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Skin graft monitoring using forward-looking infrared thermal imaging

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Abstract
This study examined the feasibility of non-invasive infrared thermography to monitor skin graft viability. Sixty-three patients with skin defects attending a single institution from May 2022 to August 2023 were included. Patients underwent full-thickness or split-thickness skin grafts based on clinical indication. Infrared thermal images were obtained on postoperative days 0, 2, 4, 6 and 8. The temperature difference between the skin graft and surrounding normal skin was assessed using image analysis software. All 33 patients with full-thickness skin grafts showed successful healing. Among the 30 patients with split-thickness skin grafts, 7 experienced failure. The groups with successful full-thickness and split-thickness skin grafts exhibited a gradual increase in graft temperature, peaking on postoperative day 6 and decreasing on postoperative day 8. Temporal temperature changes were significant in each patient group ($p < 0.001$), and the differences in temperature change patterns between the two groups with successful grafts and the group with graft failure were also significant ($p < 0.001$). On postoperative day 6, the temperature difference was highest in the full-thickness skin graft group (0.197 ± 0.335°C), followed by the successful split-thickness skin graft group (0.426 ± 0.428°C), and the split-thickness skin graft group with graft failure (-2.100 ± 0.361°C). In conclusion, infrared thermal imaging can provide a non-invasive real-time assessment of graft status and predict graft success or failure.

KEYWORDS
diabetic ulcer, skin graft, thermography

Key Messages
Infrared thermal imaging can provide a non-invasive real-time assessment of graft status and predict graft success or failure.

1 | INTRODUCTION

Skin grafting provides effective treatment and reconstruction opportunities for patients with burns, trauma or congenital skin defects, with a significant impact on quality of life.[1] Additionally, immediate reconstruction through skin graft may be a viable option in cases in which simple closure is not feasible for skin defects arising after the excision of congenital giant nevus or skin tumour.[2]

Chronic wounds are non-healing wounds that can result from diabetic ulcers, vascular diseases, pressure ulcers or wounds caused by chronic inflammation, which persist over an extended period without proper treatment. They can result from diabetic ulcers, vascular diseases, pressure ulcers or wounds caused by chronic inflammation.[3] Chronic wounds can compromise the quality of life and increase the risks of complications, such as infections, necessitating skin grafting.[4] However, the healing process following a skin graft is not always successful.[5] Therefore, careful graft monitoring after surgery is essential to prevent recurrence.

Several crucial factors contribute to the success of skin grafts. Proper adherence between the graft and recipient tissues is important during the initial skin grafting stages. The skin graft absorbs oxygen and nutrients passively in the early stages. At this point, the graft is ischemic and can survive only through diffusion until inosculation occurs. The appearance of the graft is pale during this time. A skin graft can typically endure up to 4 days of ischemia.[6–8] It is essential to keep the wound clean during this process to prevent infection.[9] New vessels then grow into the graft, supplying blood and enabling wound healing by proliferating cells. Adequate blood flow to the tissue is necessary for angiogenesis, eventually leading to graft take.[10] Generally, by the 5th postoperative day, the skin graft adheres well, and the colour of the graft changes from white to pink.[11]

Infrared thermography detects naturally emitted infrared radiation from the human skin and has gained prominence as a diagnostic tool for a range of conditions, including inflammatory disease, complex regional pain syndrome and Raynaud's phenomenon.[12] This non-contact method offers high resolution and performance and has recently emerged as a promising tool for monitoring wounds and scars resulting from burns or skin flaps.[13,14] In essence, it enables real-time observation of the blood supply and overall physiological status of the tissue by measuring the target's surface temperature and visually presenting the spatial distribution of temperature.[12]

However, research on skin graft monitoring using infrared thermography is scarce.[15] Traditional methods such as visual inspection and palpation have been used to monitor skin grafts. Nevertheless, non-invasive monitoring of skin grafts through infrared thermal imaging could be a useful and convenient approach for patients.

This study explores the current research trends in utilizing infrared thermography to monitor various aspects of wounds and investigates the advantages of this technique through comparison with existing monitoring methods. Moreover, the clinical application prospects of infrared thermography for monitoring skin grafts are examined to provide insights into the benefits of this approach in patient care and the direction of future research in the field.

2 | METHODS

2.1 | Patients

This retrospective study included 70 patients diagnosed with skin defects from May 2022 to August 2023 at a single institution. Approval was obtained from the Soonchunhyang Cheonan Hospital institutional review board (IRB number: 2023-12-002), and written consent to participate in the study was obtained from all patients.

Inclusion criteria were as follows: patients ≥18 years who underwent skin grafting either for chronic wounds lasting >3 weeks caused by trauma, burns, infection or postoperative complications or for extensive skin defects resulting from wide excision of skin cancer or giant nevus. The following exclusion criteria applied: body temperature exceeding 37.3°C during hospitalization, infected grafts, missing records and lack of follow-up observations.

2.2 | Infrared thermal imaging

A single surgeon performed the skin graft surgery using either a split-thickness skin graft (STSG) or a full-thickness skin graft (FTSG). The STSG was performed in cases with compromised blood circulation, such as diabetic ulcers, whereas FTSG was performed on the face or joint areas. STSGs were harvested using the electric dermatome with a thickness set to 0.0125 inches, whereas FTSGs were harvested with handheld instrumentation until exposure of the dermis. FTGS are thicker than STSG because they include the dermis in its entirety. Infrared thermographic images were captured immediately after skin grafting. Dressing changes were performed on postoperative days (POD) 2, 4, 6 and 8, along with simultaneous infrared thermal imaging. Two clinicians evaluated the survival of the skin grafts. In all cases where the grafts failed, the patients were diabetic foot

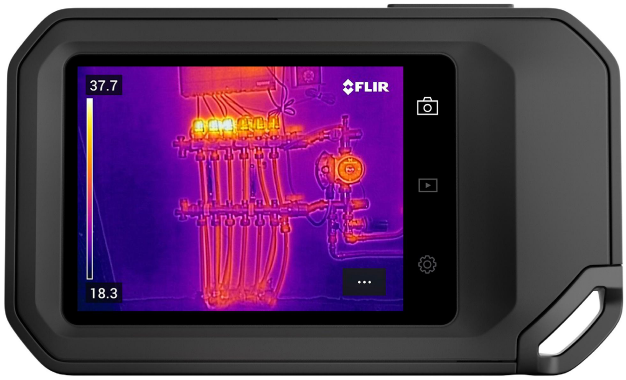

FIGURE 1 Measurement of infrared thermography. The handheld camera type device is comfortable to use and cost-effective (FLIR C5 camera, Teledyne FLIR LLC, US). It includes a thermal imager (160 × 120 pixels), a 5-megapixel visual camera (640 × 480 pixels) and an LED flashlight.

patients, and hematomas or seromas were observed. However, even in areas where no hematoma or seroma occurred, the grafts did not take. None of the patients underwent mesh grafting. Skin grafts were considered successful if graft survival exceeded 90%. Failure was defined as incomplete graft take (<90%). No partial failure cases were observed.

All patients who underwent FTSG showed successful graft attachment, whereas cases of graft failure were recorded in the STSG group. Therefore, 3 groups were established: the FTSG taken group, comprising patients in the FTSG group with successful attachment; the STSG taken group, consisting of patients in the STSG group with successful attachment and the STSG loss group, including patients in the STSG group with graft failure.

It is important to note that inconsistent infrared thermography results may occur depending on the environment.[16] Various efforts were made in this study to ensure consistent measurement conditions. First, thermal images were captured after removing wound dressings and allowing a 1-min resting period. Second, standardized operating rooms and photography zones were utilized for capturing images. Temperature was maintained between 18 and 24°C, and humidity between 50% and 55%. Then, the grafts were immersed in warm saline for 1 min after harvest before being applied. Third, infrared images were captured using a single infrared thermal camera device (FLIR C5 camera, Teledyne FLIR LLC, US), which is a handheld camera that includes a thermal imager (160 × 120 pixels), a 5-megapixel visual camera (640 × 480 pixels) and an LED flashlight (Figure 1). The clinical photographs were taken using a Cannon EOS R6 Mark II (Tokyo, Japan) camera at a consistent distance of 40 centimetre from the wound to assess the wounds and skin grafts postoperatively.

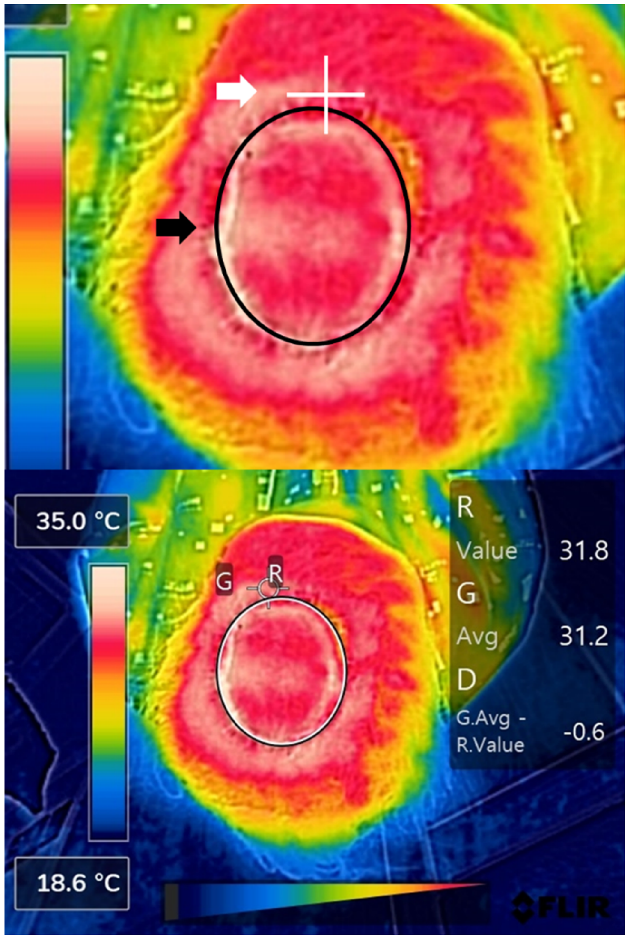

FIGURE 2 The captured images were analysed using FLIR thermal studio (Teledyne FLIR LLC, US) image analysis software. (Above) Temperature measurement method: The black line indicated by the black arrow represents the boundary of the graft, and the software calculates the average temperature value of the area. The white cross marked by the white arrow, pointing to a spot representing the normal skin temperature, allows us to obtain the temperature of that spot. (Below) The values can be obtained as follows: *R* represents the reference, indicating the spot temperature of normal skin; *G* calculates the average temperature of the entire graft area. *D* is the delta value, representing the difference between the average temperature of the graft and the temperature of the normal skin spot. For this patient, *R* is 31.8°C, *G* is 31.2°C and *D* is −0.6°C as analysed.

2.3 | Infrared thermal image analysis

The FLIR thermal studio (Teledyne FLIR LLC, US), an image analysis software, was used for data manipulation. This program enables quantitative analysis and visualization of data transmitted from the captured images to a computer. The software was used to set the skin graft area, measure the average temperature of the entire graft and compare the temperature difference between the graft and the surrounding normal skin. Despite

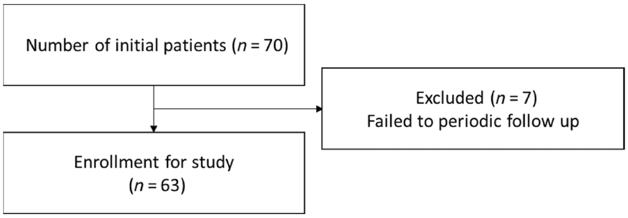

FIGURE 3 Study enrolment criteria. Every participant met the inclusion criteria, following the exclusion of 7 patients with absent follow up thermography measurements.

ensuring a consistent capture environment, considering the slight daily variation in body temperature for the same patient, temperature differences between the graft and the adjacent normal tissue were compared instead of solely comparing the graft temperature. Therefore, temperatures of points within a centimetre proximal to the graft were measured in the normal skin, and the difference was calculated on each day. The temperature difference, representing the temperature of the graft relative to the normal skin, allowed to correct for variations in the capture environment and in the patient's daily body temperature (Figure 2).

2.4 | Statistical analysis

Statistical analyses were performed using SPSS (version 27.0, IBM Corp., Armonk, NY, USA). Group comparisons were analysed using two-way analysis of variance (ANOVA), paired t-test and Fisher's exact test. For repeated measurements within each group, a generalized estimating equation analysis was conducted additionally. The Friedman test was used to analyse values over time within each group. A significance level of $p < 0.05$ was considered statistically significant for all analyses.

3 | RESULTS

3.1 | Patient demographics

Among the 70 patients, 63 satisfied the inclusion criteria, whereas 7 were excluded because of missing follow-up observations (Figure 3). The FTSG taken group comprised 33 patients, the STSG taken group comprised 23 patients, and the STSG loss group comprised 7 patients. In the FTSG taken group, the donor site was the upper clavicle in 23 patients (69.7%) and the groin in 10 patients (30.3%). In both STSG groups, the donor site was the anterolateral thigh. In the FTSG taken group, the recipient sites were predominantly the face in 20 patients (60.6%), followed by the foot in 7 patients (21.2%), and the hand in 4 patients (12.1%). In the STSG taken group, the recipient sites were primarily the leg in 12 patients (52.2%) and the foot in 7 patients (30.4%). In the STSG loss group, the foot was the recipient site in 6 patients (85.7%) and the leg in 1 patient (14.3%). Given the prevalence of lower limb and foot involvement in diabetic ischemic ulcers, these areas were common recipient sites in the STSG groups. The most common indication for skin grafting in the FTSG taken group was skin cancer excision in 26 patients (78.8%). In the STSG taken group, trauma was the predominant reason for skin grafting in 8 patients (34.8%), followed by diabetic ischemic ulcer in 5 patients (21.7%). In the STSG loss group, the most common indication for skin grafting was diabetic ischemic ulcer in 6 patients (85.7%) (Table 1).

3.2 | Infrared thermal imaging analysis

3.2.1 | Temperature Changes among the Three Groups (FTSG taken, STSG taken, STSG loss)

Distinct temperature trends were observed postoperatively between the FTSG taken and STSG loss groups, as well as between the STSG taken and STSG loss groups ($p < 0.001$). A significant time-dependent difference was observed in the mean temperature difference between the graft and normal skin within each group ($p < 0.001$). In all groups, graft temperature was initially lower than normal skin temperature postoperatively; however, the temperature of FTSG taken and STSG taken groups gradually increased with time, becoming slightly higher than that of normal skin on POD 6, decreasing on POD 8. In contrast, the STSG loss group exhibited a further decrease in graft temperature compared to normal skin by POD 8 (Figure 4). Within the FTSG taken group, there was a significant time-dependent difference in graft temperature compared to that of normal skin ($p < 0.001$). A significant time-dependent difference was also observed within the STSG taken group ($p < 0.001$) (Table 2). In the FTSG taken group, the temperature difference was lowest immediately postoperatively at −1.57°C, gradually increasing to 0.197°C by POD 6 and decreasing to −0.003°C by POD 8. In the STSG taken group, the temperature difference was lowest immediately postoperatively at −1.496°C, gradually increasing to 0.426°C by POD 6 and decreasing to 0.052°C by POD 8. However, the STSG loss group showed no significant difference in temperature over time ($p = 0.07$) (Table 2).

TABLE 1 Patient demographics.

	FTSG taken	STSG taken	STSG loss	*p*-Value
N (%)	33 (100)	23 (100)	7 (100)	
Age	66.94 ± 18.650	53.13 ± 16.799	64.57 ± 8.561	0.015
Gender				0.002
Male	11 (33.3)	13 (56.5)	7 (100.0)	
Female	22 (66.7)	10 (43.5)	0 (0.0)	
History				
Hypertension	13 (39.4)	11 (47.8)	5 (71.4)	0.296
DM	10 (30.3)	11 (47.8)	6 (85.7)	0.099
ESRD	0 (0.0)	1 (4.3)	1 (14.3)	0.093
Donor				<0.001
Supraclavicular	23 (69.7)	0 (0.0)	0 (0.0)	
Inguinal	10 (30.3)	0 (0.0)	0 (0.0)	
Thigh	0 (0.0)	23 (100)	7 (100)	
Location				<0.001
Scalp	1 (3.0)	1 (4.3)	0 (0.0)	
Face	20 (60.6)	0 (0.0)	0 (0.0)	
Trunk	0 (0.0)	2 (8.7)	0 (0.0)	
Upper extremity	1 (3.0)	1 (4.3)	0 (0.0)	
Hand	4 (12.1)	0 (0.0)	0 (0.0)	
Lower extremity	0 (0.0)	12 (52.2)	1 (14.3)	
Foot	7 (21.2)	7 (30.4)	6 (35.7)	
Diagnosis				<0.001
Skin cancer	26 (78.8)	1 (4.3)	0 (0.0)	
Trauma	1 (3.0)	8 (34.8)	0 (0.0)	
Postoperative complication	0 (0.0)	4 (17.4)	0 (0.0)	
Diabetic ulcer	0 (0.0)	5 (21.7)	6 (85.7)	
Infection	1 (3.0)	3 (13.0)	1 (14.3)	
Burn	4 (12.1)	1 (4.3)	0 (0.0)	

Abbreviations: DM, diabetes mellitus; ESRD, end-stage renal disease; FTSG, full-thickness skin graft; STSG, split-thickness skin graft.

3.2.2 | Analysis of Diabetic Ischemic Ulcers

Among the 7 patients with failed grafts, 6 had diabetic ischemic ulcers, warranting particular attention to this subgroup. Of the total 63 patients in the study, 11 had diabetic ischemic ulcers as an indication for grafting. All underwent STSG, with 5 patients (DU STSG taken) successfully engrafted and 6 patients (DU STSG loss) experiencing graft failure (Table 3). The difference in temperature change patterns by the time between the DU STSG taken and DU STSG loss groups was significant ($p < 0.001$) (Figure 5). Within the DU STSG taken group, there was a significant time-dependent difference in temperature compared to normal skin ($p = 0.002$). In the DU STSG loss group, there was no significant difference in temperature postoperatively ($p = 0.052$) (Table 4).

3.3 | Case 1

A 62-year-old male patient with a diagnosis of malignant melanoma on the right heel and no significant medical history presented to the hospital underwent wide excision surgery, and an FTSG was taken from the right thigh donor site. Infrared thermographic images were captured on POD 0, 2, 4, 6 and 8. The average temperature of the graft and the temperature difference between the graft and the homogenous temperature of adjacent normal

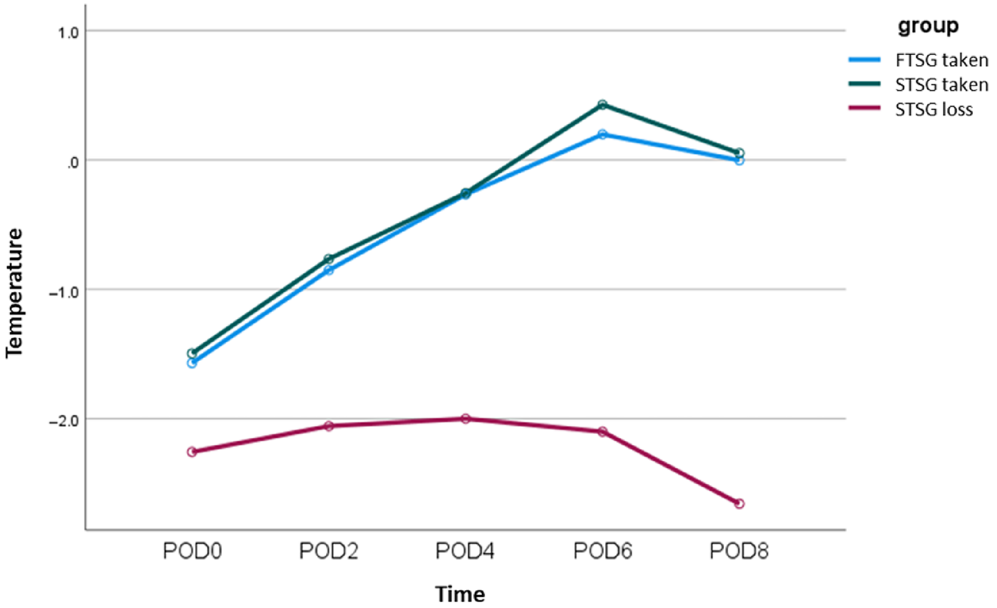

FIGURE 4 Changes in temperature over time in the 3 groups. Both 'taken' groups show an increase in temperature until POD 6, after which the differences between the graft and normal tissue converge to 0 at POD 8. In contrast, the 'loss' group does not show an increase. FTSG, full-thickness skin graft; POD, postoperative days; STSG, split-thickness skin graft.

TABLE 2 Mean temperature difference values according to POD in 3 groups.

	POD 0	POD 2	POD 4	POD 6	POD 8	*p*-Value
FTSG taken	−1.570 ± 0.768	−0.852 ± 0.505	−0.267 ± 0.432	0.197 ± 0.335	−0.003 ± 0.226	**<0.001**
STSG taken	−1.496 ± 0.535	−0.765 ± 0.492	−0.257 ± 0.564	0.426 ± 0.428	0.052 ± 0.342	**<0.001**
STSG loss	−2.257 ± 0.519	−2.057 ± 0.395	−2.000 ± 0.361	−2.100 ± 0.361	−2.657 ± 0.519	0.07

Note: Post-hoc tests revealed significant changes in mean temperature differences across PODs for both the FTSG taken group and STSG taken group. However, in the STSG loss group, there were no significant changes observed. Bold indicates statistically significant important *p* value.
Abbreviations: FTSG, full-thickness skin graft; POD, postoperative days; STSG, split-thickness skin graft.

TABLE 3 Demographics of patients who underwent grafting due to diabetic ulcer. This table is further studies on diabetic foot patients. All patients received split-thickness skin grafts due to poor perfusion, and no patients received full-thickness skin grafts.

	DU STSG taken	DU STSG loss	*p*-Value
N (%)	5 (100)	6 (100)	
Age	56.80 ± 15.369	63.33 ± 8.664	0.396
Gender			0.182
Male	3 (60.0)	6 (100.0)	
Female	2 (40.0)	0 (0.0)	
History			
Hypertension	3 (60.0)	5 (83.3)	0.545
DM	5 (100.0)	6 (100.0)	>0.999
ESRD	1 (20.0)	1 (16.7)	>0.999
Location			0.455
Lower extremity	1 (20.0)	0 (0.0)	
Foot	4 (80.0)	6 (100.0)	

Abbreviations: DM, diabetes mellitus; DU, diabetic ulcer; ESRD, end-stage renal disease; FTSG, full-thickness skin graft; STSG, split-thickness skin graft.

skin were analysed using FLIR thermal studio software. The temperature differences on POD 0, 2, 4, 6 and 8 were −1.2°C, −0.6°C, −0.2°C, +0.1°C and −0.3°C, respectively (Figure 6A,D,G,J,M). The skin graft was successfully engrafted, and the patient was discharged on POD 10 with no complications (Figure 6).

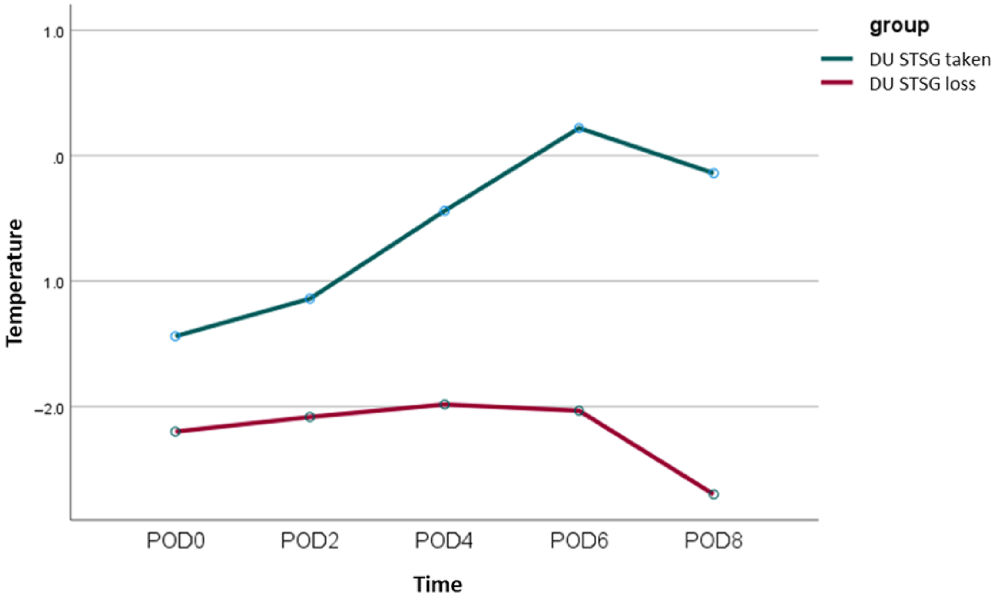

FIGURE 5 Changes in temperature over time in the group of patients with diabetic ulcer. The 'taken' groups show an increase in temperature until POD 6, after which the difference values decrease at POD 8. In contrast, the 'loss' group does not show an increase. FTSG, full-thickness skin graft; POD, postoperative days; STSG, split-thickness skin graft.

TABLE 4 Mean temperature difference by POD in 2 groups of patients with diabetic ulcers.

	POD 0	POD 2	POD 4	POD 6	POD 8	*p*-Value
DU STSG taken	−1.440 ± 0.467	−1.140 ± 0.555	−0.440 ± 0.719	0.220 ± 0.192	−0.140 ± 0.219	**0.002**
DU STSG loss	−2.200 ± 0.544	−2.083 ± 0.426	−1.983 ± 0.392	−2.033 ± 0.345	−2.700 ± 0.555	0.052

Note: Post-hoc tests revealed significant changes in mean temperature differences across PODs for DU STSG taken group. However, in the DU STSG loss group, there were no significant changes observed. Bold indicates statistically significant important *p* value.
Abbreviations: DU, diabetic ulcer; FTSG, full-thickness skin graft; POD, postoperative days; STSG, split-thickness skin graft.

3.4 | Case 2

A 63-year-old male patient with a history of hypertension, type 2 diabetes mellitus, end-stage renal disease and myocardial infarction presented with a diabetic foot ulcer on the dorsum of the left foot. The presence of foul odour and purulent discharge indicative of necrotic tissue led to debridement. Despite the orthopaedic recommendation for below-knee amputation, the patient declined. Vascular computed tomography revealed severe stenosis in both the anterior tibial artery and posterior tibial artery, making flap surgery challenging due to advanced arterial sclerosis. Consequently, a palliative STSG from the left thigh was performed. Infrared thermal images were taken on POD 0, 2, 4, 6 and 8. The temperature differences on POD 0, 2, 4, 6 and 8 were −1.6°C, −1.6°C, −2.2°C, −2.5°C and −2.7°C, respectively (Figure 7A,D,G,J,M). The skin graft eventually failed, and due to continuous deterioration of the wound, a below-knee amputation was performed (Figure 7).

4 | DISCUSSION

Skin graft surgery is an established surgical technique used to reconstruct skin defects. However, there is a paucity of research on the use of devices for skin graft monitoring. This study shows that the success or failure of skin grafts can be predicted in advance through infrared thermography.

The results of the study are consistent with the existing knowledge that skin grafts achieve engraftment around POD 5.[11] Both the FTSG taken group and STSG taken group exhibited a gradual increase in temperature after surgery, reaching the highest temperature on POD 6, with measurements showing temperatures similar to or even higher than those of the surrounding normal tissues. In contrast, the STSG loss group showed non-specific temperature changes, ultimately failing to reach the temperature of the surrounding normal tissues. On POD 6, the average temperature difference between the surrounding normal tissues and the graft was less than 0.5°C in both the FTSG taken and STSG taken groups, with the graft temperature being higher than that of the normal tissue. However, in the STSG loss group, by POD 6, the average temperature difference between the surrounding normal tissues and the graft was more than 2°C, with lower graft temperature. Therefore, based on the data analysis of infrared thermography images, failure of the skin graft may be anticipated from a finding of no increase in graft temperature over time or failure of the graft to achieve the temperature of the surrounding

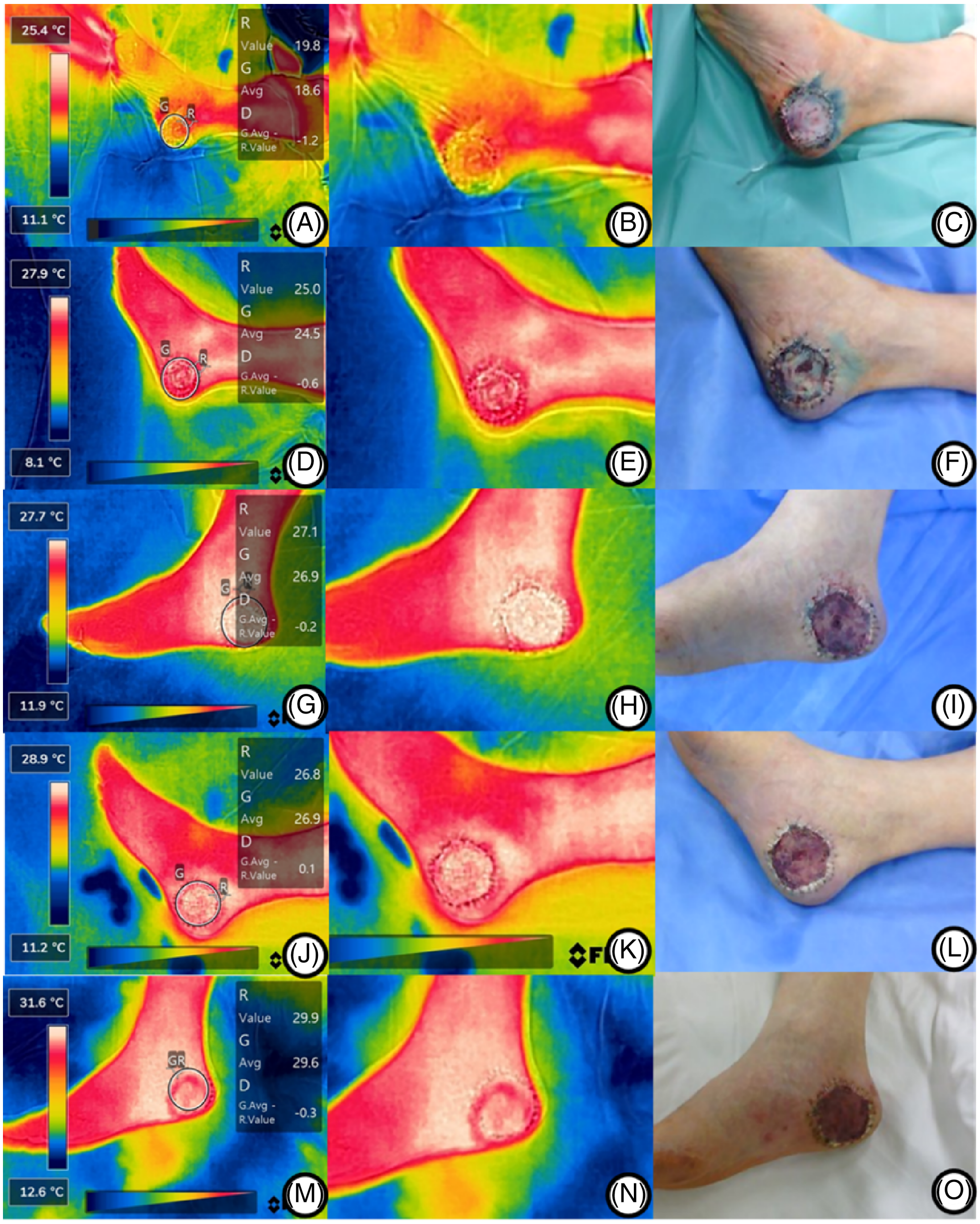

FIGURE 6 A case of FTSG taken group. A 62-year-old man was treated for malignant melanoma on his right heel. Surgery involved wide excision followed by FTSG. The top row (A–C) represents POD 0, and the bottom row (M–O) represents POD 8. The left column (A, D, G, J, M) displays images analysed with the software. In the middle column (B, E, H, K, N), it can be visually observed that the temperature of the graft is rising. Moreover, at POD 8, the colour of the graft becomes similar to that of the surrounding skin. The right column (C, F, I, L, O) shows gross images. FTSG, full-thickness skin graft; POD, postoperative days.

normal tissues by POD 6. In one case not included in the study, partial failure occurred, with 50% of the graft failing to achieve successful engraftment. The region with partial failure did not exhibit an increase in temperature, whereas the parts of the graft that had successfully taken exhibited a temperature rise to values similar to those of normal skin (Figure 8). This 'geographic pattern' supports the use of infrared thermography to predict the success or failure of skin grafts.

It is important to consider why the temperature increases as the skin graft achieves engraftment. The growth of blood vessels following skin grafting has been demonstrated in previous animal experiments. Histological analysis of grafts in a mouse model revealed actual neovascularization.[17] One hypothesis is that the temperature increase results from increased blood flow due to neovascularization. Another hypothesis is that the temperature increase is associated with the chemical reactions occurring during the inflammatory and proliferative phases. The proliferative phase typically concludes around week 1, transitioning to the remodelling phase, during which the graft's temperature aligns with that of the surrounding normal tissues.[18]

Temperature and humidity can impact the captured infrared thermal images; temperature may vary based on the patient's body temperature.[16] The temperature difference between the graft and normal skin was analysed to minimize bias in this study. Therefore, even in clinical

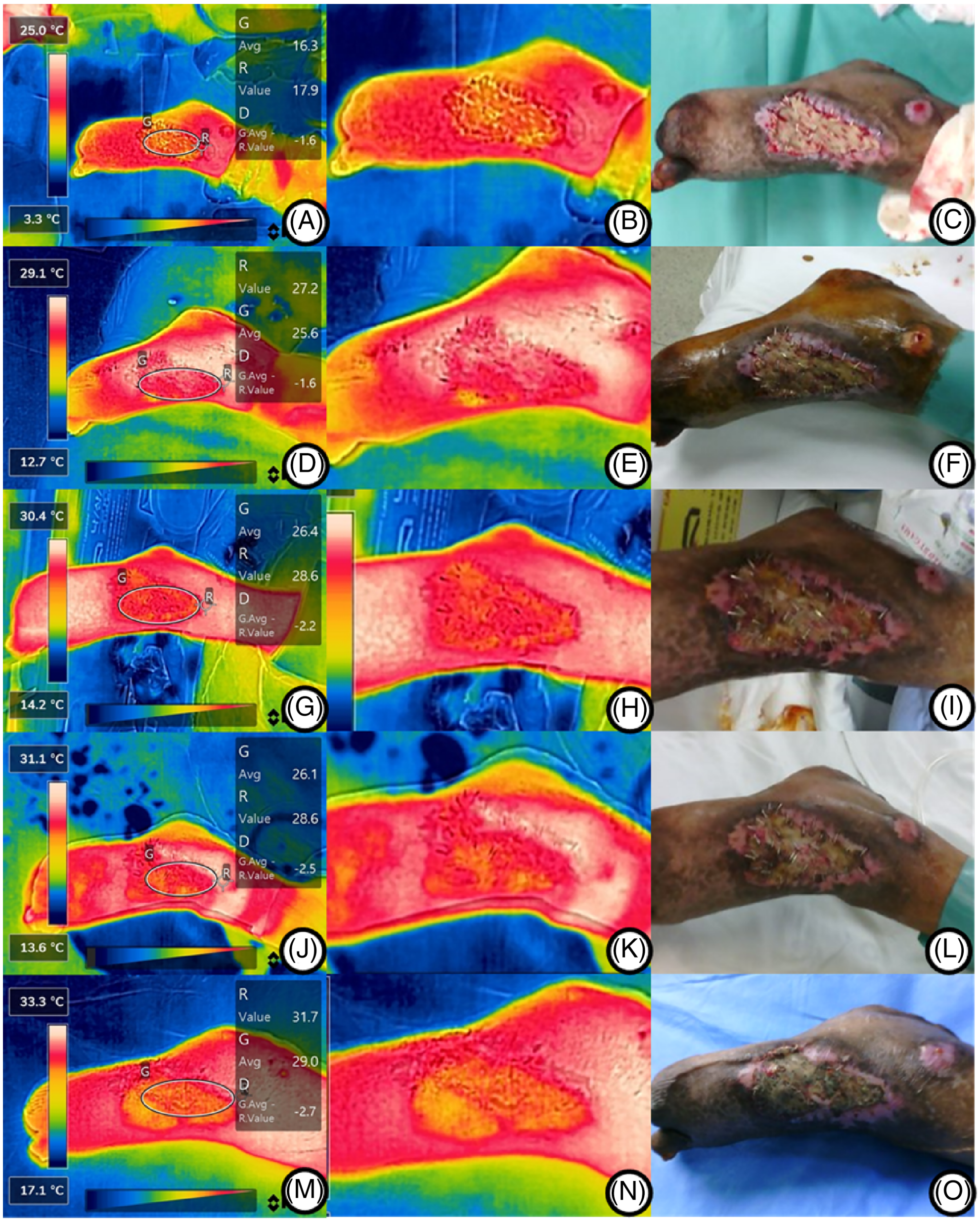

FIGURE 7 A case of STSG loss group. A 63-year-old man with diabetic gangrene on his left foot. Despite a skin graft, the wound deteriorated, followed by below-knee amputation. The top row (A–C) represents POD 0, and the bottom row (M–O) represents POD 8. The left column (A, D, G, J, M) displays images analysed with the software. In the middle column (B, E, H, K, N), it can be visually observed that the temperature of the graft is not rising. The right column (C, F, I, L, O) shows gross images. POD, postoperative days; STSG, split-thickness skin graft.

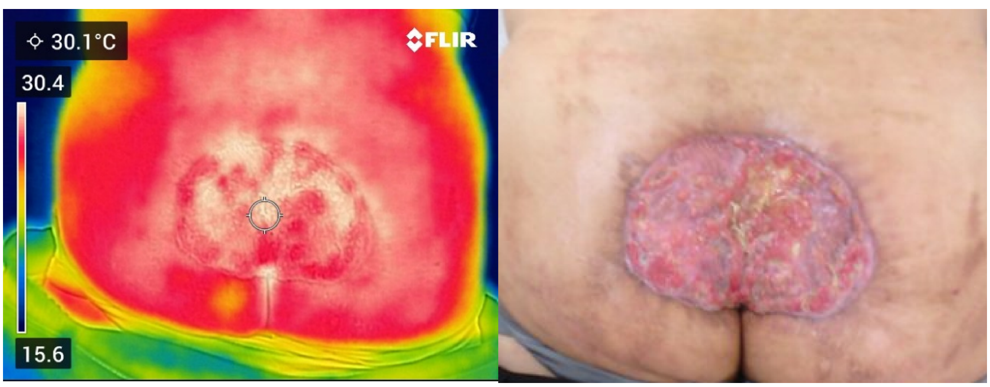

FIGURE 8 A case of geographic pattern. This is a case of Marjolin's ulcer diagnosed in the sacral area, which underwent wide excision followed by split-thickness skin graft. In this case, a 'geographic pattern' was observed characterized by an increase in temperature in some portions of the skin graft but not in others. Ultimately, the areas in which the temperature did not increase indicated graft failure, showing incomplete take of the graft.

applications, the analysis should focus on the relative temperature difference between the graft and normal skin rather than graft temperature.

Skin grafts are typically performed for chronic wounds lasting more than 3 weeks or extensive wounds in which primary closure is not feasible. If structures such as bones or tendons are exposed, flap surgery is generally performed. In patients with poor blood circulation precluding flap surgery, skin grafts may be performed along with acellular dermal matrix (ADM). In these cases, the risk of graft failure is high, and repeated debridement and revision surgery are required, leading to significant patient discomfort and prolonged hospitalization.[19] Predicting non-engrafting areas using infrared thermography could help identify such areas early, enabling early intervention and shortening hospitalization.

While skin grafting is considered a relatively simple procedure in plastic surgery. Although graft failure can be assessed clinically by visual inspection and palpation, early prediction of graft loss remains challenging. Combining quantitative data from infrared thermography with traditional graft monitoring methods may allow a more comprehensive assessment and prediction of skin graft engraftment outcomes.

Overall, 6 of 7 patients with failed grafts in this study had diabetic ulcers. Diabetic ulcers occur in patients with diabetes with poorly controlled blood sugar levels. Elevated blood glucose levels cause damage to blood vessels and nerves, particularly when blood circulation is inadequate in the lower extremities, leading to ulcer formation.[20] If diabetic ulcers are improperly treated, infections can occur, and in severe cases, this may lead to complications such as sepsis or amputation.[20] Prevention of diabetic ulcers through consistent blood glucose monitoring, maintaining a healthy diet, and proper footwear (shoes and socks) is paramount; however, if ulcers occur, early detection and treatment are crucial.[21] In cases with severe tissue loss due to delayed treatment, reconstructive procedures such as skin grafting or flap surgery may be necessary.[22] Achieving graft survival in patients with diabetic ulcers and poor blood circulation is challenging. Therefore, using infrared thermography images for monitoring skin grafts in patients with diabetic ulcers is potentially beneficial.

One of the advantages of infrared thermography images is the ability to observe real-time temperature distribution in the tissue after skin grafting by combining high resolution and fast speed. This is particularly valuable for early diagnosis of complications that may arise due to changes in blood supply and intervention. Additionally, infrared thermography is a non-contact technique that minimizes patient discomfort while obtaining accurate data. The capability to monitor while maintaining patient comfort and cooperation is a notable advantage. Furthermore, simultaneous measurement of the overall temperature of the grafted skin at multiple points allows for the evaluation of the overall health status of the graft. Data digitalization and analysis using FLIR thermal studio software enable quantitative and objective assessments.

The potential of infrared thermography in clinical practice extends beyond skin grafts to various reconstructive procedures. Infrared thermography is a versatile technique that allows real-time monitoring of changes in skin temperature and could be utilized in flap surgery and other surgical procedures. Various studies have been conducted to explore the value of infrared thermography in the field of plastic surgery. Infrared thermography shows potential for assessing complications such as necrosis and changes in microcirculation and macrocirculation. Previous research has utilized infrared thermography to predict potential complications in the healing process of lipoabdominoplasty.[23] Additionally, another study has investigated the use of thermography to map perforators for flap design in reconstructive surgery.[24] We hope that this study will further contribute to the clinical applicability of infrared thermography.

Some limitations of this study should be noted. First, the limited sample size of grafts that failed to engraft. A larger sample size of failed grafts could provide additional insights and identify trends in temperature changes. Additionally, the study did not include graft failure due to infection. Of note, if graft failure is accompanied by a severe inflammatory response due to infection, the temperature of the failed graft may also increase. Moreover, there may have been differences in the status of the wound prior to the graft, and there was insufficient exploration to confirm whether the wound's perfusion or debridement was at an appropriate level for grafting. Future studies involving a larger number of patients should include discussions on insufficient debridement and the presence of adequate perfusion prior to grafting.

5 | CONCLUSION

These results suggest that infrared thermal imaging offers new possibilities for monitoring skin grafts. Infrared thermal imaging, combining high resolution and real-time monitoring, allows for accurately assessing tissue condition and changes in blood supply after skin grafting. The convenience of non-contact monitoring proves essential when considering patient comfort, and infrared thermal imaging provides these advantages. Furthermore, data analysis provides quantitative and objective information to aid in medical decision-making. In future research, exploring the application of infrared thermal imaging in various medical fields and seeking effective integration with existing monitoring methods will be crucial. Additional research and technological advancements are expected to establish infrared thermal imaging as a fundamental tool in skin graft treatment.

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest relevant to this article was reported.

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs'.

ETHICS STATEMENT

The study was approved for exemption by the Institutional Review Board of Soonchunhyang University Hospital (IRB exemption No. 2023-12-002).

INFORMED CONSENT

The patients provided written informed consent for the publication and use of his or her images.

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