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Thermal territories of the abdomen after caesarean section birth: infrared thermography and analysis approaches to surgical site assessment

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ABSTRACT

Objective: To develop and refine qualitative mapping and quantitative analysis techniques to define 'thermal territories' of the post-partum abdomen, the caesarean section site and the infected surgical wound. In addition, to explore women's perspectives on thermal imaging and acceptability as a method for infection screening.

Method: Prospective feasibility study undertaken at a large University teaching hospital, Sheffield UK. Infrared thermal imaging of the abdomen was undertaken at the bedside on the first two days after elective caesarean section. Target recruitment: six women in each of three body mass index (BMI) categories (normal, 18.5 to 24.9kg/m^2; overweight 25 to <30kg/m^2; obese ≥30kg/m^2). Additionally, women presenting to the ward with wound infection were eligible for inclusion in the study. Perspectives on the use of thermal imaging and its practicality were also explored *via* semi-structured interviews and analysed using thematic content analysis.

Results: Twenty women were recruited. All had undergone caesarean section. From the booking BMI, eight women were obese (including two women with infected wounds), six women were overweight and six women had a normal BMI. Temperature (°C) profiling and pixel clustering segmentation (Hierarchical Clustering Segmentation, HCS) revealed characteristic features of thermal territories between scar and adjacent regions. Differences in scar thermal intensity profiles exist between healthy scar and infected wounds; features that have potential for wound surveillance. Maximum temperature differences (deltaT) between healthy skin reference and wound site, exceed 2°C in women with established wound infection. At day 2, two women had a scar thermogram with features observed in the ''infected'' wound thermogram.

Thermal imaging at early and later times after caesarean birth is feasible and acceptable. Women reported potential benefits of the technique for future wound infection screening.

Conclusion: Thermal intensity profiling and HCS for pixel cluster dissimilarity between scar and adjacent healthy skin has potential as a method for the development of techniques targeted to early infection surveillance in women after caesarean section.

Key words;

Thermal imaging, infrared thermography, abdomen, surgical site infection, Caesarean section, infection surveillance.

INTRODUCTION

Complications and adverse events occur during *and* after surgery.[1] Of the post-operative complications, wound infection is common especially after abdominal surgery.[2] Surgical site infection (SSI) accounts for 21.8% of healthcare associated infections in the US.[3] In the UK, the Health Protection Agency [4] cites SSI as the third most frequent healthcare-associated infection. The consequences being increased morbidity, a longer stay in hospital, greater antibiotic use and increased NHS costs.[5] Vulnerable patients are those with serious co-morbidity; the elderly [6] and obese patients. [7,8] Being overweight or obese and undergoing surgery is known to be an independent risk factor for SSI particularly in colorectal surgery.[9,10] Obesity and SSI risk is now a matter for increasing concern in women undergoing caesarean section.[11,12]

After abdominal delivery and caesarean section, infection can occur in all three of the SSI categories; superficial incisional SSI, deep incisional SSI and organ (or space) SSI. [13] Typically infection of skin and superficial tissues is most common after caesarean birth. Given the reported risk associated with raised body mass index (BMI)[14] there is concern that overweight and obese women who deliver by caesarean section are most vulnerable to developing SSI.[15,16]

We have shown previously that thermography has potential as a method for infection surveillance after colorectal surgery [17] where SSI rates range between 19 and 32%.[18] Within operational distances of 1 metre from the target field of view (FOV) optimal focus of digital and infrared images over the abdomen and across a range of BMI reveal qualitative thermal mapping characteristics which support thermal imaging as a credible tool for infection surveillance.[17] In the current study our aims were to further explore the potential for thermography in women undergoing caesarean section, specifically to (i) define the 'thermal territories' of the post-partum abdomen, the surgical site, and the infected surgical wound (ii) develop robust qualitative mapping and quantitative analysis systems (iii) seek the perspectives of women about the potential for thermal imaging as a future wound surveillance technique.

METHODS

Study Design

A prospective feasibility and exploratory study was undertaken over a period of seven months. The objective was to recruit a sample of six women with a booking BMI across each of three categories; normal (NORM 18.5 to 24.9kg/m²) overweight (OV 25 to <30kg/m²), obese (OB ≥30kg/m²) and who gave birth by elective caesarean section and who would remain as a hospital admission for a minimum of two days after the birth.

In the event that a woman presented with an infected wound (irrespective of booking BMI) and were admitted to the postpartum ward during the study period, the aim was to recruit these women to form an "infected wound" group of subjects. Local National Health Service (NHS) ethics approval was obtained before recruitment and data collection commenced.

Participants and Procedures

Based on the booking BMI, eligible women were identified by a member of the study team before the birth and invited to participate after their caesarean section delivery. Interested women were given a participant information sheet. Once the participant had agreed, a consent form was provided with an explanation of the study objectives and procedures and with opportunity for women to discuss and ask questions about any aspects of the study. In this study, lower abdominal, transverse incision was performed in all women of the method described by Pfannenstiel.[19] It is preferred for its cosmetic advantage, with the curve of the incision in a natural fold of skin.

Once the baby was born, women were approached once more to ensure that they were comfortable to continue to participate in the study.

Study information and participant characteristics (early pregnancy height and weight, age, parity, surgical procedure, drugs administered, body temperature, socio-economic indicators (e.g. postcode) were collected from maternal records.

Temperature measurements

Ambient conditions and body temperature (°C) measurements were made at the bedside in either a single room or multi-occupancy ward (maximum four beds). Ambient conditions for room temperature, (°C) relative humidity (% RH) and air velocity ($m.sec^{-1}$) were measured (Kestrel 3000; Weather Meter; Richard Paul Russell Ltd, Hampshire UK).

Body temperature was measured using infrared thermometry "scanning" of the skin overlying a part of the course of the temporal artery [20] (temporal artery thermometer, Temporal Scanner, Exergen, Watertown, MA, USA). Information of drugs likely to affect the pattern of body temperature was obtained from the drug chart.

Infrared thermography and imaging protocol

Thermal imaging was undertaken using a portable thermal camera (FLIR Systems T450sc) with IR detector pixel resolution of 320x240 (Thermal Vision Research Ltd, Somerset, UK). The camera was first calibrated and certified using a blackbody source (FLIR Systems Inc, Wilsonville, USA). Thermal sensitivity, <30mK with accuracy ±1°C for ambient temperature within 15-35°C and with spatial resolution 1.36mRad, image frequency 60mH. Reflective ambient radiation was obtained via imaging of reflective material.

The abdomen was exposed and any covers or dressings removed and with a duration of 10 min allowed for skin temperature to stabilise. The area from the umbilicus to ischial crest and within the region of the surgical scar was exposed and the camera focussed to this region of interest (ROI). A thin cotton sheet was placed over the suprapubic region. Where structures (hair, suture material, suture beads) were visible, these structures served to aid image focus. Three to six consecutive images were taken to obtain best possible image composition and clarity of focus, appearing on the camera screen in "iron" colour palette and using ‘’automatic’’ setting.

Image processing and analysis

A hierarchy of approaches were taken to the eventual development of a "bespoke" analysis process for this application; a) FLIR proprietary analysis tools of the of ROI (qualitative/quantitative) b) edge detection algorithm for wound scar analysis c) Hierarchical

Clustering-based Segmentation (HCS) [21] of regions with distinct variability across wound and adjacent skin territories.

i) Image processing

Data was downloaded from the IR camera to a stand-alone PC. Participant identifiers were removed from all data (demographic, images).

Post-processing was undertaken at the end of each day. FLIR systems software analysis parameters were adjusted to allow "apparent temperature" to be converted to "absolute" temperature (^{o}C). Here FLIR Research IR proprietary software allows adjustment to set parameters for; emissivity (set to 0.98) distance (set to 60cm, i.e. distance from camera to abdomen) relative humidity (%RH) and reflective ambient temperature (obtained from the temperature of reflective material before measurements commenced). Once parameter adjustments were made, a colour palette for pixel representation of temperature was selected. Rainbow high contrast (Rainbow HC) colour palette was selected and used throughout. In addition to the temperature (^{o}C) map, "raw" radiometric data was produced for each participants set of thermal images. Using Rainbow HC, the convention for the colour palette is for higher temperature/higher radiation intensity to be "brightest" and lower temperatures/lower radiation intensity to be represented by "darker" colours. From the bedside image FOV, the visual image was cropped to an image of the lower abdomen only (image not shown) and from the corresponding thermogram a rectangular box (standardised to 268x81 pixels) was used to identify the ROI. This incorporated the scar and immediate surrounding skin.

From each pixel within the ROI, two sets of data were obtained: temperature (^{o}C) (Fig 1a) and radiometric values (Fig 1b). The scale for temperature was adjusted and standardised for all participants (range, 33-37^{o}C) and for radiometric data from 20000 to 21392 units. Each rectangular area produced a maximum, minimum and average value. All data within the ROI was saved to file (Excel, Microsoft Corporation, Redmond, WA 98052-6399).

ii) Thermal territory and edge enhancement

Qualitative mapping: To enhance the visual image of the scar line a series of adjustments to the camera thermal images were made for all participants (greyscale). The first step was to obtain a reference set of pixel values (^{o}C) for healthy skin distant from the ROI; the umbilical region was selected. Subtraction of healthy skin temperature from all pixels in the ROI yielded a new thermogram. To avoid 'negative' values each pixel value was squared. Then, by calculating the square root for all the values, a new thermal image was generated. By taking a second square root calculation of the new pixel values, a simple algorithm allowed scar 'territory' to be highlighted and distinguished from the adjacent healthy skin (Fig 2a).

Data analysis and conversion between pixel values and greyscale thermal image was achieved using OriginPro 2015. (OriginPro, Origin Lab Corporation, Northampton, MA, USA). This method is robust, in the sense that, there is no requirement to adjust the colour pallet or greyscale levels in order to achieve maximum contrast.

Informed by the qualitative edge-detection analysis (Fig 2a) it was possible to proceed to quantitative analysis. Here a temperature profile line was 'drawn' through the middle of the scar or infected wound (of the unadjusted grey scale image, Fig 2b) and, with an additional skin temperature reference line taken at a point above the wound (Fig 2b), a delta plot (Fig 2c) for healthy skin reference minus wound temperature could be constructed. In this way individual "profile deviations" would become apparent from the group profile characteristics (Fig 2C).

iii). Qualitative and Quantitative segmentation of thermal territories

From the grey scale thermogram edge detection process, it became apparent that the surgical scar or, in patients with confirmed wound infection, both wound and surrounding regions were not at uniform temperatures. Further analysis of the data for each participant using the principle of HCS [21] was applied. Briefly, HCS generates a hierarchy of segmented images by partitioning an image into its constituent regions at levels of 'allowable' dissimilarity between the different regions. Radiation intensity units were used to produce HCS pixel clusters. The methodological process is outlined in Fig 3. The pixel cluster boundaries are plotted with a colour hue comparable to FLIR rainbow HC palette; darker shades representing regions of low thermal intensity and bright (white, red) pixels indicating higher thermal intensity. Pixel clusters in regions of uniform temperature will have more pixels and in regions of high variability in radiation intensity (and temperature) the clusters will have very minimal number of pixels. For example, In Fig 3B darkest areas (on black and white thermal image) represent the coldest regions along the scar; the 'cold spots'. Here variability in radiation intensity is so high that the clusters have barely a couple of pixels of similar values Fig 3 B. In contrast since the region above the scar line has more uniform temperature the clusters have more pixels (Figure 3 C). The boundaries (cut-off) for ''similarity'' are determined at a specific level of allowable dissimilarity for clustering; here we have applied "allowable dissimilarity" for thermal profiling of between 10-15%.

In processing the thermal images the HCS helps the user to:
(i) quantify the thermal properties of the different dissimilar regions i.e. between the scar or wound and the adjacent abdominal thermal territories.
(ii) visualise variability in thermal regions along and amongst the scar "line" or wound region

Statistical Analysis

Descriptive statistics of thermal values and comparisons between mean values (independent student t-test) was undertaken using SPSS (Statistical Package for Social Sciences) IBM SPSS V22.

Participant Narratives

After thermal imaging had been completed, face-to-face semi-structured interviews were undertaken with women to determine the acceptability of the procedure to them. Participants were also asked for their perspectives on the thermal imaging technique and study processes for future study development. Field notes were obtained during the interviews. Qualitative data was analysed using content analysis, where the responses given were grouped into similar themes.

RESULTS

Participants' Characteristics

Twenty women, predominately of white British origin, aged 20-39 (median 33) years were recruited (Table 1). After birth, absorbable vicryl/monocryl sutures were used to close the incision (n=8) and non-absorbable Prolene sutures with beads in 11 women. In one woman, the skin incision was closed with staples on request. The wound was covered during the first 24-48 hours with a dry dressing. Dressings were removed 30 min before imaging commenced. With the exception of two women (participants 6 and 16) all were admitted for elective caesarean section and were studied on day 2 post-operatively (Table 1). Participants 6 and 16 had both been admitted for emergency caesarean section, 11 days (participant 6) and 15 days (participant 16) previously and had returned to the ward for care of infected caesarean section wounds. Both had a BMI>25 kg/m^2 and both were in-patients at the time of the study.

Thermal imaging and study data was thus acquired from 18 women at day 2 (and with apparently "healthy" wounds) and two women with a confirmed wound infection (Table1). Ten of 20 women had a history of previous caesarean section. Two women (who had not previously undergone caesarean section) gave birth to twins (Table 1). In this series, eight women were obese (including the two women who returned to hospital with infected wounds), six women were overweight and six women had a normal booking BMI.

Ambient conditions in the post-natal wards ranged from of 20.8^{o}C to 26.6^{o}C (median 24^{o}C) with relative humidity; 41 to 73% (median 52%) in still air (<0.02.sec^{-1}). All of the women were apyrexial at the time of thermal imaging; temporal artery temperatures between 36.2^{o}C to 37.3^{o}C (median 36.9^{o}C) (Table 1).

Edge analysis and quantitative temperature profiling

Temperature difference profiling is shown for 18 of 20 women (Fig 2C). Data for patient 20 (wound closed by staples) has been omitted. The profile for participant 1 is partly occluded by adjacent structures (hair). From the difference between healthy "reference" skin and scar/wound temperature (deltaT), pixel differences along the scar/wound margin (Fig 2c) differ, for the majority of women, by not more than 1^{o}C. In four participants (6, 9, 11, 16) deltaT reveals four predominately negative deltaT plots, indicating lower scar/wound temperatures of up to 4^{o}C. In two women, (participant 6, 16) the scar at days 15 and 11 respectively were infected. In participant 11, the scar at day 2 was "lumpy"; the low deltaT along the scar indicating that the scar edge was at a consistently lower temperature than adjacent healthy (reference) skin. Also noted in Fig 2C are intervals of a 2^{o}C deltaT for participants 9 (see also Fig 1). At this early time-point (day 2) the wound was not considered to be infected.

HCS isotherm boundaries and regions

Qualitative

In exploring HCS for thermal characteristics of the scar/wound encompassed by the ROI (see Fig 3A-C) multiple clusters and boundaries were evident on thermal mapping. With the grey scale FLIR palette providing the visual focus for the scar position on the lower abdomen (Fig 4), HCS isotherm boundaries were produced to show the variability of the thermogram for six women where different isotherm boundary maps can be characterised. HCS reveals the wide variability in thermal clusters that can be distinguished but which are not evident from the corresponding greyscale palettes (Fig 4).

Qualitative Review

1. Scar and adjacent skin clusters show an ROI where the scar and surrounding regions are virtually indistinguishable within a relatively uniform ('warm') thermal map (participant 18, OV).

2. Small 'islands' of slightly lower thermal values in scar are distinguishable within 'cool' adjacent thermal territories (participant 5, NORM)

3. Large clusters of lower thermal values are distinguishable within a 'warm' ROI (participant 6- wound infection day 11, OB)

4. Scar profile has higher thermal values than adjacent and surrounding regions (participant 7, OV)

5. The scar profile is indistinguishable on the black and white image and on HCS. The thermal profile of the scar merges with adjacent and surrounding (cool) skin (participant 8, OB).

6. The scar profile is evident on HCS and surrounded by three clear regions of low thermal values which visibly correspond to large areas where exudate has accumulated and surrounds a large area of denuded skin (participant 16-wound infection day 11).

To further categorise the thermal images, the infected wounds (at later times after surgery) have prominent ''cold spots' which are identifiable as a marked deltaT on scar boundary profiling (Fig 2C) and as notable clusters within the ROI commensurate with low thermal intensity on the colour palette (Fig 4). Of note is participant 9 (Fig 1) where the pattern features are similar to that observed in wound infection (scar line 'cold spots' within the ROI are noted at day 2- infection confirmed, day 9).

Quantitative Analysis

On temperature profiling, thermal intensity differences *between* reference pixel clusters and the pixel clusters of the scar/wound (see Fig 3 for sites selected) vary (Table 2). Four participants had large (approximately >2^{o}C) (negative) differences (Table 2) and these differences in thermal intensity correspond to the ''cold spots'' on FLIR images (Fig 1 A,B) and HCS (Fig 4). Three of the four participants with a large deltaT had a confirmed wound infection when re-admitted at day 11 (participant 6) and day 15 (participant 16). For participant 9, 'cold spots' identified early *via* IRTI at day 2, subsequently resulted in wound infection at home on day 9; breakdown of tissue occurring at the original 'cold spot' sites. Wound swab reports confirmed *Pseudomonas species* in the wound and with systemic symptoms of fever and malaise. For the fourth participant (11) with a large, negative thermal profile, follow up attempts proved unsuccessful. The eventual outcome of the wound in this participant could not be confirmed. For participants 6, 16, 9,11 the maximum negative difference between reference and scar for those women with and without confirmed/suspected SSI achieved significance p=0.006.

If the HCS pixel clusters are examined *along* and amongst the scar/wound (Table 3), once again the infected wounds of patients 6 and 16 and the scar region of participant 9 (later infected) show that large differences occur along the wound i.e. differences in each of the HCS pixel clusters in this discrete scar/wound area reach 3.5-4.9^{o}C. For women with small average differences between HCS pixel clusters *along* the scar, the scar region is virtually indistinguishable from the adjacent abdominal thermal territory (Table 3) as illustrated for participant 18 (see Fig 4, panel B) .

Narratives

Thematic content analysis of women's perspectives on the use of thermal imaging revealed four themes; recruitment, personal experience, perceived benefits and repeated imaging.

Recruitment

Women gave varied reasons for taking part in the study with the most common being an awareness of the need for medical research; with the specific research objective appealing to many of the women seen as worthwhile and providing possible future benefits. Respect for research and willingness to help in generating new knowledge were particularly important factors for women volunteering to participate in the study:

"Without research things cannot progress, so that's why I did it" [P002]
"It's a really good idea to detect whether infections are likely or not as they can be nasty" [P003]
"It's a study that my children could need the results for [P004]

The second main reason for taking part was a generalised desire to help others:
"I thought it was good to help someone else" [P006]

Women stated that they were mainly recruited at the preoperative clinic, receiving an information leaflet. Some also expressed their satisfaction at receiving full explanations from the doctors which impacted on their decision to take part in the study.

Women's views were sought about possible changes to recruitment and study processes for future trial development. Women had many ideas about how to improve study recruitment including having posters about the study and wound infection in the pre-operative clinic and in the unit. They suggested providing leaflets early on in pregnancy or when booking-in to have an elective Caesarean at about 36 weeks gestation as other information is provided at this point too. This would reassure women that the study will not involve time away from their baby. Two women would also have liked midwives to have been involved in study recruitment, not just doctors:

"Have something about the study while you wait (in pre-op clinic), a poster with some images of how it would look with a haematoma, normal, with an infection" [P005]
"I think get the midwife involved." [P019]

Personal experience of thermal imaging

When asked about their personal experience of the thermal imaging procedure the majority of the women described it as "fine", "good" or having "no issues" with it (n=19). One woman felt the procedure will be helpful, but didn't comment on her experience of undergoing thermal imaging. If thermal imaging was found to be effective and therefore offered to all women who had undergone a caesarean section; all of the participants said that they would accept it:

"I'd be fine with that - with the midwife doing it as part of care" [P017]
"I think it's good - to make it part of routine (care) after having a baby. It can't make anything worse having it done." [P003]

Women mainly described this technique as a non-invasive and straightforward approach. They commented on the safety aspect of the technique and that it is pain-free and harmless therefore a good option for future developments in infection screening:
"Yes - it's pain free so it's good" [P003].
"It's not invasive or painful" [P008]

"I don't know anything about thermal imaging - but it's non-invasive so that's good" [P004]

Three women specifically described the non-invasive nature of the research as influential in their decision to take part in the study:
"It's not affected me. It's not intrusive" [P016]
"I would have thought more if I had to take medication, but this is easy" [P015]
"There's no harm in it" [P020]

Perceived benefits

Women described many potential benefits of using thermal imaging routinely if it was found to be effective, with almost all of the women seeing a benefit to reducing the number or severity of infections. Women also saw a benefit of knowing their infection risk, starting treatment earlier, decreased morbidity and length of hospital stay and preventing the negative impact on maternal-infant bonding of having an ill mother.
"It is beneficial to find out and sort out infection earlier rather than later" [P011]
"Prevention is better than a cure, you don't get sick, you have a shorter hospital stay and a shorter recovery period." [P008]

By contrast none could think of a disadvantage to routinely using thermal imaging:
"I don't think there would be disadvantages, just advantages" [P007].

However two women did comment that although they did not mind the procedure themselves, they thought some women might be uncomfortable with it:
"I felt comfortable with the process - but some women might not as you are going through so much as you go through delivery anyway" [P015]

Repeat thermal imaging

One consideration in a future trial would be to do repeated images to assess wound progression over time. Women in principal did not seem to have any problems with having repeated imaging as long as it was helpful in improving health or preventing complications. Many women (n=9) understood the benefits of doing repeated images:
"It would give a better picture of before and after with multiple photos so it would give a better answer, so I can see the benefits of it" [P001]
"One issue is with new people seeing the wound, it's inconsistent they don't know what it was like before, whereas a picture would record what it has been like for everyone else to compare." [P016]
"Repeating it would be good as I can imagine that it (wound healing) varies from person to person." [P003]

Women commented on attention to the timing of imaging to ensure it is convenient and does not interfere with mothers resting or looking after their new born infant. Some expressed their lack of willingness to come back to the hospital for extra visits but were happy to have the imaging if it could be carried out at their home.
"It's not too hard - lying there having a photo done." [P006]
"Yeah I can't see a problem. It's a quick procedure." [P019]

"You would have to pick the right time around the baby, so not when it is due a feed so it's not too inconvenient" [P001]
"Follow up would have to be at home, it would be hard to get to the hospital." [P015]

Some women highlighted the possibility of discomfort and tiredness for mothers not being prepared to have imaging soon after caesarean section, with one woman feeling that an image would not have been possible on the first day after caesarean section as she was too tired and uncomfortable, but any time after that would be fine. However another woman was keen for images to start as soon as possible to enable the earliest possible identification of infection.

Women's general enthusiasm about the trial was evident in their final comments:
"I enjoyed it; it was a great experience" [P010]
"If it works – it'll be up and running when I have my next one!" [P009]
"It would be a great idea to roll out to other major operations too." [P019]

DISCUSSION

The study explores feasibility of a novel approach to non-invasive imaging of the surgical scar in a population of women undergoing elective caesarean section. This research is the second in a series of observational studies examining the potential for IR thermal imaging in wound surveillance. The aim being to characterise the temperature map and thermal profile of abdominal wounds. In the first series, IR thermal imaging was undertaken daily in a mixed population of patients with disease (colorectal cancer) after surgical closure of enterostoma.[17] In this, the second series, a mixed cohort of apparently healthy women were studied at early times after caesarean section birth. In both cohorts we have observed features of the thermal map which emerge as potential candidate biomarkers of infection risk; 'cold spots' along the surgical scar. At later times (week 2) skin breakdown, granulation tissue and purulent exudate appear on IR imaging (and profiling) as either discrete cold spots or as larger contiguous regions (arising from the original scar). It is our hypothesis that surveillance of wounds must start early and before the appearance of purulent exudate; the hallmark of infection on clinical wound scoring systems.[22,23]

Surgical site infection is a common complication which increases the risk of morbidity. In English hospitals participating in the Nosocomial Infection National Surveillance Service (NINSS) limb amputation (14.3%) and bowel surgery (10%) had the greatest incidence of SSI.[24]. Incidence of SSI in caesarean section were not included, yet recent evidence suggests that for apparently healthy women delivering by caesarean section birth, the rate of SSI at 9.6% is as high as for bowel surgery, despite this type of surgery being considered 'clean'. The rate of wound infection was higher than expected [15] from earlier data. [25] Of the women who participated in the study, 98% received antibiotic prophylaxis.[15]

Antibiotic therapy in confirmed infection has long been the mainstay for treatment in infective conditions, but what of antibiotic prophylaxis? Here prescribing on the basis of 'just in case' is now a cause for concern. It is a practice which leads to 'overprescribing', a healthcare problem which is now the subject of a Government Review. [26] However, as antibiotic prophylaxis in obese and morbidly obese patients undergoing surgery is commonly prescribed, often with higher dosing [27] antibiotic prescribing, in the absence of confirmed infection is likely to rise further as the population of obese adult's reaches epidemic proportions.[16] It would therefore be expected that the numbers of obese women of child bearing age will rise also.

Clinicians recognise the potential hazards that obesity brings to childbirth.[28] The increase in Caesarean section delivery *per se* has been linked to overweight and obesity.[16] In the UK, Caesarean births increased from 9% (1980) to 25% in 2008-2009.[29] Worldwide, caesarean section is the most common surgery performed in women[30], but complications such as infection do arise. Rates of post-caesarean infection (endogenous and exogenous) are an estimated 10 times greater than for vaginal birth [31] and between 3-15% of women will develop a wound infection. For obese women delivering by caesarean section, the rate of infection increases two-fold with each five-unit increase in BMI > 25 kg/m^2. [32] In morbidly obese women with BMI ≥50kg/m^2, over 30% developed wound complications.[33] The increased risk for infection in obese women is suggested due to the relative avascularity of adipose tissue. Technical difficulties of handling adipose tissue (i.e more traumas to the abdominal wall) may also play a role.

In modern times the most important factor in infection reduction is antibiotics. In the Cochrane review of 2010, Smail and Gyte [34] investigated the role of antibiotic prophylaxis *versus* no prophylaxis for preventing infectious complications after caesarean section which included 86 studies involving 13000 women. With regard to wound infection, the review showed that overall risk ratio, 0.39 (CI 0.32, 0.48) favoured antibiotics despite numerous studies showing no clear benefit. But what of the value of prophylactic antibiotics for wound infection reduction in the high risk, obese and morbidly obese groups?

Yeeles *et al* [35] have shown, in a population of morbidly obese women (BMI ≥40kg.m^{-2}) undergoing Caesarean section delivery, that 51% developed a wound infection within 6 weeks of surgery. Infections were highest in the emergency surgery group. All women received intravenous antibiotics at induction of anaesthesia and 66% post-operatively (oral route). Prophylactic antibiotics did not reduce the infection risk in this group of women. This raises a question regarding the effectiveness of antibiotic prophylaxis and whether antibiotics are being prescribed appropriately and in correct doses. Swank *et al* [27] suggest that higher doses are required in women with a BMI greater than 30 kg/m^2 but would this represent an example of needless excess in antibiotic prescribing? More importantly, what alternative is on the horizon to aid a more 'tailored' approach to prescribing, especially in the light of current concerns to preserve the precious armamentarium of antibiotics?

One possibility is to profile the characteristics of wound healing in an effort to stratify patients to high and low risk on the basis of scar/wound profiling. Currently there are a limited number of scoring systems for wound infection. [23] The CDC criteria, considered to be the gold standard, require the appearance of purulent exudate and microbiology findings for infection diagnosis. For surveillance of risk after caesarean section, these criteria occur as late events. What is needed for a greater understanding is a profile of the new scar up to the point of skin breakdown and evolution of the wound. In this study we have profiles of the scar at day 2 (at which point women are discharged from hospital) and at the point of fulminant wound infection when the woman returns to hospital).

By studying the scar, and later the wound, at these time-points we have progressed our original (descriptive) observations to the development of a stepwise approach to quantitative scar/wound profiling. Importantly, we have reproduced the key characteristics of our original findings in a different population of surgical wounds; caesarean section. We have devised further qualitative approaches to describe the scar and adjacent thermal territories as well as the development of an algorithm to profile the thermal characteristics. It is clear that by segmentation of thermal data (scar and immediate adjacent territory) the ROI has a mosaic of thermal values that are undetectable using proprietary software. The composite regions of infrared radiation values provide a visual map of pixel clustering. In addition the thermal profiles for the new scar (day 2) and later (11, 15 day) infected wounds highlight the wounds where infection is confirmed. In this study we have examined feasibility of testing the hypothesis that scar line cold spots predominate in infected wounds and we have examined this by developing an automated "abnormalities" detection system. Here we posit that the "abnormality" of interest are discrete areas of low thermal intensity (cold spots) on an otherwise 'warmer scar' line or lower abdomen adjacent thermal territory.

It is accepted that the intensity of thermal radiation detected by the IR camera will depend upon surface properties, surface orientation and wavelength, (which are not necessarily uniform across the wound surface). We have attempted to overcome this by the HCS process[21] because HCS clusters pixels at hierarchical levels of allowable dissimilarity instead of a single threshold. HCS is a highlighting process well suited to thermal imaging.

Whilst the population of women in this cohort were recruited specifically to allow scar profiling across the BMI categories we have observed quantitative measures from the DeltaT algorithm which fit with our previous qualitative observations; that infected wounds are colder than healed wounds. We have also shown that: a) the scar during the first two days after caesarean section typically differs from (healthy skin temperature) reference by not more than 1^{o}C and b) that of four women with a negative scar profile (scar lower than reference temperature) in excess of 2^{o}C, two profiles were from obese women admitted late with an infected wound and one, of two participants at day 2 (the second not available for follow up) subsequently developed a wound infection. Based on our past and current observations, identifiable thermal cold spots on HCS and on deltaT quantitative profiling is a probable early ‘’flag” for SSI risk.

The authors recognise that there are limitations with the study, notably the sample size. Evens so, we have observed differences in IR radiation intensity (and temperature) (i.e. cold spots) which could potentially represent a means to stratify women to high and low SSI risk categories. In this and past studies, we have observed low thermal intensity spots in wounds where confirmation of infection is later confirmed. In the present study we have been able to follow up one of two participants with scar line cold spots and a large (>2^{o}C) deltaT at day 2, and wound infection was confirmed by day 9. It is also recognised that further work is needed in the development of this new concept for wound surveillance. This is now ongoing as we follow up the progress of wound healing from day 2 onwards in a larger population of women. Our next step is to close the current gap in knowledge of the thermal profile and scar characteristics between early times when the scar is beginning to heal through to later times (end of weeks 2 to 3) when wound breakdown and infection warrants medical attention.

Future Research

Would this technology be acceptable? From the responses of the women studied, the opinion is unanimous; IR thermal imaging as a non-invasive imaging technique for wound surveillance in obstetrics and maternal health is feasible and practical in the clinic. Most important for the new mothers is the potential for a quick method for early infection risk surveillance without the need to touch the tender wound.

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Declaration of Interest

All the authors confirm that there is no conflict of interest in the design, conduct and presentation of the research

	Age years	*Race	Parity	Previous C-section	Booking Category BMI ┼		Infant	Blood Loss	Days after surgery IR image taken	Body Temp (°C)	Ambient (°C)	RH %	SSI	Comments
1	38	WB	2	0	38.02	OB	M	601	2	37.1	24.0	45	N	Scar line not clearly visible due to other structures
2	29	I	2	2	22.0	N	M	600	2	37.0	24.8	49	N	
3	37	WB	3	0	31.4	OB	F	301	2	36.2	25.2	47	N	
4	30	I	3	3	25.2	N	M	600	2	37.1	26.4	47	N	
5	34	I	2	0	23	N	F	600	2	37.2	26.6	44	N	
6	28	WB	7	0	30	OB	M twins	N/A	11	37.1	24.1	52	Y	Confirmed SSI -day 15
7	28	S	2	1	27	OV	F	N/A	2	36.3	23.2	53	N	
8	36	WB	1	0	30.0	OB	F	N/A	2	36.9	24.1	41	N	
9	38	WB	2	0	29.2	OV	M	400	2	36.7	23.4	51	N	Confirmed SSI -day 9 *Pseudomonas Species*
10	35	P	2	1	21.3	N	M	405	2	36.8	25.7	42	N	
11	24	WB	5	3	32	OB	M	N/A	2	36.9	25.8	58	N	3 previous C-sections- one previous SSI. Not available to follow up
12	33	WB	2	1	23.9	N	F	401	2	36.6	24.5	58	N	
13	28	WB	2	0	24.7	OV	M	2000	2	37.2	24.4	62	N	
14	33	WB	2	2	37	OB	F	301	2	37.0	23.2	58	N	
15	37	I	2	1	27	OV	F	400	2	36.7	21.7	73	N	
16	38	WB	1	0	30.8	OB	F	1500	15	36.8	20.8	57	Y	*Conformed SSI -day 11*
17	29	WB	3	2	32.3	OB	M	201	2	36.9	22.8	56	N	
18	23	WB	0	0	27	OV	F Twins	600	2	37.3	22.6	55	N	
19	39	WB	1	0	29.7	OV	M	201	2	37.0	22.7	47	N	
20	20	WB	4	2	26.8	OV	M	300	2	36.9	21.6	57	N	Surgical staples used to close wound

Table 1: Patient demographics, body mass index, body temperature and ambient conditions at the time of thermal imaging of infected and non-infected C-section surgical site

*WB, White British; I, Indian; S, Somali; P, Pakistan . N/A; not available: ┼:BMI Category- N, Normal, OV, overweight; OB, obese; SS1, surgical site infection

	Maximum Negative Difference °C	Average Negative Difference °C	Maximum Positive Difference °C	Average Positive Difference °C
Pt_01	Scar- view obstructed by adjacent structures			
Pt_02	1.4 (183, 106)	0.41	0.4 (127, 104)	0.17
Pt_03	1.6 (165, 119)	0.34	1.2 (80, 124)	0.63
Pt_04	0.3 (166, 137)	0.31	2.5 (57, 130)	1.50
Pt_05	1.7 (185, 113)	0.57	1.0 (228, 107)	0.35
Pt_06	3.1 (112, 124)	0.76	0.4 (153, 118)	0.26
Pt_07	0.0	0.0	3.4 (206, 128)	2.11
Pt_08	0.1 (224, 150)	0.05	2.1 (272, 149)	0.84
Pt_09	2.3 (151, 133)	0.97	0.9 (73, 137)	0.36
Pt_10	0.1 (102, 123)	0.08	1.7 (145, 121)	0.85
Pt_11	1.7 (193, 14)7	0.84	0.4 (62, 143)	0.26
Pt_12	1.6 (32, 158)	0.53	1.1 (121, 171)	0.45
Pt_13	0.7 (97, 174)	0.24	0.6 (217, 181)	0.31
Pt_14	0.6 (69, 96)	0.22	2.1 (140, 117)	1.19
Pt_15	0.4 (181,155)	0.14	2.9 (62,136)	1.10
Pt_16	3.2 (217, 140)	0.93	3.3 (106, 137)	0.85
Pt_17	0.1 (224, 132)	0.06	2.4 (51, 141)	1.02
Pt_18	0.3 (179, 134)	0.15	1.3 (120,134)	0.15
Pt_19	0.8 (246, 139)	0.25	1.1, (209, 152)	0.47
Pt_20	1.8 (179,137	0.80	3.1 (33, 132)	1.60

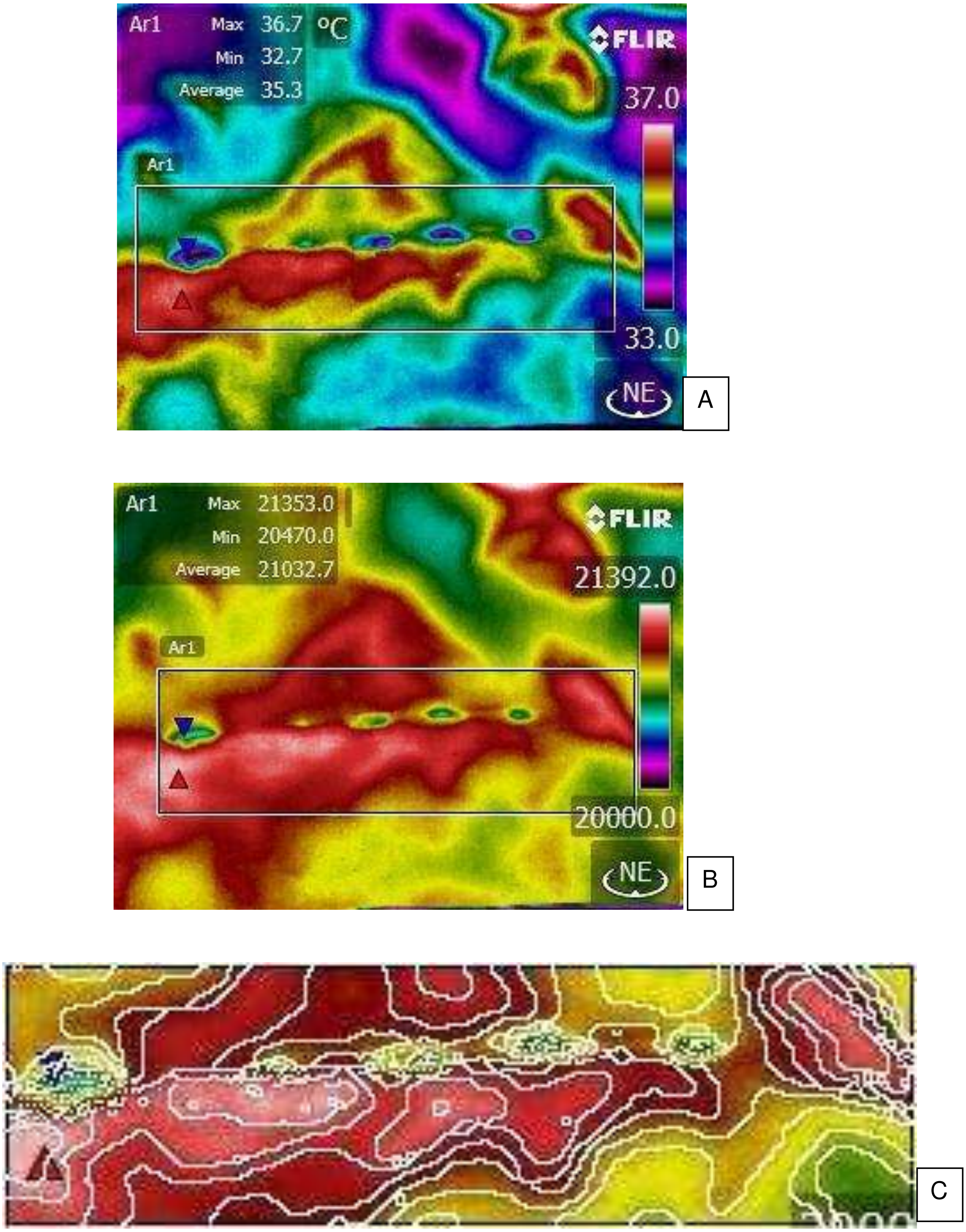
Table 2: Participant, thermal values between skin 'reference' and the scar/wound.

For each participant, thermal value differences for "reference" minus scar/wound are reported with corresponding ROI co-ordinates in parenthesis. For maximum and average (negative) deltaT values scar is lower than reference thermal values at a given ROI co-ordinate. For maximum and average positive differences, scar/wound has higher thermal values compared to "reference" at corresponding ROI co-ordinates. Note- for participant 20: incision closed with metal ‘clips’.

	Temperature (^{o}C)				
Case	Minimum	Maximum	Average	Maximum Difference	Average Difference
Pt_01		Scar obstructed by adjacent structures			
Pt_02	34.0 (183, 106)	35.6 (111, 102)	35.04	1.6	0.42
Pt_03	34.7 (122, 116)	36.5 (143, 116)	36.07	1.8	0.26
Pt_04	33.1 (166, 137)	35.4 (57, 130)	34.36	2.3	0.43
Pt_05	33.4 (185, 113)	34.8 (104, 114)	34.2	1.4	0.44
Pt_06	33.0 (112, 124)	36.5 (159, 117)	35.31	3.5	0.75
Pt_07	32.9 (95, 133)	35.7 (149, 133)	34.93	2.8	0.67
Pt_08	33.8 (224, 150)	35.4 (54, 163)	34.61	1.6	0.32
Pt_09	32.6 (39, 142)	35.8 (73, 137)	34.47	3.2	0.90
Pt_10	34.6 (103, 124)	36.4 (146, 122)	35.73	1.7	0.41
Pt_11	32.6 (191, 147)	35.1 (60, 146)	33.86	2.5	0.58
Pt_12	33.8 (59, 167)	35.4 (197, 170)	34.74	1.6	0.46
Pt_13	34.6 (274, 166)	35.7 (160, 183)	35.27	1.1	0.27
Pt_14	34.2 (69, 96)	36.1 (142, 117)	35.46	1.9	0.44
Pt_15	34.6 (103, 150)	35.8 (24, 115)	35.30	1.2	0.29
Pt_16	30.9 (130, 138)	35.8 (105, 137)	33.78	4.9	0.87
Pt_17	33.3 (224, 132)	35.4 (203, 134)	34.56	2.0	0.60
Pt_18	35.8 (60, 128)	36.5 (109, 133)	36.15	0.8	0.26
Pt_19	35.8 (180, 160)	36.9 (260, 133)	36.47	1.0	0.24
Pt_20	31.6 (179, 137)	34.9 (33, 132)	33.19	3.4	1.14

Table 3: Participant, thermal values *along* and *amongst* the regions of the scar/wound.

Table shows the minimum, maximum and average temperature values of cluster of pixels along and amongst the scar/wound. Also shown are the maximum and average temperatures calculated by comparing the differences between each of the different pixel clusters.
Note-patient 20; incision closed with metal ‘clips’. For estimating the values in both Table 2 and Table 3 the regions on and around the 'clips' were avoided/rejected.


Ar1 Max 36.7 °C
Min 32.7
Average 35.3
FLIR
37.0
Ar1
33.0
NE
A
Ar1 Max 21353.0
Min 20470.0
Average 21032.7
FLIR
21392.0
Ar1
20000.0
NE
B
C
Fig 1

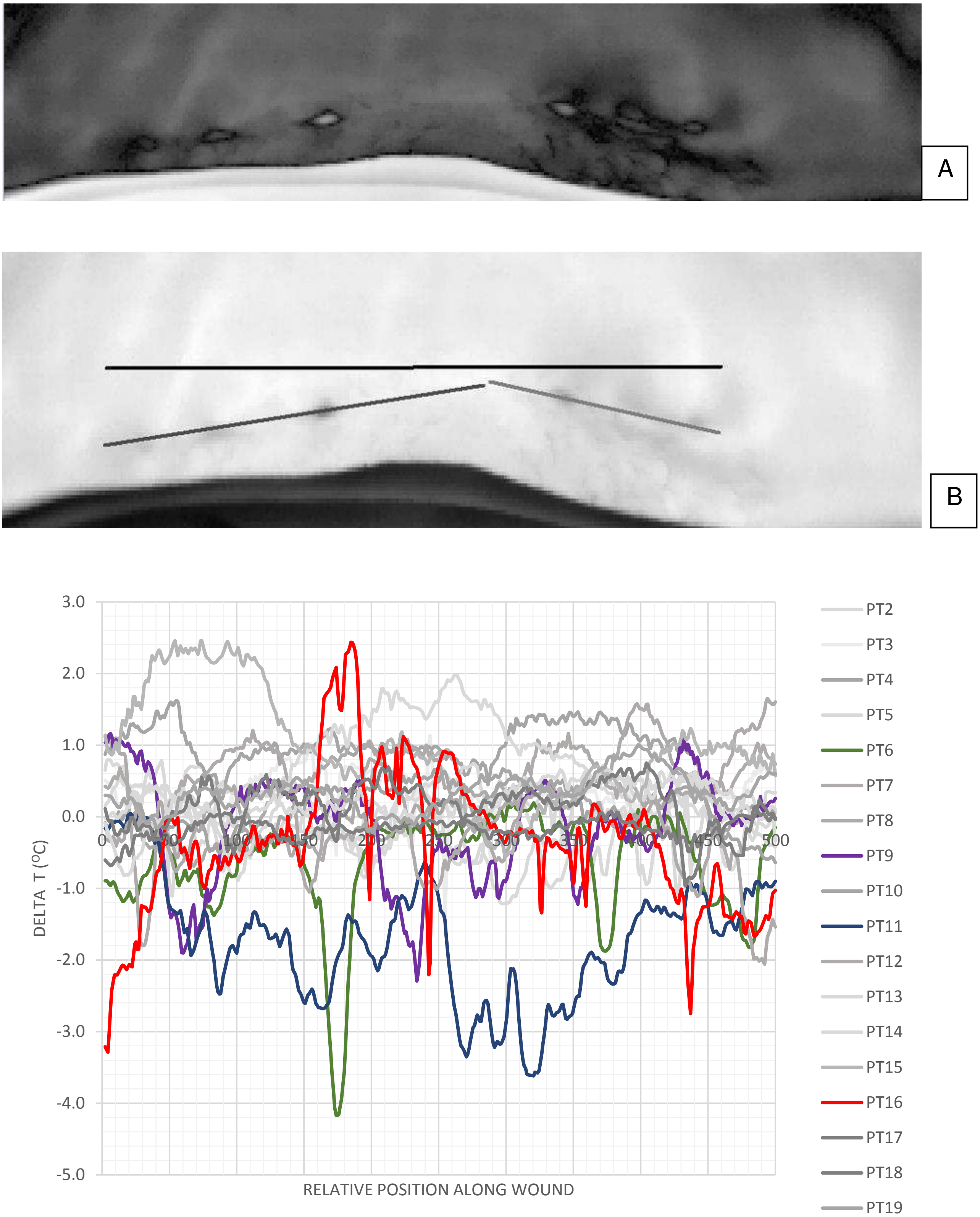

A
B
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
0
50
100
150
200
250
300
350
400
450
500
DELTA T (ºC)
RELATIVE POSITION ALONG WOUND
PT2
PT3
PT4
PT5
PT6
PT7
PT8
PT9
PT10
PT11
PT12
PT13
PT14
PT15
PT16
PT17
PT18
PT19

Fig 2

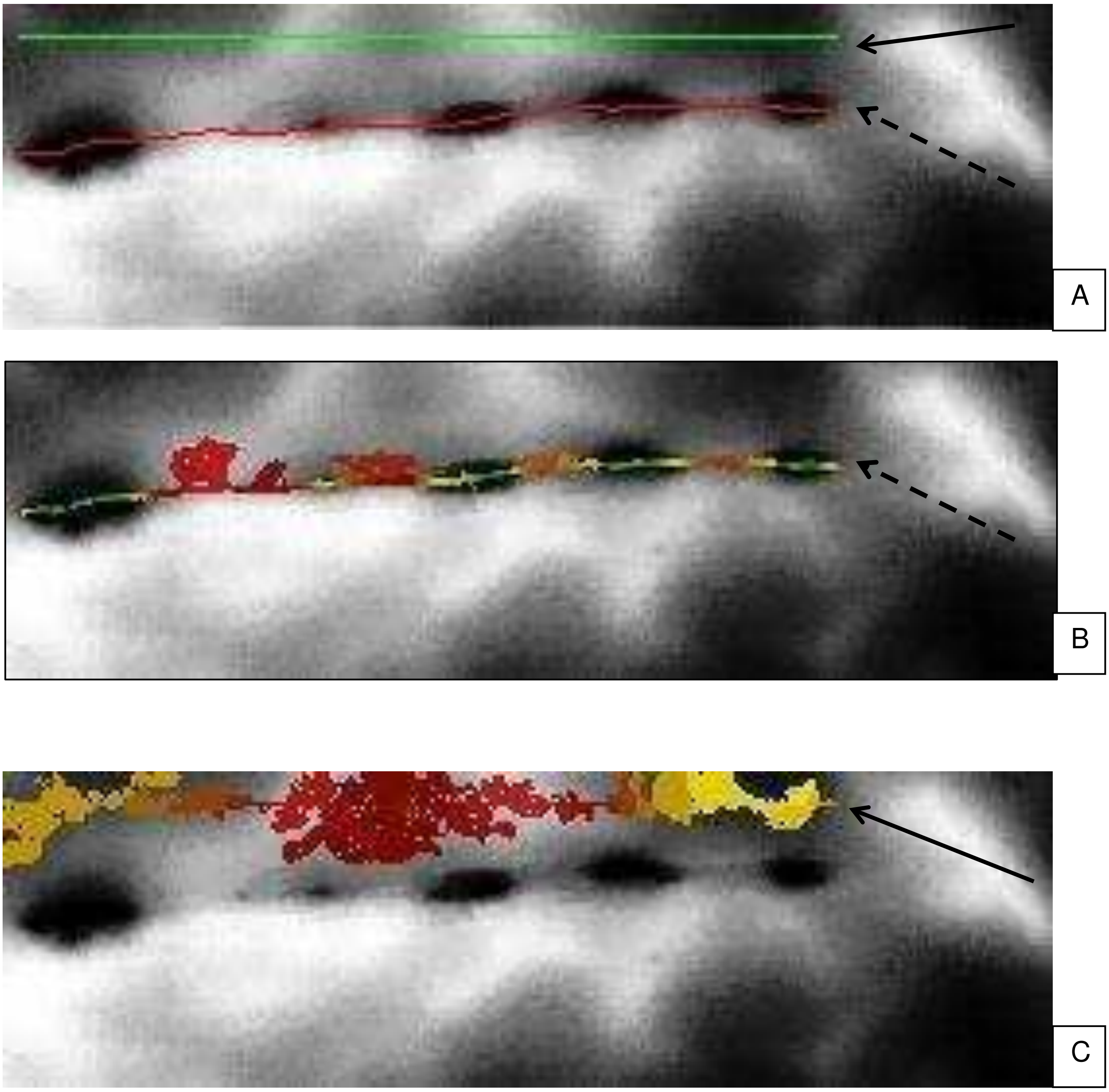


Fig 3

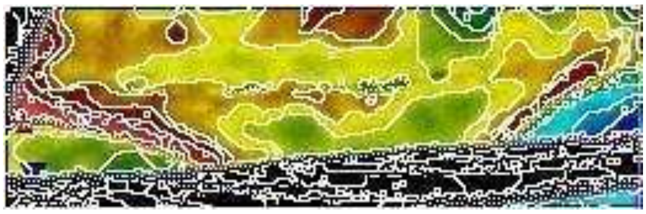
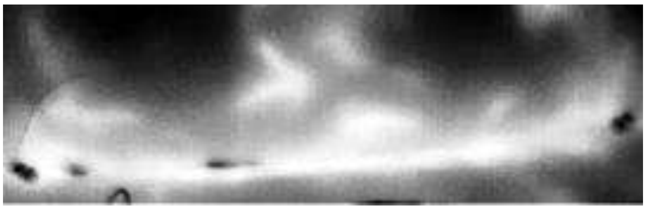
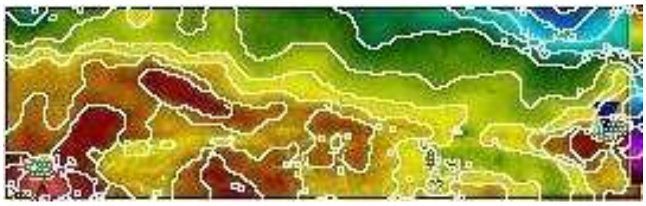
Case	Thermal Image A	Isotherms B
Pt_01		
Pt_05		
Pt_06		
Pt_07		
Pt_08		
Pt_16		
Pt_18		

Fig 4

Figure Legends

Fig 1.
Thermal image data with rectangular ROI superimposed on the image is displayed using Rainbow HC colour palette. For colouring, thermal data is scaled between the temperature value range 33-37^{o}C (A) and between the radiometric value range 20000.0 to 21392.0 (B). Making use of the same colour palette, HCS major segmented regions have similar temperature ranges and are outlined using isotherms (white boundaries) (C). In each of A,B,C, five identifiable areas can be observed as 'cold spots' where surface temperatures are lowe (minimum temperature, blue arrow) approximately 4^{o}C lower than adjacent thermal territories (36.7^{o}C, red arrow). HCS, at a "fine" level of dissimilarity (15%) has successfully outlined the ROI isotherms as well as the isotherm 'cold spots'.

Fig 2

Greyscale enhancement and edge detection (A) for ROI of participant 6 (wound infection at day 11) and B, position of reference (top) and scar (bottom) lines used in the analysis for graphical representation (C) of deltaT values (^{o}C) for 18 women. Negative deltaT values of 2-3^{o}C are evident for two participants with confirmed wound infection, green, (participant 6) and red (participant 16). For participants 11 (blue) and 9 (purple) scar thermal profiles at day 2 also show low deltaT values (for explanation-see text).

Fig 3

Graphical representation of the method used for the HCS analysis. In this example (patient 9) a healthy skin 'reference line' (A,⟵) is placed at a site above the scar and a second line over the course of the incision (A,← – –). Using an HCS segmentation level (10% in this application) pixel clusters along scar line are identified (B) as are the pixel clusters of reference (C). For pixel cluster differences between skin "reference" and scar/wound - see Table 2

Fig 4

Typical examples of greyscale image (panel A) of scar site at day 2 (patients 1,5,7,8,18) and at day 11,15 for participants 6,16 (infected wounds) respectively. Panel B shows the corresponding HCS isotherms where regions of similar temperature profiles are evident. Pixels of similar thermal intensity appear as the same colours. Fig 4 also highlights the more subtle gradations of thermal values within each isotherm which are not apparent using standard FLIR palette (in this example, panel A) on greyscale.

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