An observational study of temperature and thermal images of surgical wounds for detecting delayed wound healing within four days after surgery

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An Observational Study of Temperature and Thermal Images of Surgical Wounds for Detecting Delayed Wound Healing within Four Days after Surgery

Abstract

Aim: This study aimed to elucidate the infrared thermal patterns and temperature readings of the surfaces of surgical wounds for detecting delayed wound healing within four days after surgery.

Background: The nursing assessment of surgical wounds within the first four days after surgery is commonly based on visual and physical examination. Surgical wounds with delayed healing may be not detected if they do not exhibit signs such as redness or exudate within four days after surgery.

Design: This study was conducted using prospective observational design with reference to the STROBE Statement to examine the temperatures of surgical wounds in their natural settings.

Methods: Based on convenience sampling, 60 participants admitted to the colorectal surgical ward for enterostoma closure from January to November 2013 were recruited.

Results: Although both infected and non-infected surgical wounds exhibited a significant increase in wound temperature from Days 1 to 4, the infected wounds revealed a statistically significantly lower temperature than the non-infected ones. Within the infrared thermal images, the infected wounds presented with partial warming of the skin surrounding and along the incision, suggesting that delayed healing could be identified.

Conclusion: This study demonstrates that delayed wound healing can be detected within the first four days after surgery for early intervention of prevention and treatment before discharge.

Keywords (MESH Terms): Infrared, Spectrophotometry, Surgical-site infection, Surgical-wound infection, Thermography

Relevance to Clinical Practice

What does this paper contribute to the global clinical community?

- This paper provides evidence-based information for healthcare professionals in assessing surgical wounds for delayed healing within the first four days after surgery.
- The findings herein enables the early detection of delayed wound healing, based on which early intervention of prevention and treatment may be instituted for affected patients before their discharge.

Introduction

Surgical-site infections have been reported to be one of the common healthcare-associated infections, affecting almost one third (31%) of hospitalized patients (Centers for Disease Control and Prevention, 2015), with 49% to 84% of surgical-site infections left undetected for discharged patients (Smith et al., 2004; Sands et al., 1996). The sequela is that patients are burdened with greater healthcare costs associated with more medical interventions and higher healthcare maintenance (DiPiro et al., 1998). Two established tools, the ASEPSIS scoring system and the United States Centers for Disease Control (CDC) criteria, are available for assessing surgical-site infections (Siah, & Childs, 2012). However, both tools met limitations in detecting infections early. A study on 4773 patients has detected an incidence of 19.2% for surgical-site infections with the CDC criteria but only 6.8% with the ASEPSIS scoring system, revealing substantial differences in the infection rates (Wilson et al., 2004). Practical problems also exist: nurses met challenges in detecting surgical-site infections due to differing perceptions and assessment approaches to the key wound parameters such as the description of wounds (Greatrex-White, & Moxey, 2013; Keast et al., 2004). It has been reported that, in practice, the documentation of wound beds, dimensions, exudates, state of surrounding skins, and skin sensations were recorded for less than 5.0% of patients after surgery (Garland et al., 2010). Without a definitive, objective detection method to assess the surgical wound for delayed healing, the phenomenon of patients being discharged to their community with undetected surgical-site infections will continue, resulting in delayed treatment, longer medical interventions, higher healthcare maintenance, and associated healthcare costs (Wick et al., 2008; Weiser et al., 2008; Jarvis, 2007; Sands et al., 2003; DiPiro et al., 1998; Sands et al., 1996).

Background

The elucidation herein of temperature changes of non-infected and infected surgical wounds is founded upon the works of Rubner to utilise ‘calor’ (Walter, 1992), the Latin word for “heat,” as a putative thermal measure for early assessment of surgical-site infections. In the thermal setting of surgical-site infections, leucocytes produce 9.1 μW to 28.4μW of heat during phagocytosis (Shimoyama et al., 1991; Hayatsu et al., 1988). However, assessment of surgical-wound temperatures depends on the sense of touch, which thereby introduces subjectivity. Therefore, to measure the heat emitted from the skin surface based on the degree of tissue vascularity (Bentley, 1998; Max, 1991), infrared thermography was employed. The human skin, which is capable of emitting 98% of its heat, produces a reliable measurement of the emitted heat as it could be translated into actual quantifiable temperature values in degree Celsius by the thermal detector (Calixto-Carrera et al., 2009).

Aim and objectives

This study aimed to elucidate the infrared thermal patterns and temperature readings of surgical-wound surfaces for detecting delayed wound healing within four days after surgery. The objectives were as followed:

1. To observe the abdominal skin surface temperature readings of non-infected and infected abdominal surgical wound surfaces in the first four days after abdominal surgery.
2. To elucidate the infrared thermal patterns of non-infected and infected abdominal surgical wound surfaces in the first four days after abdominal surgery.

Method

Study design

This was an extended study from a previous pilot report on ten patients to affirm the findings therein (Siah & Child, 2015). In this study, the abdominal surgical wounds were observed to provide a detailed description of their temperature readings and infrared thermal patterns through a prospective observational design with reference to the STROBE Statement to examine the temperatures of surgical wounds in their natural settings (See supplementary file). Ethics approval was obtained from the Centralized Institute Review Board (CIRB).

Study setting

The study was conducted from January to November 2013 in a 53-bed surgical ward of a tertiary hospital, with a specialized department for colorectal surgery. Surgical patients admitted to the ward were assessed for eligibility; those meeting the inclusion criteria were given an explanation of the study, duration and frequency of visits before written consent was acquired. Given its observational nature, the study introduced no changes to the medical and nursing pre- and post-operative care (e.g. daily wound dressing and oral analgesia), regardless of whether the patients participated in the study.

Upon recruitment, the participants were given an explanation of the study. On the first visit (before surgery), their demographic, clinical data, and infrared thermal images of the abdomen were taken. After surgery, they were visited daily until either the fourth day after surgery or discharge, whichever was earlier, to obtain temperature readings and infrared thermal images of the abdominal surgical wounds. A phone call was made on the seventh day and the thirtieth after surgery to interview them on their wound condition according to the CDC guideline.

Participants

Convenience sampling was used in this study to identify participants from the inpatient elective list. The inclusion criteria were adults of 21 years of age requiring enterostoma closure. Surgical patients were excluded if they had co-morbidities that might alter the abdominal skin surface temperature, intra-abdominal drains, or skin inflammation and scar formation, and with limited mental capacity of potential participants.

Variables

Variables of interest included the demographic data (age, sex, and ethnicity) and clinical data (body mass index, abdominal girth, thickness of adipose tissues, abdominal skin surface temperature, body 'core' temperature, co-morbidities, type and site of enterostoma closure). The temperature readings and infrared thermal patterns of the enterostoma were also collected. The main outcome of this study was the occurrence of surgical-site infection, as diagnosed based on the CDC criteria: purulent exudates, a systemic fever of more than 38°C, site pain, tenderness, localized swelling, redness or heat within 30 days after surgery (Horan et al., 2008).

Data measurement

The technical set-up of the infrared thermal camera for imaging was referenced from the standard procedure for infrared thermal imaging in clinical practice (Ammer & Ring, 2008). The emissivity of the camera was set at 0.98 (Calixto-Carrera et al., 2009). Ambient conditions of the clinical room – such as relative humidity (in percentage), air velocity, and room temperature – might affect the absorption of optical radiation (Larkin, 2011; Stuart, 2004; Gaussorgues, 1994; Nicolai, 1956) through conduction and convection (Max, 1991). Therefore, these parameters were monitored with the Hot-Wire Anemometer, model TES-1341 (TES Pte, Taipei).

Bias

Being an observational study in nature is prone to broad types of bias (Nikolaos, 2014). As this study was directed towards wounds in the colorectal-related abdominal region, it therefore may cause a selective bias and may reduce the external validity. To reduce the effect of recall bias, all required data were closely monitored and recorded timely by the investigator within ethical boundary of this study.

Study size

The incidence of surgical-site infection after enterostomas closure has been reported to range from 2% to 41% (Tan et al., 2012; Li et al., 014). Therefore, a sample size of 61 participants was calculated based on the population proportion formula $(Z_{\alpha/2})^2 * P(1-P) * 1/E^2$, where $Z_{\alpha/2}$ was for a 5% level of significance, P was the estimate for a 20% surgical-site infection rate, and E was the 5% margin of error at the 95% confidence level (Suresh, & Chandrashekara, 2012). Given the anticipatory allowance for a 10% refusal and withdrawal rate, the final sample size was 68 participants.

Quantitative variables

At the outset, all infrared thermal images in each phase were coded individually and saved systematically in the database for analysis and processing. They were then categorised into infected and non-infected abdominal surgical wounds based on the CDC criteria. Before analysing the temperature readings from the images, ambient parameters and distances were entered into the Research IR software settings (FLIRSystems Inc., Sweden) to reflect the true temperature readings.

Upon the extraction of temperature readings from the infrared thermal images, the images were subjected to simplification through the thresholding method to detect for anomalous pixel spectra and diverse instrumental artefacts. This was followed by the conversion and computation of the infrared thermal images by the Multivariate Image Analysis approach to differentiate the temperature differences and, in turn, by a second inspection for anomalous pixel spectra (Wise, & Geladi, 2000). Finally, the temperatures were adjusted manually to span the range from 30°C to 38°C to ensure a uniform comparison across images during mapping. Given the standardised temperature range in this study, each colour unit ran from the lowest temperature to the highest in sequential shades of purple, blue, green, yellow, red and white (in that order). Three of the six colours – purple, blue and green – were matched by the infrared thermal device to the temperature range from 30°C to 34.9^0C and were referred as the 'cold' colours in this study. The others – yellow, red and white – were matched to the range from 35°C to 38°C and were referred as the 'warm' colours. Collectively, these colours formed the infrared thermal patterns of the infected and non-infected surgical wounds to elucidate the pathophysiology of tissue injury in this study.

Statistical methods

Statistical analysis of the participants' demographic and clinical data was performed with the SPSS Statistics version 20. The frequency distributions were used to describe categorical data including sex, ethnicity, type of surgery, and site of surgical wound, whereas the means and standard deviations were used to describe continuous data including age, body mass index, abdominal girth, thickness of adipose tissues, abdominal skin surface temperature, length of hospitalization, and days taken to diagnose surgical-site infections based on the CDC criteria. To discern differences in the inter-day temperature readings (i.e. for each day from Days 0 to 4) for both non-infected and infected abdominal surgical wounds, the Friedman test was used. To discern differences in the surgical-site temperatures between non-infected and infected surgical wounds on each day from Days 0 to 4, the Mann-Whitney U test was used. The level of statistical significance was set at $p < 0.05$.

Result

Participants

During the screening for eligibility, 71 participants admitted for enterostoma closure were approached. One participant with a dry, flaky skin condition over his abdomen and three participants who required additional surgical interventions were excluded from the study. Three participants rejected the invitation, leaving 64 participants enrolled for the study. During data collection, one participant dropped out from the study due to anastomotic leak and three participants were non-contactable upon discharge (Figure 1), leaving 60 participants for analysis in the study.

During the data collection, the immediate transfer of three participants to the high-dependency unit after surgery (Day 0) rendered them temporarily unavailable. They were transferred back to the general ward on Day 1 and the data collection resumed. On Day 3, two participants were discharged; on Day 4, another eight participants were discharged. On Days 7 and 30, follow-up calls on all the 60 participants' surgical wounds were made (Figure 1).

Descriptive data

The participants consisted of 27 females and 33 males aged between 47 and 82 years (mean = 65.22, SD = 9.29). A total of 53 (88.40%) of them were Chinese, followed by five (8.30%) Malays and two (3.30%) others (Table 1). Based on the CDC criteria, 15 participants (25.0%) developed surgical-site infections, as was within the range of incidence (2% to 41%) of such infections after enterostomas closure reported in the literature (Tan et al., 2012; Li et al., 2014). No statistically significant differences were detected for both demographic and clinical data between participants with and without surgical-site infections (Table 1). The Friedman test and Mann Whitney U test were used due to a violation of the assumption of normality ($p < .001$).

Outcome data

The median and interquartile range (IQR) values of the temperature readings of the abdominal surgical wounds were analysed for differences. For participants with surgical-site infections, the median body core temperature is 36.4°C (IQR = 36.1°C–36.7°C) (mean = 36.3°C, SD = 0.4°C). For those without, it is 36.4°C (IQR = 36.2°C–36.7°C) (mean = 36.4°C, SD = 0.3°C). For non-infected surgical wounds, the median skin surface temperature readings taken from Days 0 to 4 ranged from 33.8°C to 35.7°C (mean range = 33.9°C to 35.6°C). For infected ones, they ranged from 33.8°C to 35.6°C (mean range = 34.1°C to 35.4°C) (Figures 2a and 2b).

Main results

In the Friedman test, a statistically significant difference was observed for the skin temperatures taken across the five-time points ("Day 0" to "Day 4"), $\chi 2$ (4, n = 12) = 14.8, $p < 0.005$ for infected surgical wounds. Inspection of the median values reveals a progressive elevation in the median temperature from Day 0 to Day 4 after surgery (Table 2). Likewise, a statistically significant difference was observed for the wound temperatures taken across the five-time points ("Day 0" to "Day 4"), $\chi 2$ (4, n = 39) = 54.1, $p < 0.001$ for non-infected surgical wounds. Inspection of the median values also reveals a progressive elevation in the median temperature from Day 0 to Day 4 after surgery (Table 2).

In the Mann Whitney U test, no statistically significant difference was observed in the temperature readings on Day 0 (immediately after surgery), on Day 3 and on Day 4 after surgery, between participants with non-infected surgical wounds and those with infected ones. However, statistically significant differences were detected in the highest temperature readings of the surgical wounds on Day 1 (U = 211.5, Z = –2.15, *p* = 0.03, r = 0.27) and on Day 2 after surgery (U = 220.0, Z = –2.01, *p* = 0.04, r = 0.25) between the infected and non-infected wounds. Likewise, statistically significant differences were detected in the median temperature readings on Day 1 after surgery (U = 216, Z = –2.07, *p* = 0.03, r = 0.26) and on Day 2 after surgery (U = 171.5, Z = –2.84, *p* = 0.01, r = 0.36) between the infected and non-infected wounds. A statistically significant difference was also observed in the lowest temperature readings on Day 2 after surgery (U = 185.5, Z = –2.60, *p* = 0.01, r = 0.33). For Days 1 and 2 after surgery, the readings of the infected wounds were found to be significantly lower than those of the non-infected ones; for Days 3 and 4, no such differences were observed (Table 2).

Infrared thermal images of abdominal surgical wounds from Day 0 to Day 4 after surgery

A total of 318 infrared thermal images were collected from 45 participants with non-infected abdominal surgical wounds and 15 with infected ones. Before surgery, no differences were noted in the infrared thermal patterns between the two groups of participants. Immediately after surgery (day 0), the surgical incisions were identified in relation to the staple landmarks reflected in green or blue colours. The surgical incisions were embedded within the surrounding skin and characterized by green, blue and purple, as are commensurate with lower temperature readings (Figure 3a).

By Day 1 after surgery, the non-infected surgical incision characterized by green and yellow diminished in size and morphed into a shade of red and white. Conversely, the infected surgical wound, notwithstanding the emergence of (minimal) yellow colouration near the incision indicative of warming, exhibited strips of blue or purple and registered a lower temperature reading than the surrounding skin surface (Figure 3b).

On Day 2, the infrared thermal colouration of the non-infected incision showed no ‘cold’ spots. Conversely, the colouration of the infected wound was still visible as blue and purple green along the incisions. Two characteristics could hitherto be concluded for an infected wound based on the infrared thermal images. The first was the partial warming of the skin surrounding the surgical incision and the second was the manifestation of ‘cold’ surgical incisions in infected surgical wounds, both of which constitute distinguishing features compared with a non-infected surgical wound (Figure 3c).

By Day 3 after surgery, the infrared thermal colouration of the non-infected wound had remained as white. Conversely, the colouration of the infected wound had remained predominantly visible as blue and green (Figure 3d).

By Day 4 after surgery, the non-infected wound had remained ‘warm,’ for which no ‘cold’ spots in the abdominal infrared thermal patterns were detected. Conversely, the infected wound was characterized by ‘cold’ spots of green or blue (Figure 3e).

Discussion

Key results

Immediately after surgery, infrared thermal patterns denoting a ‘cold’ incision were observed for both infected and non-infected surgical wounds. This is caused by the accumulation of interstitial fluid, which consists mainly of glycosaminoglycans, salt solution, and plasma proteins beneath the surgical wound surface immediately after surgery in response to cell injury in order to exchange nutrients and waste products between blood capillaries and tissue cells (Sussman, & Bates-Jensen, 2012; Wiig & Swartz, 2012). As interstitial fluid contains few blood vessels, minimum heat is generated and thus the area is shown to be colder within the infrared thermal images (Carter et al, 2014; Wiig, & Swartz, 2012). Given the variation in the volume of interstitial fluid from one surgical wound to another, the ‘cold’ areas might thus likewise differ in size among the participants.

On Days 1 and 2, the non-infected surgical wound underwent normal physiological healing, during which the amount of interstitial fluid beneath the skin surface reduced such that angiogenic capillaries could infiltrate and deliver nutrients and oxygen to promote tissue growth (Tonnesen et al., 2000). This phenomenon, in the context of non-infected wounds, explains the diminution of the ‘cold’ areas and the ‘warming’ pattern along the incision on Days 1 and 2 after surgery. However, in the context of infected ones, insufficient blood supply or accumulation of interstitial fluid beneath the wound might underlie the lower temperatures. Scallan et al. (2010) have opined that prolonged accumulation of interstitial fluid in surgical wounds would limit the exchange of oxygen, nutrients, and by-products for cellular metabolism. Since studies have suggested that adequate blood supply within the wound bed is required to deliver oxygen and to sustain normal wound healing, the presence of ‘cold’ spots along the surgical wound indicates poor blood supply, leading to delayed wound healing (Demidova-Rice et al., 2012; Guo, & DiPietro, 2010). On Days 3 and 4, the infrared thermal patterns of the non-infected wounds showed minimal differences in the colours from Day 2. However, the presence of ‘cold’ spots persisting on the infected wounds on Days 3 and 4 suggested no improvement in wound healing due to poor blood flow. Given such poor blood flow or hindered angiogenesis, the concomitant impairment in the delivery of essential supplies e.g. oxygen and nutrients, to the surgical wound culminate in wound dehiscence and infection (Sussman & Bates-Jensen, 2012; Davis, 2008; Neville, 2000).

Limitations of Study

To the best knowledge of the author, this is the first study that pioneers the elucidation of the infrared thermal patterns and temperature readings of surgical wounds as part of a nurse-led improvement of assessing surgical wounds after enterostoma closure. Nonetheless, some limitations are noteworthy. Firstly, the number of a sample-size calculation was conducted based on the infection rate but this study could not meet the desired sample size due to constraints in the availability of participants and time. Therefore, the statistical power might have been insufficient to detect differences in the surgical wound surface temperatures due to a small sample size. Further research involving multiple study centers should be conducted to expand the sample size to observe the thermal trends of both infected and non-infected surgical wounds. The second limitation concerns the variability in the surgical data such as the lengths of incisions and numbers of staples. This in practice translated into differences in the number of measurement points on the abdomens of the participants, whose inclusion inevitably introduced variability into the findings. Lastly, this study included only participants admitted for closure of enterostoma, which is classified as a type of clean/contaminated wound (2.4 times more at risk of infections) based on the American College of Surgeons, National Surgical Quality Improvement Program (ACS-NSQIP) system (Ortega et al., 2012). Despite the possible selective bias that might compromise external validity, such inclusion was intended to allow uniform and sequential comparisons across thermal images of wounds in only the colorectal abdominal region. Further research should be conducted on other anatomical sites with adipose tissues of different thickness and structural curvature, such as the head, chest, hands, and legs, to determine the trend of temperature readings and the presence of 'cold' spots along surgical incisions from Days 1 to 4 after surgery.

Interpretation of results

Collectively, the temperature differences from Days 0 to 4 for both non-infected and infected surgical wounds denoted signs of warming up after surgery, and are consistent with the conventional association of heat with inflammation (Horan et al., 2008; Bishop & Lee, 1997). The heat secondary to inflammation was released through the blood, causing the skin to become hyperaemic and warmer (Davis, 2008). However, the temperatures of the infected wounds were noted to be lower than those of the non-infected ones in the first two days after surgery, which might indicate diminished blood flow to the surgical wound. Diminished blood flow might have been associated with surgical-site infections. The physiological sequelae of diminished blood flow are numerous. Firstly, according to Velnar, Bailey and Smrkolj (2009), lesser blood flow to the surgical wound would delay the acute inflammatory response to stimulate the body to generate chemotactic mediators. Secondly, it would impair cellular oxygen perfusion, thus leading to tissue hypoxia (Al-Qattan, & Al-Kattan, 2004; Holzheimer, & Mannick, 2001; Nathan, & Ding, 2010; Trowbidge, & Emling, 1997; Velnar et al., 2009). Both the failure to elicit an acute inflammatory response and tissue hypoxia would lead to delayed wound healing, causing wound dehiscence (Lawrence and Gilroy, 2007). Lastly, inadequate blood supply to the surgical wound would lead to impaired delivery nutrients to promote the growth of new tissues (Trowbidge, & Emling, 1997). Therefore, new tissues – which are essential for proliferation at later stages of wound healing – will not be formed, explaining the slower apposition of wound margins beneath the incised epidermis. In the meantime, pockets of interstitial fluid which do not generate heat accumulated beneath the skin surface of infected surgical wounds due to poor lymphatic drainage; this prevented apposition of wound margins (Carter et al, 2014; Wiig, & Swartz, 2012). This might therefore explain the lower temperature of the infected wounds on Days 1 and 2. In essence, the presence of 'cold' spots is a distinctive feature for infected surgical wounds from Days 0 to 4 after surgery. Such spots provide important information for the identification of poor healing locations beneath the surgical incision which will otherwise not be discerned through physical assessment.

Generalisability

This study has elucidated the thermal patterns of surgical wounds through non-invasive and no-contact infrared thermography in determining the occurrence of poor wound healing in the first four days after enterostoma closure. Temperature changes over the surfaces of the surgical wounds were found to be governed by the amount of heat emitted from the skin surface. The use of infrared thermography aids in quantifying the otherwise subjective sense of heat into temperature readings and infrared thermal patterns during the inflammatory process. In this study, temperature readings and infrared thermal patterns have been demonstrated to be feasible methods to differentiate infected surgical wounds from non-infected ones between Days 1 and 4 after surgery through the assessment of 'cold' spots or areas along the incision, which might enable the early detection of poor wound healing. However, due to insufficient large-scale prospective studies, infrared thermography is currently not a widely accepted tool for its medical utility. Therefore, infrared thermography can be regarded as a complementary approach to support the current clinical approach to boost both sensitivity and specificity.

Conclusion

Assessment of surgical wound for infection is an integral part of nursing management in the care of patients after surgery. In this study, the sign of heat was converted into temperature readings through an infrared thermal camera. The findings have suggested that the readings of the infected wounds (abdominal sites) were lower than those of the non-infected ones and could serve as a proxy indicator for nurses to detect poor wound healing. Therefore, the measurement and observation of the thermal profiles of abdominal surgical wounds may provide evidence-based information to healthcare professionals to objectively assess the wounds in detecting poor healing within the first four days after surgery. Accordingly, patients with delayed wound healing may be identified earlier for timely intervention involving prevention and treatment before discharge. Having said that, further research expanding to multi-centers studies on other wound sites should be conducted to observe the temperature trend of both the infected and non-infected surgical wound.

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