abdominal skin temperature and NEC.

Participants: All infants admitted to the intensive care nursery at Duke University Medical Center (DUMC) between June 1, 2009, and Dec 31, 2009 were used to select study subjects, who were chosen by convenience sample for trial enrollment. Inclusion criteria included a birth weight < 1000 grams and 23-29 weeks gestational age. Gestational age was assigned by obstetrical dating. Exclusion criteria included any major congenital anomaly, genetic disorder, congenital intestinal anomalies, or congenital heart disease. During the study period, 55 infants met entry criteria, and 15 of these infants were considered for trial enrollment.

Enrollment resulted in an initial cohort of 15 subjects, of which two subjects were excluded, leaving 13 subjects as our final study cohort (9 male, 4 female). The excluded infants include one infant who died of presumed NEC totalis before thermal imaging data could be recorded, and one infant who had an unsuspected intestinal atresia identified at laparotomy.

The study protocol and informed consent form were approved by the Duke University Medical Center Institutional Review Board. The study was explained to parents of eligible infants by a member of the study team and enrollment began after one parent signed the IRB-approved informed consent form. No family who was offered study enrollment declined participation.

Infant environment: Twelve infants of the 13 study infants were housed in a Draeger Caleo® incubator (Dräger Medical, Telford, PA) set on servo-control, with one infant housed in an exposed overhead warmer bed. The incubator controls includes a thermostat to regulate exogenous heat input by feedback based on axillary skin temperature as measured by a skin probe. This set-point was set at 36.7 °C for infants in this study. We recorded the axillary temperature as measured by the temperature probe at the time of thermal imaging studies to confirm accuracy of thermal imaging.

Figure 1. Thermal imaging of ELBW infant in supine position using hand held FLIR® SC640 infrared camera (FLIR, North Ballerica MA). We performed thermal imaging through the top of an incubator that had a custom made cut-out in the lid, covered with plastic wrap to preserve heat but allow transmission for thermal imaging. This technique allowed for imaging in 2-3 minutes without disturbing the normal thermal environment of the child Images were obtained with the camera positioned from a distance of approximately 1 meter, at a 90° angle over the infant.

NEC diagnosis and grading: We defined infants as having NEC based on radiographic findings of suspected or definitive pneumatosis intestinalis, portal venous gas, or pneumoperitoneum. This definition is consistent with a Bell's II or III grade,[12] which are currently used by several recent and ongoing large clinical studies to standardize the diagnosis of NEC.[13]

We did not include clinical variables such as feeding intolerance, bloody stools or abdominal distension for the diagnosis of NEC for this study, due to ambiguity in the medical record regarding the specific times that these clinical events occurred. Our comparison between abdominal skin temperature and NEC was confined to those infants (n=10) who had infrared thermal imaging as well as abdominal radiographs (anterior-posterior and either lateral or left-lateral decubitus views)

Table 1. The Duke Abdominal Assessment Scale (DAAS) for assessment of radiographic findings associated with necrotizing enterocolitis (NEC). DAAS is a standardized 10-point radiographic scale that increases with NEC disease severity.[14,15]

SCORE	FINDING
0	Normal gas pattern
1	Mild diffuse distention
2	Moderate distention or normal with bubbly lucencies that are likely stool
3	Focal moderate distention of bowel loops
4	Separation or focal thickening of bowel loops
5	Featureless or multiple separated bowel loops
6	Possible pneumatosis with other abnormal findings
7	Fixed or persistent dilation of bowel loops
8	Pneumatosis highly probable or definite
9	Portal venous gas
10	Pneumoperitoneum

performed on the same day. In the remaining three infants in the study, the thermal imaging and radiographs were not performed on the same day, and therefore these infants were not included in this portion of the analysis.

Each two-view radiographic series was scored using the Duke Abdominal Assessment Scale (DAAS) scale by one of six attending pediatric radiologists, each of whom have at least 4 years experience using the DAAS system (Table 1).[14,15] None of the radiologists had knowledge of the thermography results prior to the assignment of the DAAS scores. In previously published studies, substantial inter-observer agreement ($\kappa = 0.89$) was found between two radiologists when DAAS scores were assigned independently, and higher DAAS scores are associated with more severe NEC as measured by need for surgical intervention.[14,15] In our current study, DAAS scores of 8-10 (suspected or definitive pneumatosis intestinalis, portal venous gas, or pneumoperitoneum) were collectively used to define infants with radiographic NEC.

Thermal imaging: For thermal imaging, we used a FLIR® SC640 infrared camera (FLIR, North Ballerica, MA). The camera was factory calibrated within 0.2 °C and then checked against a standard blackbody and skin temperature measured with external temperature probes. Each thermography pixel of area could be analyzed separately, with measurement of each area of skin temperature precise to 0.1°C. Accuracy of temperature measurement was randomly checked on a regular basis, and the camera retained its calibration within 0.2 °C against the blackbody and external temperature probes on all occasions.

To minimize changes to the infants' thermal environment during the imaging procedure, thermal imaging was performed through the top of an customized incubator that had a cut-out in the lid, which was covered with plastic wrap to preserve heat yet allow transmission for thermal imaging. Images were obtained with the camera positioned from a distance of approximately one meter, at a 90° angle over the infant (Figure 1). The infant was imaged in a supine position, consistent with standard clinical care. The thermal environment of each subject was not disturbed during imaging. Subjects were followed for 2-10 days (maximum 30 days of life), with thermal imaging performed either daily or every other day (total days of imaging ranged from two to five per infant).

Analysis of skin temperature over regions of interest: Infrared imaging data was downloaded into a laptop computer, and ExaminIR® (FLIR, North Ballerica, MA) software was used to measure the temperature at any single pixel on the picture. ExaminIR® software performs real-time image analysis and provides playback features to analyze image sequences stored on a camera or computer and will convert the passive infrared radiation emitted by the target surface to a two-dimensional image relating to the temperature distribution at the target surface. Skin temperature was measured to the nearest 0.1 °C.

To facilitate skin temperature analysis, we adopted previously published techniques to measure the mean skin temperature over a desired region of interest (ROI) using the ExaminIR® software.[8,10] The software has analysis tools including spot, line, and area measurements of skin temperature. For our analysis, we used a segmentation tool to develop oval regions of interest over the majority of the abdomen or thorax. Within each ROI, the ExaminIR® software calculated the mean skin temperature using every pixel in the ROI, as well as additional metrics including the skin temperature maximum, minimum, and standard deviation.

We compared the mean abdominal skin temperature ($T_{abdomen}$) to the mean thoracic skin temperature ($T_{non\text{-}abdomen}$) within each ROI using paired Student's t-test, with $p < 0.05$ considered significant. The thorax was chosen to confirm the accuracy of

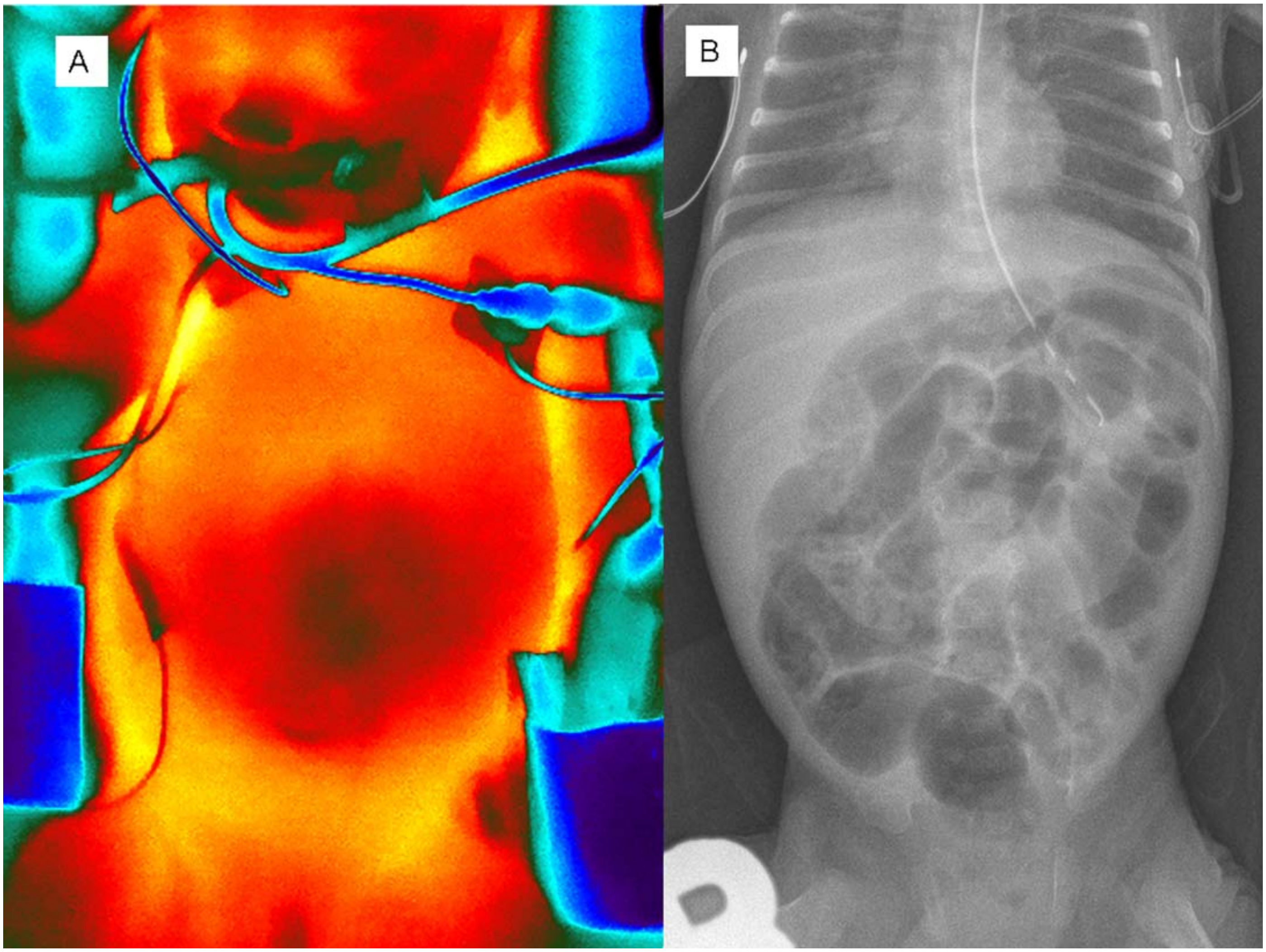

Figure 2. Comparison of concurrent infrared thermal image (A) and abdominal radiograph (B) of a single ELBW infant with NEC. Images were taken on same day, with both images oriented with head superior. Thermography image is taken with FLIR SC640 camera (FLIR, North Ballerica MA) and expressed using color palette. Bright, red-yellow areas (i.e. over thorax) correlate with higher temperature compared to darker, blue areas (i.e. central area of abdomen, periphery around infant) which correlate with cooler temperature. Abdominal radiograph shows fixed featureless bowel segments, pneumatosis intestinalis and portal venous gas, consistent with NEC and graded using the Duke Abdominal Assessment Scale (DAAS) as grade 9.[14,15]

the thermography by comparing thoracic temperature to the readings obtained from the contiguous axillary temperature probe. The abdomen and thorax ROIs were kept consistent in shape and location among infants and were similar in size (abdominal 15,390 ± 1,206 pixels versus thoracic 15,091 ± 1,832 pixels, mean ± SD, p=NS by paired Student's t test). All statistical analyses were performed with use of Microsoft Excel 2003 software (Microsoft, Redmond, WA).

Association between abdominal skin temperature and NEC: In 10 infants, we had sets of thermal images and abdominal radiographs collected on the same day. Data from these 10 infants were used to identify an association between abdominal skin temperature and the radiographic diagnosis of NEC. Infants with a DAAS score 8-10 (suspected or definitive pneumatosis intestinalis, portal venous gas, and/or pneumoperitoneum) were defined as having radiographic NEC. We compared the abdominal temperature of infants without radiographic NEC (n=7) to infants with radiographic NEC (n=3), using unpaired Student t-test, with a p value < 0.05 considered significant.

Results

Participants: 13 ELBW infants satisfied entry criteria and completed the study, with a gestational age range from 25-29 weeks. Birth weight was 861 ± 154 grams (mean ± standard deviation). Five of the 13 infants were enrolled within 24 hours of life, and 8 infants were enrolled between days 7-21 of life.

Ten (10) infants had radiographic and thermal imaging performed on the same day and were included in the analysis of association between abdominal skin temperature and con-

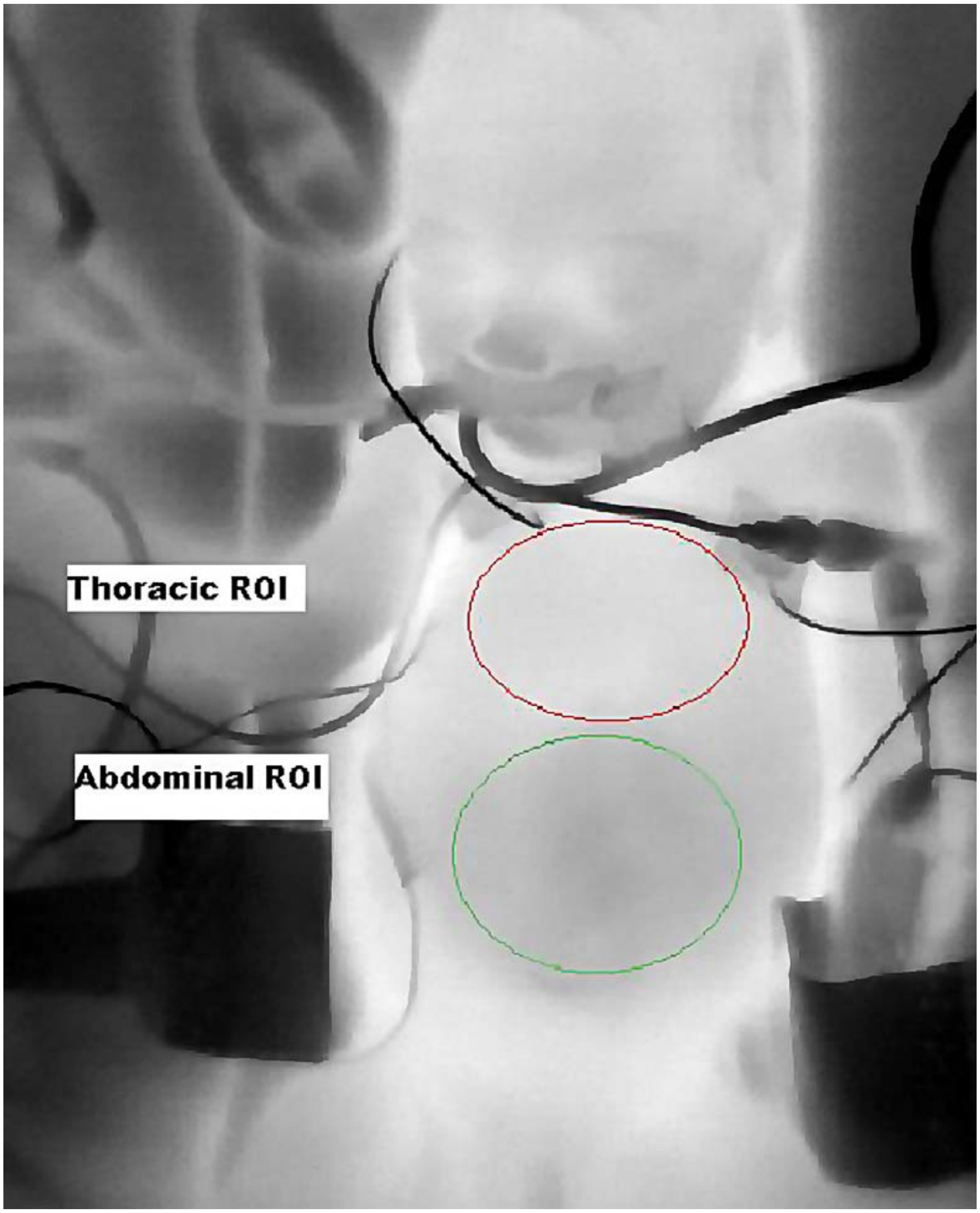

Figure 3. Definition of oval regions of interest (ROI) of a single ELBW infant with NEC. ROIs are easier to see using black and white palate, with ROI over the abdomen seen in green, and thorax in red.

current radiographic findings of NEC. Two infants with radiographic NEC underwent surgical intervention with either exploratory laparotomy and/or peritoneal drain placement.

Thermal imaging: We obtained infrared thermal imaging pictures on several days (range 2-10 days) on the 13 ELBW infants, yielding 47 total images. The infrared camera performed well during this study. During the course of the study, the time to take thermal images decreased from 10 to about 3 minutes. As a result, we were able to conduct bedside imaging during periods of care such that infants were not moved or positioned separately from routine nursing care.

There were no adverse events noted by either the nursing or physician staff during thermal imaging. Other than maintaining infants in a supine position and removal of the diaper, no infant needed to be touched during the imaging. No change in axillary body temperature as a result of positioning the infant was recorded by nursing staff during thermal imaging.

Measurement of skin temperature using thermal imaging: Using the ExaminIR® software, we were able to easily view stored thermal images. We used this software to view the abdomen in either black and white or color palettes. The scale and intensity of thermal images can be controlled by software analysis tools (Figure 2A), and thermal images can be compared to abdominal radiographs (Figure 2B).

We calculated the mean skin temperature over either the abdomen or thorax region of interest using the ExaminIR® software (Figure 3). The thoracic temperature ROI was located adjacent to the axillary temperature probe. The thoracic skin temperature (36.8 ± 0.9 °C) was equivalent to the axillary temperature (36.7 ± 0.9 °C, p=NS by paired t-test).

Difference between abdominal and thoracic skin temperature: For the overall cohort of 13 infants (47 measurements), we found that the abdominal skin temperature (36.4 ± 0.9 °C) was lower than the thoracic skin temperature (36.8 ± 0.9 °C, $p < 0.05$ by paired Student's t-test; Figure 4).

Association between abdominal skin temperature and NEC: We had concurrent thermal images and abdominal radiographs in ten infants, yielding 25 total measurements. In these 10 infants, we found that those with radiographic NEC (n=3) had lower abdominal skin temperature (35.3 ± 0.8 °C, 6 measurements) compared to those without NEC (n=7) (36.6 ± 0.9 °C, 19 measurements) ($p < 0.05$ by unpaired Student's t-test, Figure 5).

In view of this analysis, we subsequently reanalyzed the entire cohort of all 13 patients, and excluded those 6 measurements of infants with radiographic NEC. In the remaining measures without radiographic NEC (41 measurements), the abdominal and thoracic skin temperatures were similar (abdominal 36.6 ± 0.9 °C, thoracic 36.8 ± 0.9 °C, p=NS by paired t-test).

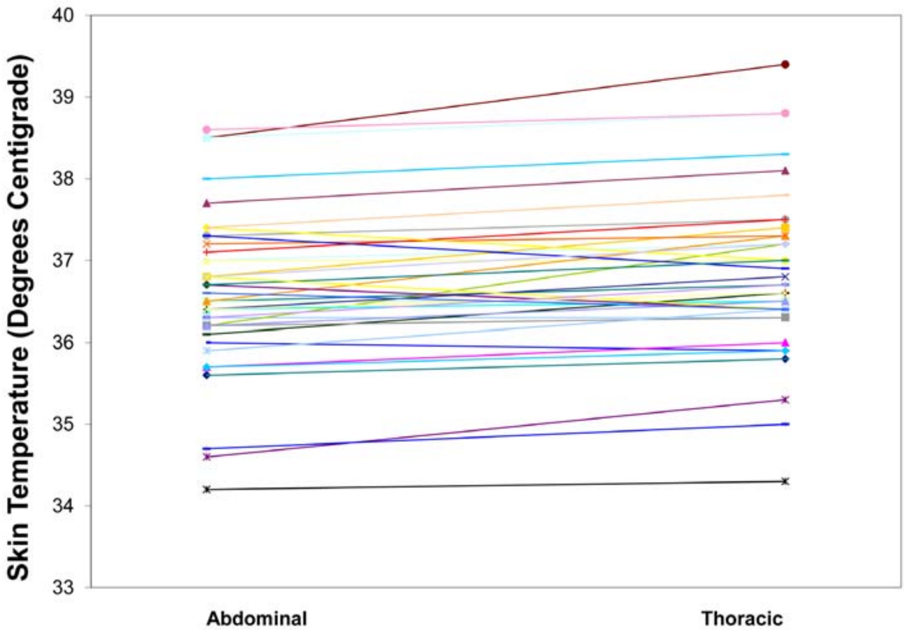

Figure 4. Scatterplot of paired abdominal and thoracic skin temperature measurements in 13 ELBW infants (47 paired measurements) as determined by infrared thermography. The mean abdominal temperature (36.4 ± 0.9 °C) was lower than the mean thoracic temperature (36.8 ± 0.9 °C, $p < 0.05$ by paired Student's t-test).

Discussion

Infrared thermal imaging is a non-invasive technique to measure skin temperature over the visible body simultaneously.[8] Thermography measures the passive infrared radiation emitted by the target surface, and converts this radiation into a two-dimensional image relating to the temperature distribution at the target surface. Infrared imaging has been shown recently to be a useful method to measure body surface temperature in adults in various clinical and research settings.[8-10,16] Given the range of pathology in ELBW infants which may be related to poor perfusion such as NEC and brain injury, use of a non-invasive method to accurately assess regional thermal control may be helpful. Prior to our studies, only one single report from over 30 years ago with early use of this technology had examined thermal imaging in ELBW infants.[11]

The study of perfusion in infants has recently been examined by several other techniques, including Doppler ultrasonography[17-19] and near infrared spectroscopy (NIRS).[20,21] Although these studies have validated a role for Doppler ultrasound and NIRS to identify aspects of perfusion in ELBW infants, these technologies are expensive, require skilled technicians, and mandate prolonged contact with the infants, limiting their role in clinical research studies of ELBW infants.

Thermoregulation in ELBW infants is controlled by complex neurologic mechanisms.[5,7,22] Peripheral temperature correlates with peripheral perfusion,[23] and peripheral vasoconstriction is necessary to maintain intestinal perfusion during periods of stress. Normal peripheral vasoconstriction responses are ineffective in some ELBW infants, allowing the infant's central body temperature to become cold.[2,3,24] These studies suggest that abnormal thermoregulation in ELBW infants may contribute to a variety of disease processes related to poor control of central and peripheral perfusion, including NEC.

Necrotizing enterocolitis (NEC) remains a difficult disease to understand.[13] NEC results from a combination of loss of the intestinal epithelial barrier, dysfunction of the mucosal immune system and poor intestinal perfusion, although it is unclear why only some ELBW infants become affected.[6,25,26] Given the recent studies which suggest that abnormal regulation of perfusion and body temperature occurs in some ELBW infants,[1-4] our interests are in defining processes to accurately examine perfusion abnormalities in ELBW infants and further characterize the role of perfusion defects in NEC. Our current findings suggest that thermography may be a useful adjunct to study these physiologic processes, and may be helpful to define the association between the maturation of perfusion and NEC.

In our current study, we found that infrared thermal imaging is feasible to perform in ELBW infants. Our secondary findings showed infants with radiographic NEC have decreased abdominal skin temperature compared to infants without NEC, which is not surprising given the likely presence of advanced intestinal ischemia by the time NEC is definitively diagnosed. It must be emphasized that the current study was designed to assess the feasibility of thermal imaging, and should be considered similar to a Phase 1 trial to assess safety. Thus, this exploratory study was not powered to definitively address our secondary aims.

Although beyond the scope of this study, it would be of considerable interest whether there are periods of low abdominal skin temperature which precede clinical or radiographic findings of NEC. We found that infants with radiographic NEC have decreased abdominal skin temperature compared to infants without NEC, which is not surprising given the likely advanced intestinal ischemia by the time NEC is definitively diagnosed. It is possible that detection of early changes in abdominal skin temperature may allow for interventions to ameliorate the onset or severity of NEC, such as implementation of bowel rest, antibiotics, etc. Moreover, it is unclear whether any of the known specific risk factors associated with NEC, such as early feedings or perinatal stress, also result in acute changes in abdominal skin temperature. Future studies of thermoregulation in ELBW infants will need to investigate all of these critical issues.

In the course of this study, we learned several critical lessons for the use of thermography in ELBW infants. Most recent studies of thermal imaging in adults have relied on measurement of skin temperature over a specific single area of interest. However, measurements of skin temperature in infants kept within environmental-controlled incubators are affected by external heat input. Incubators work by the recognition of infant hypothermia, increasing ambient heat until the infant's axillary temperature reaches the set-point of the incubator. This heat input represents a complex variable which affects skin temperature analysis. To address this issue, we found that by comparing two areas in each single infant, each infant could serve as their own control and thereby control for external heat input. However, it is likely that further physiologic analysis of regional skin temperature in ELBW infants will require sophisticated quantitative analysis of external heat input.

In keeping with the exploratory nature of this study, we recognize that many questions remain concerning themoregulation in infants and NEC. For example, it is unclear whether decreased abdominal skin temperature is associated with abnormal peripheral vasoconstriction responses, which are traditionally measured by use of continuous monitoring with skin thermistor probes. Similarly, it remains to be shown whether the small differences in regional skin temperature seen in our study in children with NEC have significant physiologic importance. Finally, thermal imaging requires purchase of an infrared camera and software, which would minimize its role in routine clinical care. However, the ease of this technology and safety for use in frail infants should facilitate its role in neonatal research settings.

In conclusion, this study has confirmed the feasibility of thermal imaging for study of skin temperature in ELBW infants. Our secondary findings showed that there is a decrease in abdominal skin temperature compared to thoracic skin temperature in these infants, which appears to be due to the presence of NEC in some infants. Given the ease of the thermography in ELBW infants, further study of the relationship between thermoregulation and disorders of perfusion in ELBW infants may benefit from the use of infrared thermal imaging.

Disclosures

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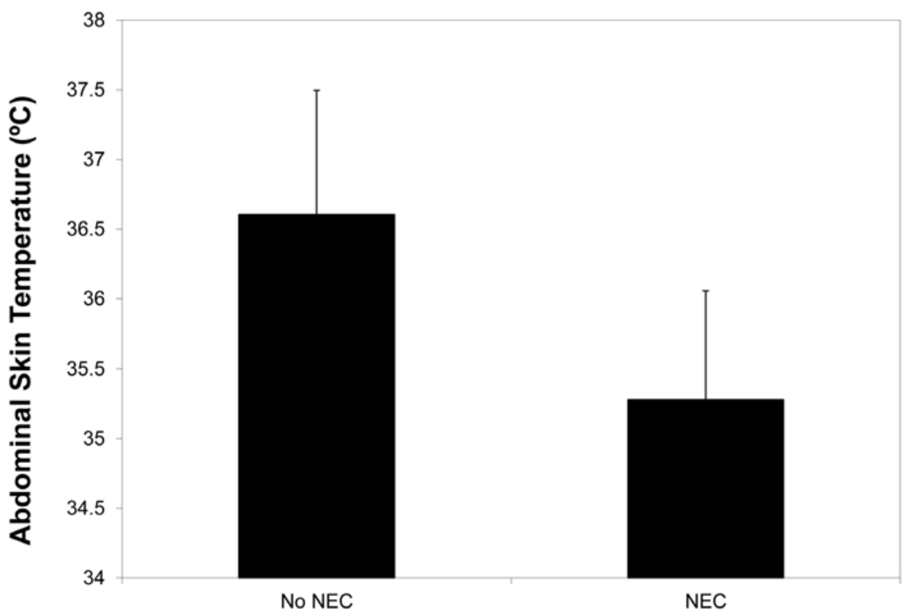

Figure 5. Mean abdominal skin temperature in 10 ELBW infants who had concurrent infrared thermography images and abdominal radiographs (total 25 measurements). Infants categorized using radiographic findings either having no NEC or as having NEC (based on suspected or definite pneumatosis intestinalis, portal venous gas, pneumoperitoneum, also characterized as DAAS grade 8-10).[14,15] Error bars represent standard deviation. The mean abdominal skin temperature was higher in infants without NEC (36.6 ± 0.9 °C, 19 total images) compared to infants with NEC (35.3 ± 0.8 °C, 6 total images, $p < 0.05$ by unpaired Student t-test).

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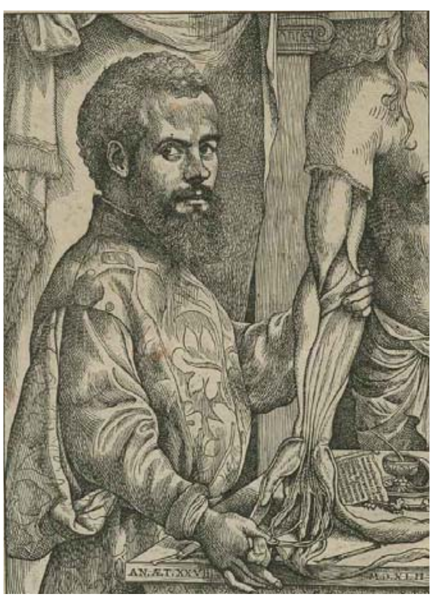

Portrait of Vesalius

Andreas Vesalius, 1514-1564
De humani corporis fabrica libri septem.