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Umbilical temperature correlation with core and skin temperatures at rest, in the heat and during physical activity

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Abstract

Purpose—to determine the correlation of umbilical temperatures (T_{umb}) with simultaneously recorded chest wall temperature (T_{chest}) and rectal temperature (T_{rectal}) in adults during rest, heat exposure and exercise.

Methods—A total of 28 healthy men, wearing different types of clothing (athletic garb, a spandex full body heating garment, firefighter bunker gear) had average and peak umbilical, chest wall and rectal temperature measurements taken during sedentary temperature stabilisation stages, heat exposure periods and active exercise phases.

Results—Curvilinear relationships were noted between T_{chest} and T_{umb} compared with T_{rectal} and their association became noticeably positive and linear at approximately 35.5 °C. Polynomial regression analysis of T_{rectal} with linear and quadratic forms of T_{chest} and T_{umb} indicated an overall R_2 of 0.657 and 0.767, respectively. Bivariate analysis of a restricted data set (where T_{chest} and $T_{umb} \geq 35.5°$), indicated that T_{umb} was significantly associated with T_{rectal} ($r_{average} = 0.710$, $p < 0.001$; $r_{peak} = 0.841$, $p < 0.001$) and T_{chest} was also significantly associated with T_{rectal}, but less so ($r_{average} = 0.570$, $p < 0.001$; $r_{peak} = 0.699$, $p < 0.001$).

Conclusions—the umbilicus offers a non-invasive, peripheral site for measurement of temperature that more closely correlated with body core temperature than T_{chest} when core temperature was ≥35.5 °C.

Keywords

Temperature; umbilicus; chest; rectal; correlation

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Disclosure statement

The authors report no declarations of interest.

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National institute for Occupational Safety and Health. Mention of a product or use of a photo does not constitute NIOSH endorsement.

Introduction

Core temperature (T_{core}) measurement is utilised extensively in medical evaluations and research studies as it is the single best indicator of the body's thermal status [1]. T_{core} (i.e. intracranial, deep thoracic, oesophageal, intraabdominal, rectal) reflects the temperature of the related anatomic region's internal milieu. Drawbacks to the use of T_{core} measurements are that they are invasive, oftentimes uncomfortable, difficult to safely maintain inserted and associated with hygiene issues [2,3]. The need for a simple, non-invasive method to measure T_{core} is evident [2], and the use of skin temperature as an index of T_{core} is an attractive notion, but requires that the former be a reliable method of monitoring the latter [4]. The splanchnic abdominal organs (excluding the kidneys) of a resting human produce 33% of the body's heat, though accounting for only 3.8% of body mass [5]. Intraabdominal T_{core} is generally measured with an ingested telemetric sensing capsule [6], but this method is hampered by the possibility of temperature gradients along the gastrointestinal tract, acute modifying effects of fluid and food ingestion on T_{core} and the uncertainty of sensor transit time [7]. Skin temperature is a function of measurement depth [4] and body orifices and depressions (e.g. external auditory canal, medial canthus of the eye, nares) are consistently warmer than flat skin surfaces because of cross-radiation of heat from their opposing skin surfaces and reduced air current effects [8,9], as well as closer proximity to internal heat sources. The umbilicus (navel) is a skin depression that is regularly identified as the warmest area of the abdominal wall on infra-red imaging studies [9–13], suggesting that it may offer a window into intraabdominal T_{core}. This assumption is plausible because of its anatomic features and attachments to various intraabdominal organs that may serve as thermal conduits (Table 1) [8,9,13–22]. A study of afebrile infants and children, reporting insulated umbilical temperatures (T_{umb}) comparable with oral and rectal readings [23], suggests that T_{umb} could possibly serve as a surrogate index [4] for T_{core}, but adult data is scarce. This study was undertaken by the National Personal Protective Technology Laboratory of the National Institute for Occupational Safety and Health (NIOSH) to determine the relationship of T_{umb} with other concurrent body temperature readings in adults at rest, during heat exposure and while involved in exercise. Such data could be important for researchers and those individuals who are engaged in activities where physical stress, environmental factors, or the use of encapsulating protective clothing can result in significant elevations of T_{core}.

Materials and methods

The study data was collected from subjects in three ongoing, but unrelated, NIOSH studies conducted under different conditions of clothing, ambient environments and work rates. The three studies were approved by the NIOSH Institutional Review Board and written informed consent was obtained from subjects that allowed for the inclusion of material pertaining to themselves, acknowledgement that they cannot be identified via this article, and that they have been fully anonymised. All subjects were healthy, non-smokers who were medically screened by a licenced physician prior to study entry. Each individual's testing was completed on one laboratory visit and a physician was present during subject testing for safety purposes. Subjects ($n = 28$) for the current report were categorised into three groups (A, B and C) based upon the clothing worn for the studies. Group anthropometrics (±SD) and clothing are described, as follows:

Group A: 11 men (age 21.6 ± 0.9 years, height 186 ± 6.9 cm, weight 79.2 ± 6.8 kg, body mass index [BMI] 23.0 ± 2.0 kg/m^2) who wore athletic shoes, shorts and tee shirts.

Group B: 7 men (age 25.6 ± 5.4 years, height 179 ± 9.1 cm, weight 80.1 ± 8.5 kg, BMI 25.0 ± 1.7 kg/m^2) wearing a hooded, full body, spandex garment with internal tubing that circulates warm water for heating (Figure 1) and athletic shoes.

Group C: 10 men (age 23.4 ± 2.7 years, height 181 ± 9.2 cm, weight 79.54 ± 6.1 kg, BMI 26 ± 2.7 kg/m^2) wearing shorts and a tee shirt under firefighter full bunker gear consisting of pants, jacket, hood, gloves, boots and helmet (Morning Pride Manufacturing Co., Dayton, OH), and a self-contained breathing apparatus (SCBA) with full facepiece respirator (the SCBA was not activated during the study due to its 40 min usage capacity that would not have been sufficient to carry out the study tasks).

Baseline temperature measurements (Study phase I)

Prior to measurement of rectal (T_{rectal}), anterior chest wall (T_{chest}) and T_{umb} baseline temperatures, stabilisation of body temperature occurred with subjects seated for 15 min in an environmental chamber at the following ambient conditions: 25 °C/50% relative humidity (RH) (Group A), 25 °C/50% RH (Group B), and 30 °C/70% RH (Group C). Group B's heating garment was not activated during these baseline measurements. Group C subjects did not wear the SCBA tank during baseline measurements, but did wear the full facepiece respirator, without a regulator.

Heat exposure temperature measurements (Study phase II)

Subjects were seated for the same temperature measurements as obtained in the baseline studies. Group A subjects underwent passive heating seated in an environmental chamber (40 °C, 30% RH) for 30 min. Group B subjects sat in environmental chamber (40 °C, 50% RH) while wearing athletic pants and a sweatshirt over the full body heating garment that was being actively infused with 46 °C water until the subject reached a T_{rectal} 0.5 °C above baseline (heating phase averaged 65.8 ± 5.7 min to complete). Group C subjects sat in an environmental chamber (30 °C, 70% RH) for 15 min (SCBA tank was not worn during this phase).

Exercise temperature measurements (Study phase III)

During exercise, subjects had the same temperature measurements as obtained in the baseline studies. Group A subjects pedalled a cycle ergometer, at an initial resistance of 75 watts, to volitional fatigue (average of 26.9 ± 5.1 min to termination) in environmental chamber conditions of 40 °C and 50% RH. Group B subjects pedalled a cycle ergometer, at an initial resistance of 75 watts increasing by 25 watts every 10 min, to volitional fatigue (average of 15.4 ± 3.2 min to termination, in environmental chamber conditions of 40 °C and 50% RH (the hooded sweatshirt and pants were removed and the heating garment was not activated during this phase). Group C subjects (wearing the SCBA, but breathing through the respirator without a regulator) treadmill exercised at 40% VO_2 max for 40 min in environmental chamber conditions of 30 °C and 70% RH.

Measurement equipment

T_{rectal} measurements were obtained using a Precision 401 rectal thermistor probe (YSI Temperature, Dayton, OH) with a 4.7mm tip that was inserted 13 cm into the rectum. T_{chest} measurements used a Precision 409 b skin thermistor (Grant Industries, Surrey, UK) with a 9.5mm tip applied to the right anterior chest wall at the second intercostal space region and insulated with a folded sterile cotton gauze pad covered by a moisture-and-air-permeable, transparent adhesive dressing (Tegaderm™, 3M Company, St. Paul, MN). T_{umb} was measured with a Precision 401 rectal thermistor (Grant Industries), housed in a cone-shaped, pliable silicone shell that conformed to umbilical dimensions (Figure 2). The thermistor was attached with a waterproof, transparent adhesive dressing (Tegaderm) and insulated with a self-adherent neoprene patch (5.5 cm diameter, 3mm thickness) applied over the adhesive dressing.

Statistical analysis

Two different forms of T_{rectal}, T_{chest} and T_{umb} were used in the analysis: (1) the average of the temperature taken throughout the study, and (2) the peak temperature reached throughout the course of the study. Through the varied experimental conditions and corresponding phases, a sufficient range in the variables was obtained.

The associations were visually explored through scatter plots between T_{rectal}, T_{chest} and T_{umb}. Visual inspection of the scatter plots revealed the appearance of a curvilinear relationship between each of the forms of the less invasive temperature measurements and T_{rectal} (Figure 3). The curvilinear relationships were verified through four distinct hierarchical polynomial regressions (R^2) in which T_{rectal} was regressed on both the linear and quadratic forms of T_{chest} and T_{umb} while controlling for age, height, BMI and weight. These hierarchical regressions took the form of:

$$\begin{aligned}\text{Average Rectal Temperature} = & B_0 + B_1(\text{Age}) + B_2(\text{Height})\\ & + B_3(\text{Weight}) + B_4(\text{BMI}) + B_5(\text{Average Umbilical Temp})\\ & + B_6(\text{Average Umbilical Temp}^2)\end{aligned}$$

Consistent with a hierarchical regression approach, the control variables were entered in model 1, model 2 includes the addition of the linear form of the independent variable, and model 3 includes the addition of the quadratic form of the independent variable.

Hierarchical polynomial regressions were repeated for average T_{chest}, average T_{umb}, peak T_{chest} and peak T_{umb}, and the total R^2 (the coefficient of determination, a statistical measure of how close the data are to the fitted regression line), change in R^2 (ΔR^2), unstandardised regression coefficients (B), and significance levels were noted for each of the corresponding steps.

Results

Subject anthropometrics and descriptive statistics for variables by study and phase are presented in Table 2. For the first set of regressions, in which the average T_{rectal} was modelled as the dependent variable, age was the only significant control variable ($p = 0.006$) (Table 2). There was a significant increase in R^2 when the linear form of the average T_{umb} was added in model 2 ($\Delta R^2 = 0.242$, $p < 0.001$). There was also a significant increase in R^2 when the quadratic form of average T_{umb} was added ($\Delta R^2 = 0.224$, $p < 0.001$). The overall R^2 for the final model in which the average T_{umb} was used as the predictor was 0.583 (Table 3; Figure 3).

When the linear form of average T_{chest} was added to the control variables, there was a significant increase in R^2 ($\Delta R^2 = 0.236$, $p < 0.001$). There was an additional significant increase in R^2 when the quadratic form of average T_{chest} ($\Delta R^2 = 0.124$, $p < 0.001$). The overall R^2 for the final model in which the average T_{chest} was used as the predictor was 0.477 (Table 3; Figure 4).

For the second set of regressions, in which the peak T_{rectal} was modelled as the dependent variable, none of the control variables significantly predicted the outcome. There was a significant increase in R^2 when the linear form of peak T_{umb} was added to the model ($\Delta R^2 = 0.425$, $p < 0.001$). There was an additional significant increase in R^2 when the quadratic form of peak T_{umb} was added in model 3 ($\Delta R^2 = 0.264$, $p < 0.001$). The overall R^2 for the final model in which peak T_{umb} was used as the predictor was 0.767 (Table 3; Figure 5).

The linear form of peak T_{chest} also significantly increased the R^2 when added to the model ($\Delta R^2 = 0.402$, $p < 0.001$). There was an additional significant increase in R^2 when the quadratic form of peak T_{chest} was added to the model ($\Delta R^2 = 0.177$, $p = 0.014$). The overall R^2 for the final model in which peak T_{chest} was used as the predictor was 0.657 (Table 3; Figure 6).

Discussion

As is indicated by the overall model R^2, T_{umb} explains more of the variance in T_{rectal} when both the average and peak temperatures are considered. These analyses suggest that T_{umb} shares a stronger association with T_{rectal} than the T_{chest} counterpart. It seems prudent, however, to further consider the application and to explore the contexts that optimise the practical utility of the use of the T_{umb} as a less invasive surrogate method of temperature measurement.

As can be observed from Figures 3–6, the association between each of the predictors and the forms of T_{rectal} noticeably becomes positive and linear at the approximate point of 35.5 °C. In order to explore the strength of the linear association at this point, bivariate correlations were computed between each of the predictors and the appropriate form of T_{rectal} in the restricted dataset (where T_{umb} and T_{chest} ≥35.5 °C [thereby excluding most of phase I trials]). These correlations are reported in Table 4.

Consistent with the results of the polynomial regressions, T_{umb} displayed higher bivariate correlations with T_{rectal} when compared to T_{chest} across the types of average and peak variables. Also consistent with the results of the polynomial regressions, the associations are higher in the peak variables when compared to the average temperatures. T_{umb} was significantly associated with T_{rectal} ($r_{average} = 0.710$, $p < 0.001$; $r_{peak} = 0.841$, $p < 0.001$).

T_{chest} was also significantly associated with T_{rectal}, but less so ($r_{average} = 0.570$, $p < 0.001$; $r_{peak} = 0.699$, $p < 0.001$) (Table 4).

It has been stated that the temperature of an organ depends partially upon its depth below the skin and its anatomical relationship to the abdominal cavity [4,24]. The umbilicus serves as an appropriate example that, due to its thinness relative to the abdominal wall [21] and its attachment to the peritoneum [17], likely functions as a conduit for intraperitoneal heat. Although T_{chest} and T_{umb} are technically both skin temperature measurements, the generally higher T_{umb} values in this study indicate that additional heat was being dissipated across the umbilicus, the additional source being heat from the peritoneal cavity. Further, the umbilicus itself is relatively avascular and thus retains heat better than more vascular structures [25]. The amount of heat flowing to the surface from the peritoneal cavity is a function of the temperature gradient between the surface of the body and the heat-producing intraperitoneal organs, as well as the overall conductivity of the human body [26]. Principal sources of body heat in the resting individual are intraperitoneal, chiefly from the liver and, to a lesser extent, the intestines [24]. One study (75 healthy subjects), utilising inserted thermocouples, reported a morning mean liver temperature of 36.68 ± 0.03 °C and corresponding T_{rectal} of 36.89 ± 0.04 °C in a temperate ambient environment [27]. This data aligns with findings from another human study (11 healthy subjects) that noted a liver temperature averaging 0.44 °C below T_{rectal} under similar ambient conditions [28]. However, liver temperature does not equate precisely with intraperitoneal temperature in the basal state because the latter will be lower due to a peritoneal cavity temperature gradient across the abdominal wall (in normal weight individuals) and diaphragm [28,29]. Data on direct intraperitoneal temperature measurements are limited, but a study of gasless laparoscopy (thereby negating the effects of pressurised CO_2 gas on intraabdominal temperatures) reported a mean intraabdominal temperature of 36.46 ± 0.56 °C [30]. Based on available data, it appears that intraperitoneal temperature may be ~0.2 °C less than liver temperature that is itself 0.2–0.6 °C subrectal temperature [31]. Further, although the umbilicus itself is collagenous scar tissue and relatively avascular, arterial blood flow to the umbilical skin from sub-dermal blood vessels and perforating vessels of the deep inferior epigastric artery [22] may attenuate some of the heat transfer to the umbilicus from the peritoneal cavity in the basal state. Also, insulated skin sites have been shown to be less effective in the thermoneutral range than in detecting the onset of heat strain [32]. An exception to this would be in persons with umbilical hernias wherein the T_{umb} would more directly reflect intraintestinal temperature [9]. Thus, the temperature offset between T_{rectal} and intraperitoneal temperature must be taken into consideration when evaluating T_{umb}.

T_{umb} values generally exceeded T_{chest} in this study due to the minimum air current effects and minimal radiant heat exchange on the umbilicus (dependent on umbilical depth to some degree) [9] and the umbilicus' aforementioned intimate anatomic relationships with the peritoneal cavity and its contents (Table 1). Additionally, sensor insulation been shown to be important to prevent heat loss from the skin [33,34], even when wearing protective clothing as in study Group C [3]. However, this was not entirely the case as noted during phase II (heating) studies, when use of the heating garment resulted in T_{chest} that actually exceeded T_{rectal} (Table 1), a recognised phenomenon that occurs when the skin is warmed by an outside heat source that directly contacts the temperature sensors [34]. Of added note, during the exercise phase of study Group C, the peak and mean T_{umb} values were within 0.5 °C of T_{rectal}, a level of accuracy required between skin site and T_{rectal} to be considered clinically utilitarian (though this value has not been firmly established) [1,35]. This result was clearly impacted by the relatively impermeable, encapsulating firefighter ensemble worn that, combined with heat and exercise, resulted in a hot, humid microclimate conducive to the convergence of skin and core temperatures [4,36].

Fox and Solman [37] first introduced the concept of zero heat flux, wherein an insulated, heated skin surface sensor equilibrates skin temperature with deep body temperature creating a region of zero heat flow that allows for measurement of core temperature at the skin surface. An early study [38] at various ambient conditions, noted that there was good agreement between a heated sensor at the sternum with tympanic membrane and ingested sensor temperatures in warmer ambient temperatures at decreased walking speeds. Ball et al. [39] noted a mean difference of 0.1 ± 0.5 °C between a sternal zero heat flux sensor and T_{rectal}. Studies comparing a forehead zero heat flux sensor with T_{rectal} reported a mean difference of 0.9 ± 0.4 °C [40] and 0.12 ± 0.24 °C [41]. One recent study, examining the relationship between core temperature measured by ingested core temperature sensor, skin temperature measured by ceramic heat flow sensor and heat flux of subjects who treadmill walked in different ambient environments reported R^2 values of 0.40 for the forehead and 0.75 for the sternum [42]. A similar study by the same authors reported an R^2 of 0.70 for the sternum compared with T_{rectal} [43]. Thus, in some studies [42,43], the sternum is associated with the highest R^2 values that compared to T_{rectal} and align with the reported values for T_{umb} data from this study. The use of a “double sensor” (one probe adjacent to the skin and separated by a standard insulator from a second probe facing the environment) has been investigated in several studies [44–46]. Kimberger et al. [44] compared a forehead “double sensor” with oesophageal temperatures in perioperative and intensive care patients; 98% of measurements were within 0.5 °C of oesophageal values with a mean bias of 0.08 °C and limits of agreement of −0.66–0.50 °C between methods [44]. Gunga et al. [45] compared forehead “double sensor” readings with T_{rectal} over 36 h of bedrest and reported $r = 0.704$ with 0.08 ± 0.32 °C difference between methods. Another study [46], comparing T_{rectal} and a helmet-mounted forehead “double sensor” at 25–55% VO_2Max for 2 + h each at ambient temperatures of 10, 25 and 40 °C reported correlations of 0.49, 0.69 and 0.75, respectively. This study’s finding, that use of the umbilicus as a temperature measurement site correlates best with T_{rectal} when $T_{umb} \geq 35.5$ °C, implies that this parameter might be most useful in monitoring situations that are associated with heat stress and hyperthermia. T_{umb} might be especially useful in situations where moderate-to-high physical activity is associated with elevated ambient heat and the use of restrictive clothing (e.g. firefighters, military personnel, foundry workers, etc.).

Limitations of this study include the relatively low number of subjects tested in each group and the fact that no women subjects were tested so that we cannot comment on the possible effect of gender on T_{umb}. We did not analyse T_{umb} in relation to umbilicus depth, so there exists the possibility of deeper umbilici transmitting higher temperatures [9]. Further, we did not test obese individuals whose panniculus could have served as an abdominal wall insulator [14]. Skin thickness at measurement sites (e.g. forehead skin 1.81 mm) impacts temperature measurements and, although the anterior chest wall skin thickness (1.37 mm) is less than that of the abdominal skin covering the umbilicus (1.91 mm), the underlying chest muscle layer likely would increase the functional thickness of the chest wall [47,48]. An equipment limitation observed occasionally during testing was that, due to the relatively small contact area of the T_{umb} sensor (4.7 mm), motion-related displacement during exercise activities, with resultant loss of contact between the umbilicus and the sensor, necessitated repeat testing. This can occur with even minor movement of the sensor [34]. In an attempt to circumvent this limitation, pilot testing using a wireless semiconductor temperature sensor with a larger surface area (I-Button, Dallas, TX) was carried out, but unsuccessful due to the sensor's diameter (16.5 mm) exceeding the internal dimensions of the umbilicus. A similar wireless sensor, with smaller dimensions, might offer a reasonable solution to minimising T_{umb} sensor displacements.

Finding a skin site that correlates closely with core temperature has been the subject of much research interest for a number of years because of the varied issues associated with core temperature measurements (invasiveness, discomfort, etc.). Use of insulated skin temperature sensors, as in this study, results in closer correlations between skin and core temperatures than uninsulated sensors during exercise and heat exposure states and can allow for the development of prediction equations [3,31]. The umbilicus offers a temperature measurement site that, with the use of an appropriately-sized wireless sensor, could offer an unobtrusive site for temperature measurements that would not interfere with an individual's ongoing activities. Further, in studies that might employ an externally applied heat source (as with this study's heating garment), a small sensor housed in the recesses of the umbilical depression might be shielded from the effects of direct contact with a heating source. An appropriately-sized, wireless T_{umb} sensor could be programmed to deliver a vibratory or audible alarm to the wearer that, upon reaching a pre-programmed temperature setting, would indicate the need for heat remediation strategies to be undertaken. The umbilicus offers the possibility of a skin measurement site that correlates reasonably well with core temperature when T_{rectal} is ≥35.5 °C. Future studies are needed to address the overall utility of T_{umb}, as well as for validation of this study's findings.

Conclusions

This study has demonstrated that, when taking average and peak temperatures into consideration, T_{umb} correlated well with T_{rectal} compared with T_{chest}. The umbilicus, due to its anatomical features and relationships (Table 1), offers a non-invasive, peripheral site for measurement of temperature that correlates reasonably well with core temperature when T_{rectal} is ≥35.5 °C. Development of an insulated, wireless skin temperature sensor, that fits snuggly within the recesses of the umbilicus, may offer a non-invasive temperature measurement capability that supplements current methods of temperature measurement.

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Figure 1.
Heating garment utilised by Group B.

Figure 2.
Umbilicus temperature in a silicone sleeve.

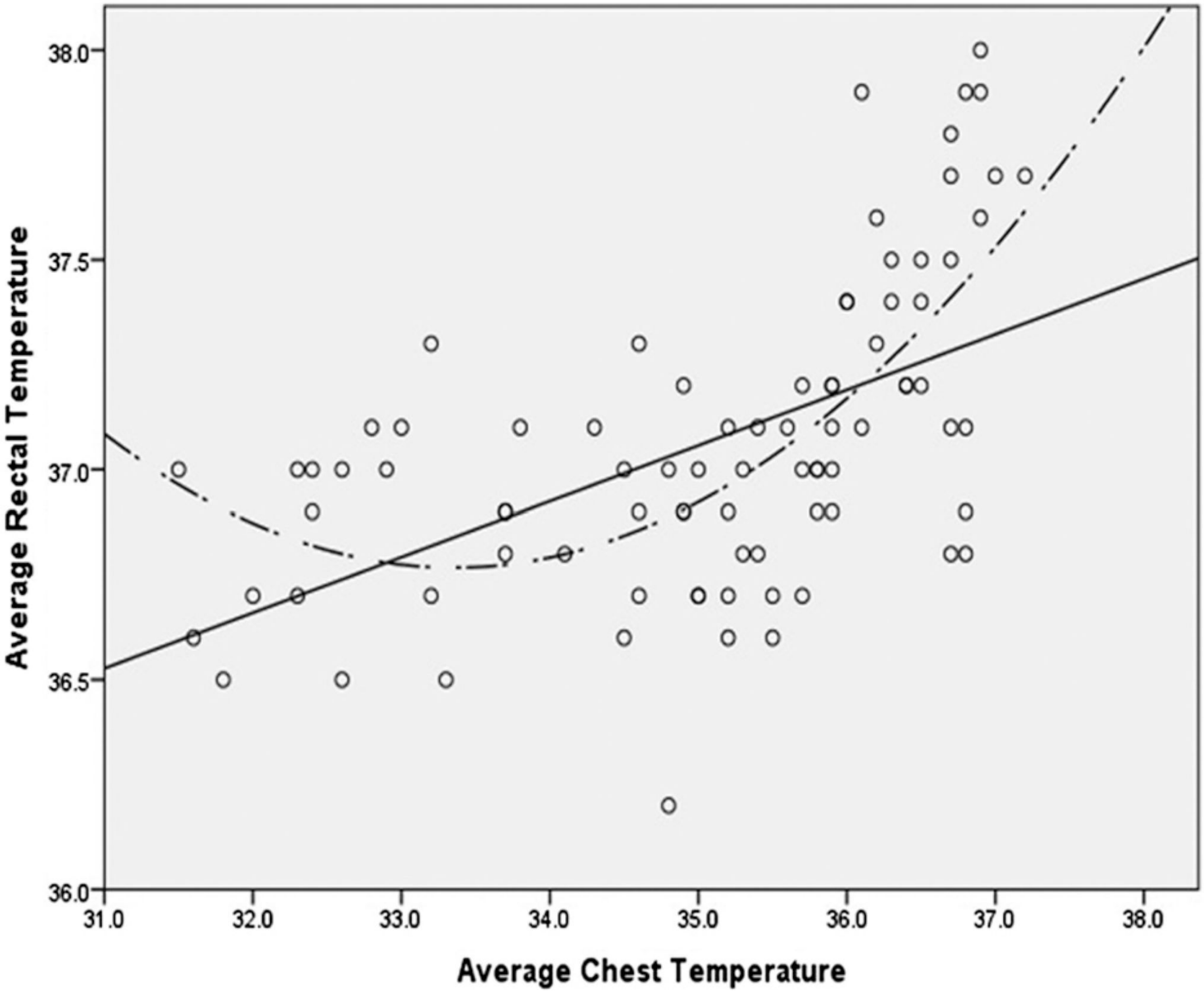

Figure 3.

Average T_{rectal} regressed on linear and quadratic average T_{umb} (overall R^2 0.583).

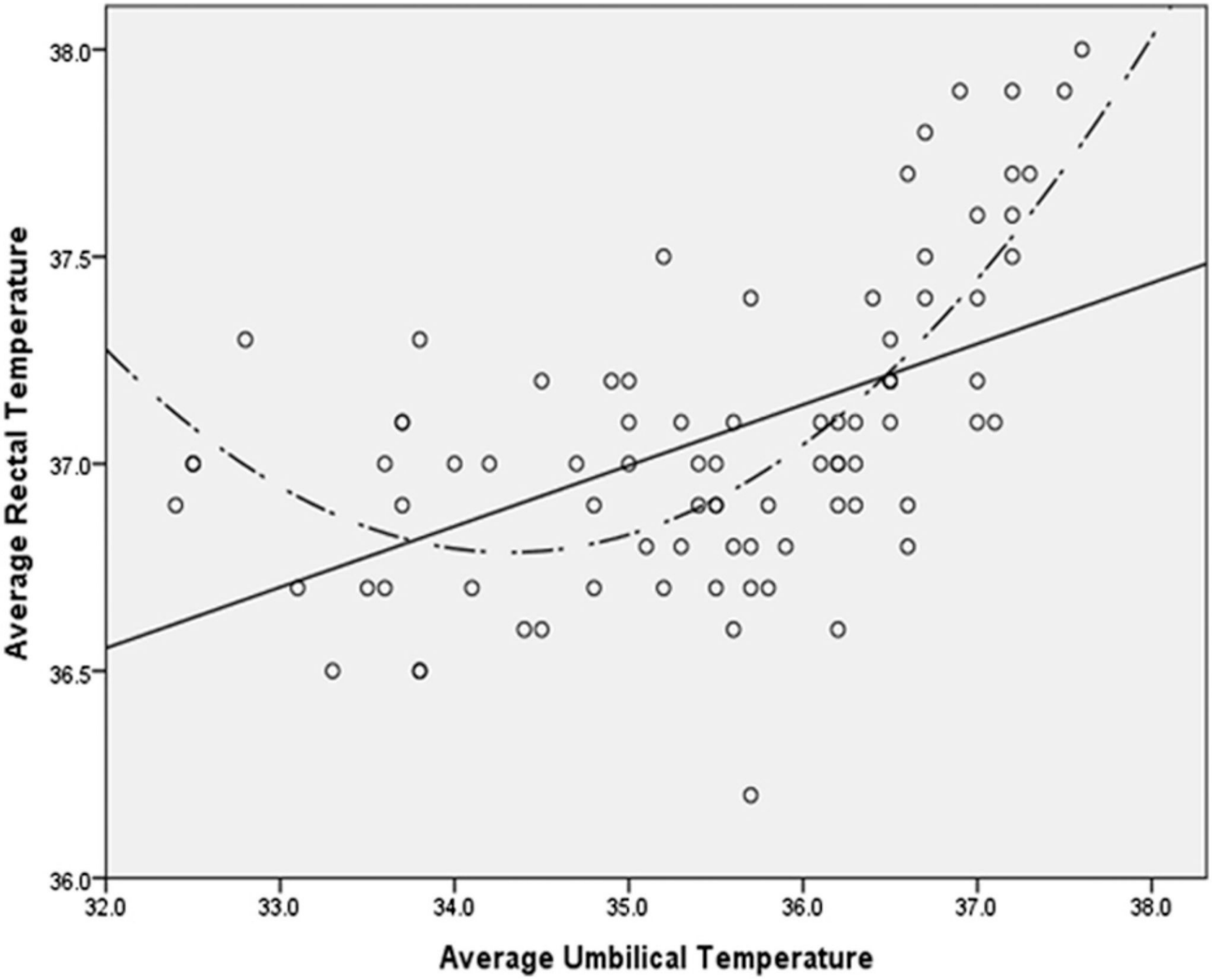

Figure 4.

Average T_{rectal} regressed on linear and quadratic average T_{chest} (overall R^2 0.477).

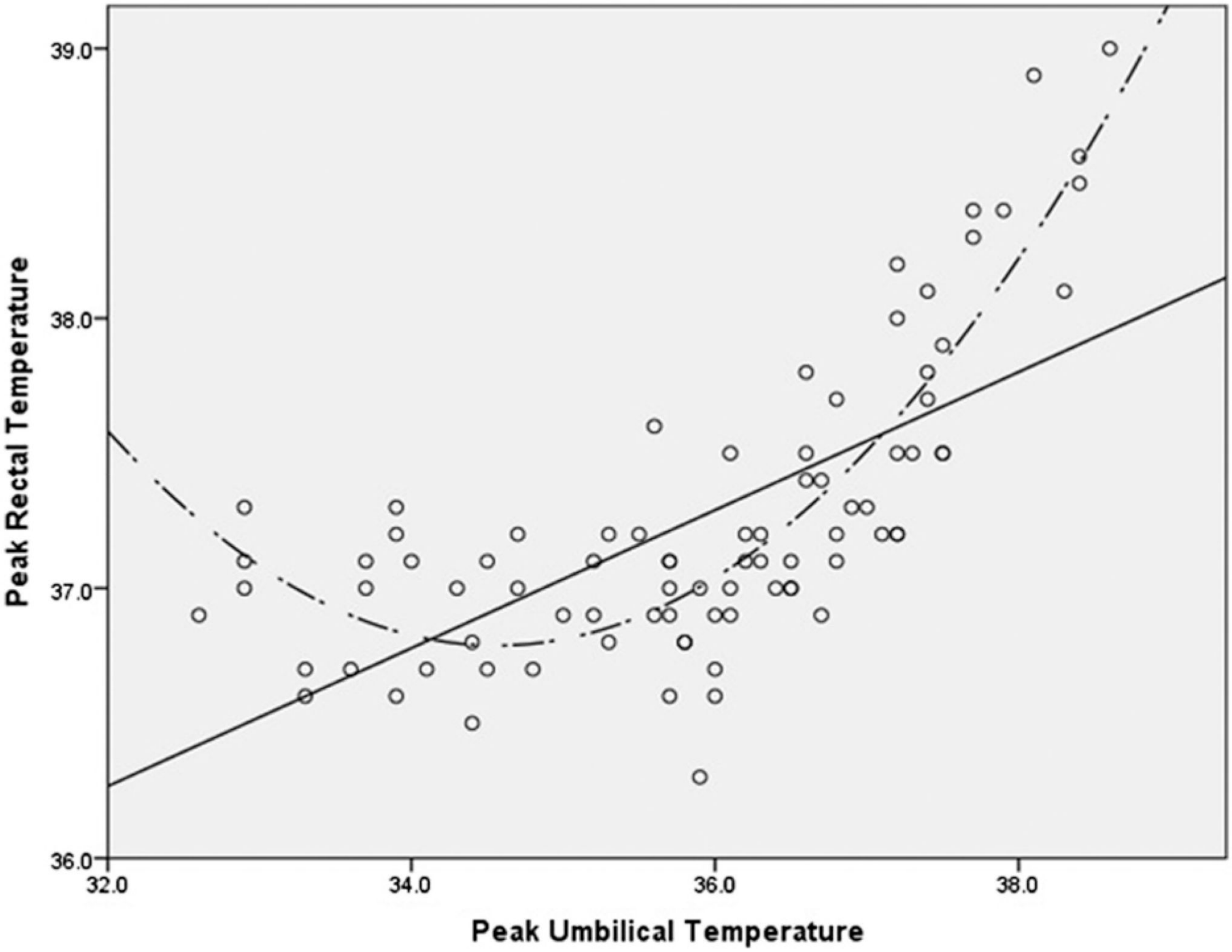

Figure 5.

Peak T_{rectal} regressed on linear and quadratic average T_{umb} (overall R^2 0.767).

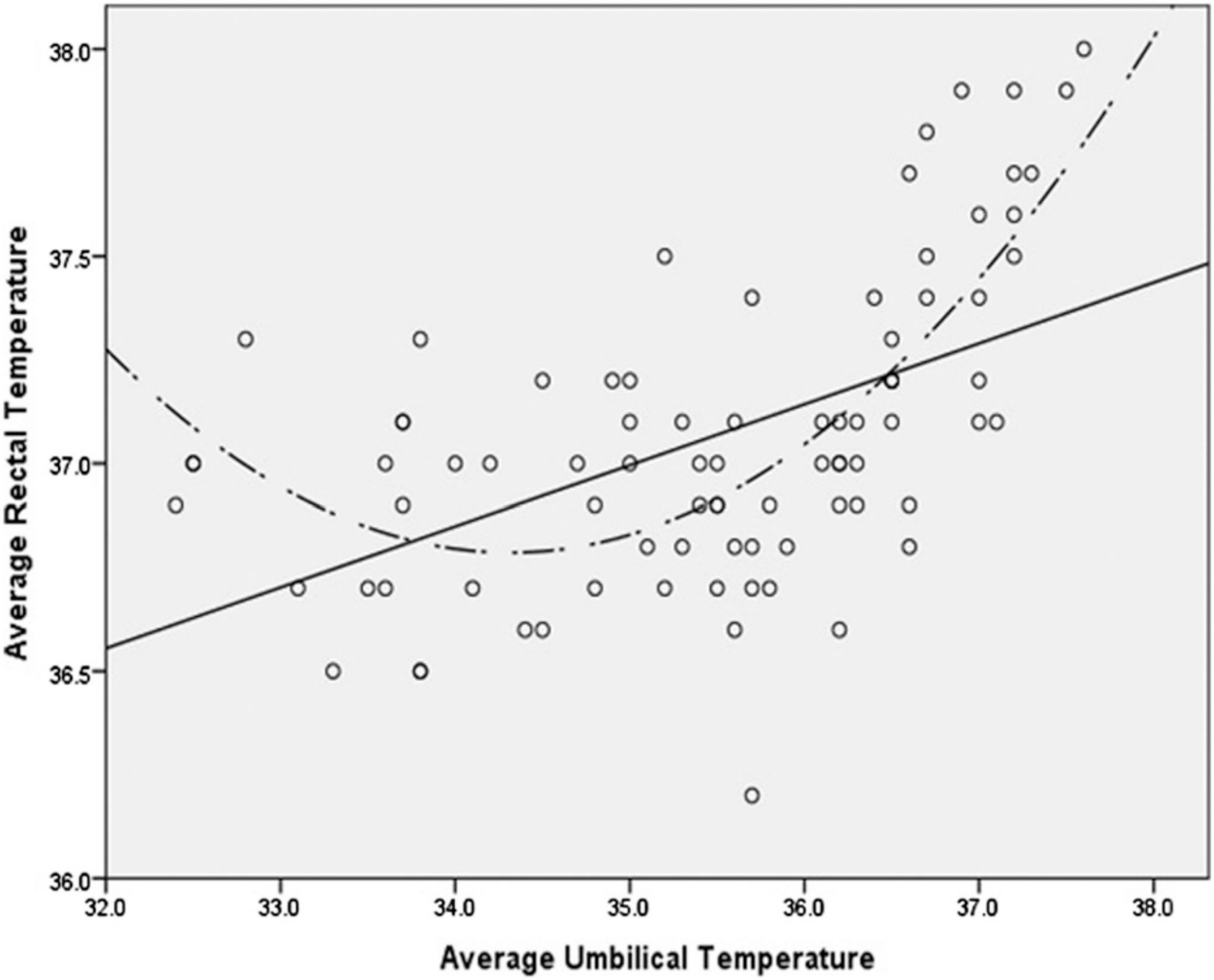

Figure 6.

Peak T_{rectal} regressed on linear and quadratic peak T_{chest} (overall R^2 0.657).

Table 1

Anatomical rationale for the relationship of umbilical temperature with intraabdominal temperature.

In non-overweight persons, the umbilicus is thinner (men, 8.1 ± 4.8 mm; women, 10.6 ± 4.9 mm) [21] than the rest of the abdominal wall, as there is little fat or muscle associated with its inner surface to insulate it from core heat (fat is a poor conductor and good insulator of heat) [14,15].
The inner surface of the umbilicus is free and separated from the abdomen only by the parietal peritoneum [16] that is tightly adherent to the umbilical ring [17] and porous so that it can transmit heat radiating from the peritoneal cavity.
As a body cavity, the umbilicus allows for cross-radiation from its opposing walls, with little heat loss, so that its surface temperatures more closely approximate core temperatures [8,9,11].
The central depression of the umbilicus moderates the effects of air currents upon its skin temperature (dependent on umbilical depth) [8].
The umbilical cord remnants (hepatic ligamentum teres, medial umbilical ligaments, urachus), attached proximally to the underside of the umbilicus and distally to intraabdominal organs, are vascularised [18–20] and can transmit intraabdominal heat along a vascular temperature gradient [11].

Table 2

Subject characteristics and descriptive statistics by study and phase.

Characteristics	**Study A**	**Study B**	**Study C**
Number of subjects	11	7	10
Age (years)	21.6 ± 0.9, 20–23	25.6 ± 5.4, 21–36	23.4 ± 2.7, 21–29
Weight (kg)	79.2 ± 6.8, 68–89	80.1 ± 8.5, 62–89	79.5 ± 6.1, 67–86
Height (cm)	86 ± 6.9, 174–196	179 ± 9.1, 165–193	181 ± 9.2, 165–196
BMI (kg/m^2)	23 ± 2.0, 20–26	25 ± 1.7, 23–27	26 ± 2.7, 22–30
Variables			
Study phase I			
Avg. rectal Temp.	36.9 ± 0.3, 36.5–37.3	36.9 ± 0.1, 36.7–37.1	37.0 ± 0.3, 36.5–37.4
Avg. chest Temp.	32.7 ± 0.8, 31.6–34.6	33.9 ± 0.8, 32.6–34.8	34.0 ± 1.6, 31.5–36.0
Avg. umbilical Temp.	33.4 ± 0.6, 32.4–34.5	34.5 ± 1.2, 32.5–35.7	34.6 ± 0.8, 33.3–35.7
Peak rectal Temp.	37.0 ± 0.3, 36.6–37.3	36.9 ± 0.2, 36.7–37.1	37.0 ± 0.2, 36.6–37.5
Peak chest Temp.	33.1 ± 0.8, 32.2–34.9	34.4 ± 0.6, 33.1–35.0	34.3 ± 1.5, 31.8–36.2
Peak umbilical Temp.	33.7 ± 0.6, 32.6–34.8	34.6 ± 1.2, 32.9–35.8	34.8 ± 0.9, 33.3–36.1
Study phase II			
Avg. rectal Temp.	36.8 ± 0.3, 36.2–37.2	37.0 ± 0.2, 36.8–37.2	37.0 ± 0.3, 36.5–37.4
Avg. chest Temp.	35.1 ± 0.4, 34.5–35.9	36.3 ± 1.1, 33.7–36.8	35.1 ± 0.9, 33.3–36.3
Avg. umbilical Temp.	35.5 ± 0.6, 34.4–36.2	36.2 ± 0.5, 35.6–37.0	35.4 ± 0.8, 33.8–36.4
Peak rectal Temp.	36.8 ± 0.3, 36.3–37.2	37.3 ± 0.2, 37.2–37.5	37.0 ± 0.2, 36.5–37.4
Peak chest Temp.	35.4 ± 0.4, 34.6–36.3	37.4 ± 0.3, 37.1–38.0	35.6 ± 0.9, 33.9–36.5
Peak umbilical Temp.	35.8 ± 0.6, 34.5–36.5	37.2 ± 0.2, 37.0–37.5	35.9 ± 0.7, 34.4–36.6
Study phase III			
Avg. rectal Temp.	37.0 ± 0.3, 36.6–37.5	37.7 ± 0.2, 37.5–37.9	37.5 ± 0.3, 37.1–38.0
Avg. chest Temp.	35.9 ± 0.2, 35.5–36.3	36.7 ± 0.3, 36.1–37.2	36.5 ± 0.4, 36.0–37.0
Avg. umbilical Temp.	36.1 ± 0.5, 35.2–36.6	36.9 ± 0.3, 36.6–37.3	37.1 ± 0.3, 36.5–37.1
Peak rectal Temp.	37.2 ± 0.2, 36.9–37.6	37.9 ± 0.2, 37.7–38.2	38.4 ± 0.4, 37.5–39.0
Peak chest Temp.	36.1 ± 0.3, 35.7–36.6	36.9 ± 0.2, 36.7–37.3	37.5 ± 0.5, 36.4–38.0
Peak umbilical Temp.	36.4 ± 0.5, 35.6–36.9	36.6 ± 0.3, 36.6–37.4	38.0 ± 0.4, 37.3–38.6
Overall			
Avg. rectal Temp.	36.9 ± 0.3, 36.2–37.5	37.2 ± 0.4, 36.7–37.9	37.2 ± 0.4, 36.5–38.0
Avg. chest Temp.	34.6 ± 1.5, 31.6–36.3	35.6 ± 1.5, 32.6–37.2	35.2 ± 1.5, 31.5–37.0
Avg. umbilical Temp.	35.0 ± 1.3, 32.4–36.6	35.9 ± 1.3, 32.5–37.3	35.7 ± 1.2, 33.3–37.6
Peak rectal Temp.	37.0 ± 0.3, 36.3–37.6	37.4 ± 0.4, 36.7–38.2	37.5 ± 0.7, 36.5–39.0
Peak chest Temp.	34.9 ± 1.4, 32.2–36.6	36.2 ± 1.4, 33.1–38.0	35.8 ± 1.7, 31.8–38.0
Peak umbilical Temp.	35.3 ± 1.3, 32.6–36.9	36.3 ± 1.4, 32.9–37.5	36.2 ± 1.5, 33.3–38.6

For age, height, BMI and variables the Mean ± SD and range are reported. Temperatures are in °C.

Table 3

Results for hierarchical polynomial regressions.

	ΔR^2	R^2	Adj. R^2	B	Std Err.	t	p
Average rectal temperature as dependent variable							
Model 1	0.116	0.116	0.072				0.042
Age				0.032	0.011	2.83	0.006
Height				0.037	0.038	0.96	0.339
Weight				−0.040	0.045	−0.88	0.381
BMI				0.140	0.143	0.98	0.331
Average umbilical temperature							
Model 2	0.242	0.359	0.318				<0.001
Average umbilical Temp				0.138	0.025	5.43	<0.001
Model 3	0.224	0.583	0.551				<0.001
Average umbilical Temp^2				0.095	0.015	6.44	<0.001
Average chest temperature							
Model 2	0.236	0.353	0.311				<0.001
Average Chest Temp				0.121	0.023	5.33	<0.001
Model 3	0.124	0.477	0.436				<0.001
Average Chest Temp^2				0.058	0.014	4.28	<0.001
Peak rectal temperature as dependent variable							
Model 1	0.078	0.078	0.032				0.163
Age				0.029	0.018	1.62	0.109
Height				0.089	0.059	1.49	0.139
Weight				−0.107	0.070	−1.53	0.130
BMI				0.358	0.222	1.61	0.110
Peak umbilical							
Model 2	0.425	0.503	0.471				<0.001
Peak umbilical Temp				0.249	0.030	8.17	<0.001
Model 3	0.264	0.767	0.749				<0.001
Peak umbilical Temp^2				0.120	0.013	9.34	<0.001
Peak chest							

	ΔR^2	R^2	Adj. R^2	B	Std Err.	t	p
Model 2	0.402	0.480	0.447				<0.001
Peak chest Temp				0.225	0.029	7.76	<0.001
Model 3	0.177	0.657	0.631				0.014
Peak chest Temp^2				0.083	0.013	6.31	0.014

B: unstandardised regression coefficients reported; Std Err.: is the standard error of the regression coefficient; *t*: *t*-test for regression coefficient; *p* significance level of the *t* test for the unstandardised regression coefficient.

Table 4

Correlations between rectal temperature with umbilical and chest temperature in restricted dataset.

	Average rectal temperature	**Peak rectal temperature**
Average umbilical temperature	0.710 *	
Average chest temperature	0.570 *	
Peak umbilical temperature		0.841 *
Peak chest temperature		0.699 *

Restricted dataset includes all observations in which both chest and umbilical temperature measurement are greater than or equal to 35.5 °C.

* $p < 0.001$.