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Comparative study of cooling techniques for perforator detection in DIEP flap reconstruction using dynamic infrared thermography



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Summary Dynamic infrared thermography (DIRT) is a non-invasive technique for perforator mapping in Deep Inferior Epigastric artery Perforator (DIEP) flap breast reconstruction. Its accuracy is highly dependent on the cooling technique used to enhance thermal contrast. This study compares eleven cooling techniques based on cooling uniformity, artifact minimization, and usability. Techniques included both conductive and convective approaches and were evaluated using a Pugh Decision Matrix. The top three techniques, including the standard technique, were further assessed in a pilot clinical study. Water-based cooling with neoprene insulation and intensive pre-cooled pad cooling demonstrated the highest uniformity (mean standard deviations of 0.79 and 0.82 °C, respectively) and minimal artifact formation. Pilot clinical validation supported these findings. These techniques offer reliable and practical solutions for enhancing thermal contrast and image clarity in DIRT-based preoperative planning in DIEP flap surgery.
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Abbreviations: DIRT, Dynamic Infrared Thermography; DIEP, Deep Inferior Epigastric artery Perforator; CTA, Computed Tomography Angiography; ROI, Region of Interest; NETD, Noise Equivalent Temperature Difference; FOV, Field of View; IFOV, Instantaneous Field of View; MFOV, Measurement Field of View

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Breast cancer is the most frequently diagnosed cancer worldwide, with 2.3 million new cases reported in 2020. By 2045, the incidence is projected to increase by 92.8%.[1] Among breast cancer patients, there has been a growing trend toward breast reconstruction, particularly using autologous techniques such as Deep Inferior Epigastric artery Perforator (DIEP) flap surgery.[2,3] This technique, which uses the patient's own abdominal tissue for breast reconstruction, relies on precise perforator selection to ensure adequate blood supply, reduce the risk of tissue necrosis, and improve surgical outcomes.[4,5]

Dynamic infrared thermography (DIRT) is a non-invasive technique for perforator selection in DIEP flap surgery, offering an alternative to computed tomography angiography (CTA) by avoiding the use of ionizing radiation and contrast agents.[6] The effectiveness of DIRT, however, is highly dependent on the cooling technique used to prepare the tissue for thermal imaging.[7] Optimizing cooling techniques is essential to improve the accuracy of perforator detection and reduce the occurrence of false-positive hotspots. The primary criteria for an optimal cooling technique include uniform cooling, absence of artifacts, and sufficient cooling capacity.

De Weerd et al.[8] tested a pressed aluminum plate wrapped in a sterile drape, but reported non-uniform cooling and artifacts due to uncooled creases. Thiessen et al.[9] evaluated sterile compresses soaked in saline at 5 °C, which were similarly inadequate due to residual water leading to uneven cooling. A technique using a sterile water-filled bag at 3–5 °C, as described by Thiessen et al.[9] and Meier et al.,[10] showed the best balance of sufficient cooling, ease of use, and uniform temperature distribution, although it remained prone to creasing artifacts that could lead to false hotspot interpretation.[10,11]

Evaporative cooling techniques have been considered but excluded from this study due to limitations identified in earlier work. Alcohol spray, as investigated by Walle et al.,[12] caused rapid and uneven evaporation, leading to non-uniform cooling. Forced evaporative cooling using a fan, tested by Muntean et al.,[13] resulted in inconsistent temperatures ranging from 23–25 °C. Verstockt et al.[14] further demonstrated that such techniques not only resulted in uneven temperature distribution but also obstructed visibility post-cooling, making them unsuitable for DIRT analysis.

To allow for standardized application of each cooling technique, the region of interest (ROI) must be precisely defined, ensuring that all techniques are evaluated on an anatomically consistent and clinically relevant area. In DIEP flap planning, the lower abdomen is cooled to identify the optimal perforators. These perforators are typically located near the umbilicus, specifically lateral and inferior to the umbilicus in the rectus abdominis muscle. According to He J. et al.[15] and Bailey S. et al.,[16] perforators should be selected lateral to the umbilicus in Hartrampf zones I or II. Based on these anatomical guidelines, the perforators of interest are consistently located within a rectangular ROI measuring 200 mm in the sagittal plane and 140 mm in the transverse plane. The umbilicus is positioned 100 mm sagittally from both vertical borders of the rectangle, and 40 mm and 100 mm from the upper and lower transverse borders, respectively. This anatomical region is illustrated in Figure 1.

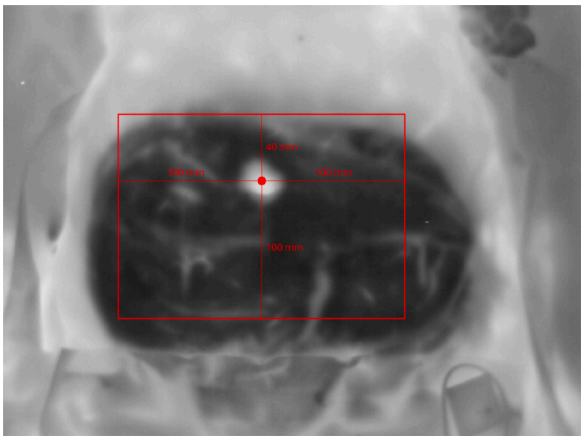


Figure 1 The ROI for perforator identification.

This study aims to systematically compare and refine cooling techniques for use in DIRT, enhancing its reliability as a preoperative tool for DIEP flap surgery. By comparing eleven different cooling techniques, this study seeks to identify the most effective approach in terms of cooling uniformity, artifact minimization, and perforator detection accuracy. The findings will contribute to optimizing preoperative planning, ultimately improving surgical outcomes and patient care.

Materials and methods

Study design and participants

This observational study was conducted in two consecutive phases: an experimental evaluation of cooling techniques on healthy volunteers, followed by a clinical pilot assessment on patients undergoing DIEP flap surgery. Ethical approval was obtained from the local ethics committee (Belgian registration number: B3002024000116), and written informed consent was obtained from all participants. This study was reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines.[17]

In the experimental phase, eleven cooling techniques were evaluated in five healthy adult volunteers (mean age 33.8 ± 8.2 years, mean BMI 25.3 ± 4.1 kg/m^2; age range 24–46, BMI range 20.9–30.1). Although male participants were included, this was not considered a limitation, as abdominal thermal response is not expected to differ significantly by sex.[18] In the clinical phase, the three best-performing techniques were applied in five female patients scheduled for DIEP flap reconstruction (mean age 48.8 ± 11.3 years, mean BMI 27.9 ± 4.6 kg/m^2; age range 34–59, BMI range 21.2–33.6).

Cooling techniques

A total of eleven cooling techniques were evaluated, each applied for a standardized duration of 180 s. The reference technique, referred to as the standard water-based cooling

technique, involved placing a sterile water-filled bag (500 × 400 mm, 5 °C) directly on the abdomen, as described by Thiessen et al.[9] and Meier et al.[10]

Three modified versions of this technique were tested using insulating layers positioned between the water bag and the skin, with the aim of reducing uncooled creases and improving thermal uniformity. The first variant used a cotton towel (500 × 700 × 0.1 mm, thermal conductivity 0.05 W/(m·K)), the second employed a neoprene mousepad (320 × 270 × 2 mm, 0.1 W/(m·K)), and the third utilized a thermal pad (400 × 200 × 2 mm, 6 W/(m·K)).

In a separate technique termed elastic water-based cooling, a latex balloon filled with water at 5 °C was applied to the abdominal surface. Two additional techniques involved directly applying thermal pads (400 × 200 × 2 mm, 6 W/(m·K)) to the skin after pre-cooling. One of these pads was cooled to 5 °C (mild pre-cooled pad cooling), while the other was cooled to -10 °C (intensive pre-cooled pad cooling).

Cryogenic air-based approaches were also included. In the cryogenic air bag cooling technique, a sterile bag was filled with cryogenic air at -30 °C using the Cryo 6 system (Zimmer Medizin Systeme, Ulm, Germany) at a flow rate of 1000 L/min, and gently pressed against the abdomen. In this setup, the air is vented through an opening near the cooler's inlet to maintain pressure equilibrium. Another technique, cryogenic air buffer cooling, involved directing cryogenic air onto a thermal pad (400 × 200 × 2 mm, 6 W/(m·K)) that acted as a buffer between the airflow and the skin.

Finally, two contactless convective techniques were tested using the Cryo 6 system. In the stationary cryogenic air cooling configuration, the outlet (20 mm diameter) was held perpendicular to the abdominal surface at a fixed distance of 200 mm, delivering air at -30 °C and 1000 L/min. In the moving cryogenic air cooling technique, the same distance and output were maintained, but the outlet was manually moved across the abdomen during the cooling period.

A summary of all cooling techniques, including their applied temperature and duration, is provided in Table 1. To ensure consistency and minimize operator-dependent variability, all cooling techniques were applied by the same individual.

Thermal imaging setup

Thermal recordings were obtained using a FLIR A655sc infrared camera (FLIR Systems, Inc., Wilsonville, OR, USA), operating in the long-wave infrared range (7.5–14 μm). The system features an uncooled microbolometer detector with a thermal sensitivity (NETD) below 30 mK and a pixel pitch of 17 μm. It is equipped with a 25° field-of-view (FOV) lens with a focal length of 24.6 mm, capturing 16-bit RAW thermal image sequences at a resolution of 640 × 480 pixels and a frame rate of 50 Hz. The camera was mounted perpendicularly at a fixed distance of 1060 mm from the abdominal surface to ensure complete and consistent coverage of the ROI across all participants. At this position, the FOV at the level of the umbilicus measured 470 × 350 mm, corresponding to an instantaneous field of view (IFOV) of 0.73 mm and a measurement field of view (MFOV) of 2.19 mm (3 × 3 pixels).

For each cooling session, image acquisition began 5 s prior to the end of cooling and continued for 5 s thereafter, resulting in a total sequence duration of 10 s at a frame rate of 50 Hz. To ensure that each cooling technique was tested independently and without interference from residual thermal effects, an acclimatization period of one hour was maintained between subsequent measurements.

Outcome measures and analysis

Cooling techniques were compared using a Pugh Decision Matrix, which enables a structured comparison of alternatives across multiple weighted criteria.[19] The standard water-based cooling technique was selected as the baseline technique, and each alternative was evaluated relative to this reference using a three-point scale: + (better), 0 (equal), or - (worse). Weights were assigned to reflect the relative importance of each criterion, based on stakeholder input.[20] The total score per technique was calculated by summing the individual weighted ratings across all criteria. This analysis is presented in Table 2.

Five evaluation criteria were defined. The primary outcome was cooling uniformity (weight 0.40), assessed by calculating the standard deviation of pixel temperatures

Table 1 Comparison of cooling techniques based on temperature and duration.

Cooling technique	Temperature (°C)	Time (s)
Standard water-based cooling	5	180
Water-based cooling with cotton insulation	5	180
Water-based cooling with neoprene insulation	5	180
Water-based cooling with thermal pad insulation	5	180
Elastic water-based cooling	5	180
Cryogenic air bag cooling	-30	180
Cryogenic air buffer cooling	-30	180
Mild pre-cooled pad cooling	5	180
Intensive pre-cooled pad cooling	-10	180
Stationary cryogenic air cooling	-30	180
Moving cryogenic air cooling	-30	180

Table 2 According to the Pugh Decision Matrix, water-based cooling with neoprene insulation and intensive pre-cooled pad cooling are the most suitable techniques.

Criterium	Uniformity	Artifacts	Cooling capacity	Usability	Cost	Score
Weight	0.4	0.3	0.1	0.1	0.1	
Water-based cooling with neoprene insulation	0	+	-	0	0	0.2
Intensive pre-cooled pad cooling	0	+	-	0	-	0.1
Standard water-based cooling	0	0	0	0	0	0
Water-based cooling with cotton insulation	0	0	-	0	0	-0.1
Cryogenic air buffer cooling	-	+	+	0	-	-0.1
Stationary cryogenic air cooling	-	+	+	0	-	-0.1
Mild pre-cooled pad cooling	0	0	-	0	-	-0.2
Cryogenic air bag cooling	-	+	+	-	-	-0.2
Moving cryogenic air cooling	-	+	+	-	-	-0.2
Elastic water-based cooling	-	+	-	-	0	-0.3
Water-based cooling with thermal pad insulation	-	0	0	0	-	-0.5

within the ROI immediately after cooling. The area surrounding the umbilicus was excluded due to its deeper anatomical location and inconsistent cooling behavior. A lower standard deviation indicated a more homogeneous cooling profile.[21]

Artifact formation (weight 0.30) was assessed qualitatively by inspecting for uncooled creases, irregular temperature gradients, or other visual disturbances that could interfere with perforator hotspot detection. Artifacts may arise not only from physical deformation but also from insufficient or uneven cooling, which can reduce thermal contrast and lead to premature or diffuse hotspot visibility.

Cooling capacity (weight 0.10) was defined as the lowest skin temperature within the ROI following cooling. Although deeper cooling is often assumed to enhance contrast, prior studies have shown that lower temperature differentials do not necessarily correlate with improved hotspot visibility. For example, Zetterman et al.[7] recommended intensive cooling for clearer contrast, while Weum et al.[6] achieved comparable results using room-temperature air flow, resulting in skin temperatures around 29 °C.

The final two criteria, usability and cost, were each weighted at 0.10. Usability encompassed the number and complexity of steps involved, the ease of handling, and the feasibility of integrating the technique into standard clinical workflows. Cost evaluation included material and equipment expenses with particular consideration of the Cryo 6 system, which represents a significantly higher acquisition cost than other approaches.

To validate the decision matrix results in a clinical context, the top three scoring techniques, including the standard reference, were subsequently tested in a pilot study involving five clinical patients.

Results

All eleven cooling techniques were tested in five healthy volunteers, and all measurements were successfully completed. Based on the results of this experimental phase, the three best-performing techniques, including the standard reference, were subsequently validated in five clinical DIEP flap patients. The analysis reveals varying levels of efficacy across techniques, particularly regarding cooling uniformity, artifact reduction, and usability. These findings are visually illustrated in Figure 2, which demonstrates the superior performance of water-based cooling with neoprene insulation and intensive pre-cooled pad cooling in terms of uniformity and minimal artifact formation. Quantitative assessments revealed that the mean temperature standard deviation for the most effective techniques ranged between 0.79 and 0.82 °C, underscoring their high degree of uniformity. The standard water-based cooling technique also exhibited commendable uniformity, albeit with a susceptibility to uncooled creases that could compromise image clarity. In contrast, cryogenic air cooling techniques displayed suboptimal uniformity, with temperature standard deviations reaching up to 6.95 °C. Notably, the moving cryogenic air configuration offered a marked improvement, reducing the standard deviation to 1.89 °C (Figure 2).

In the subsequent clinical pilot, involving five DIEP flap patients with complete datasets and no missing values, both water-based cooling with neoprene insulation and intensive pre-cooled pad cooling consistently outperformed the standard technique in terms of temperature uniformity. Neoprene insulation resulted in the lowest standard deviation in three patients, while intensive pre-cooled pad cooling performed slightly better in the other two. In those cases, the difference in temperature standard deviation between both techniques was 0.08 °C and 0.06 °C, indicating only minor variation. These results suggest a generally stable ranking of effectiveness across individuals, with only limited inter-patient variability in the relative performance of the top techniques. Figure 3 illustrates the clinical validation and supports these technical findings. Interestingly, while intensive pre-cooled pad cooling showed superior performance in the technical evaluation, it ranked slightly below water-based cooling with neoprene insulation in the clinical pilot. This discrepancy may reflect anatomical differences or subtle challenges in the consistent application of colder materials in a surgical context. Nevertheless, both top-performing techniques outperformed the standard technique, confirming their clinical potential.

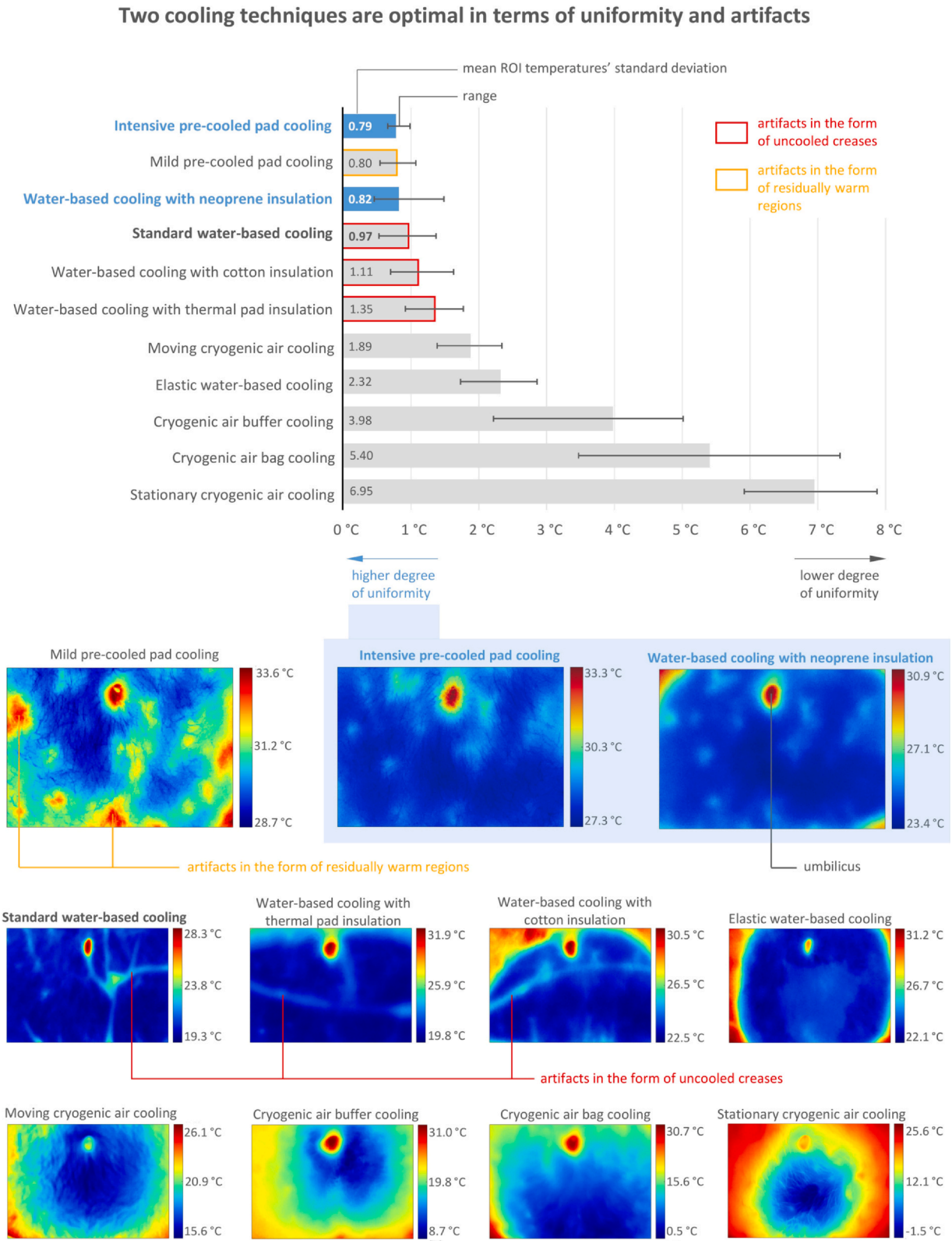


Figure 2 Intensive pre-cooled pad cooling and water-based cooling with neoprene insulation provide optimal uniformity and minimal artifacts. Note: Each image has an individually adjusted temperature scale due to substantial differences in cooling capacity among techniques. As a result, visual differences in color distribution may exaggerate perceived non-uniformities.

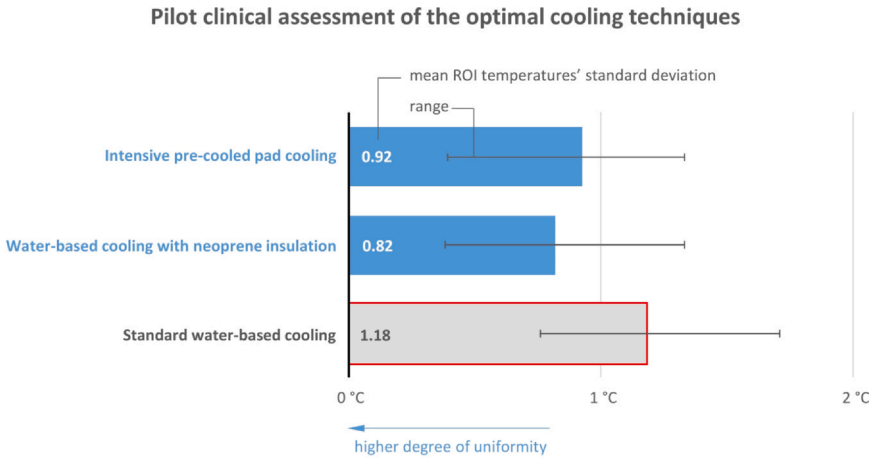


Figure 3 Pilot clinical assessment of the optimal cooling techniques in five DIEP flap patients supports their effectiveness and reveals differences in clinical uniformity. Water-based cooling with neoprene insulation performs best in this context, indicating that application consistency may influence outcomes.

Artifact analysis was conducted qualitatively, with water-based cooling with neoprene insulation and intensive pre-cooled pad cooling techniques demonstrating minimal artifact formation (Figure 2). While mild pre-cooled pad cooling demonstrates high uniformity and minimal artifacts in the form of uncooled creases, its limited cooling capacity results in residually warm regions that can lead to false-positive hotspot identification. The standard water-based cooling technique, while effective in maintaining uniformity, frequently results in the presence of uncooled creases, also increasing the likelihood of false positives.

Evaluations of usability indicate that water-based cooling techniques with insulation and pre-cooled pads are straightforward to prepare and require minimal training. Conversely, cryogenic air cooling techniques present challenges due to their operational complexity and higher associated costs. The elastic water-based cooling technique is found to be impractical due to its slippery surface, substantial weight, and tendency to cause splashing.

A summary of the weighted evaluation is presented in Table 2, confirming that water-based cooling with neoprene insulation achieved the highest overall score (0.2), followed by intensive pre-cooled pad cooling (0.1). The standard water-based cooling technique scores neutrally at 0, while techniques such as cryogenic air bag cooling and elastic water-based cooling score negatively due to their subpar performance across key criteria.

Discussion

The findings of this study underscore the critical importance of selecting an optimal cooling technique for DIRT in DIEP flap surgery. Both water-based cooling with neoprene insulation and intensive pre-cooled pad cooling exhibit superior uniformity and artifact minimization, essential elements for accurate and reliable perforator identification. The consistent efficacy of these techniques supports their adoption in clinical settings, where reliability and operational simplicity are crucial.

The observed difference in performance ranking between the experimental setup and the pilot clinical assessment underscores the influence of contextual factors such as anatomical variability and application consistency. While both water-based cooling with neoprene insulation and intensive pre-cooled pad cooling consistently outperformed the standard technique, their relative performance showed minor variation between patients. In three out of five clinical cases, water-based cooling with neoprene insulation resulted in the lowest temperature variation, suggesting more consistent performance across individuals, possibly because of its ease of positioning and surface stability. In the other two cases, intensive pre-cooled pad cooling yielded slightly lower temperature variation, but the improvement over neoprene insulation was minimal. This overall pattern indicates a generally stable ranking with limited inter-patient variability. These findings highlight the importance of validating these trends in larger and more diverse clinical populations to confirm reproducibility and refine technique selection.

A notable advantage of these techniques is their minimal artifact generation. The reduction of uncooled creases significantly decreases the risk of false-positive hotspots, thereby facilitating clearer identification of perforators during the warming phase. While these techniques showed a lower cooling capacity compared to cryogenic approaches, their performance remained sufficient for clinical use, ensuring that perforator detection was not compromised. These findings reinforce the clinical utility of DIRT as previously demonstrated by De Weerd et al.,[8] and support recent insights from Meier et al.[10] regarding the necessity of uniform cooling to avoid artifacts such as false hotspots.

In addition to their technical performance, the top-performing techniques demonstrated strong clinical practicality. For both water-based cooling with neoprene insulation and intensive pre-cooled pad cooling, setup was simple and quick. The water-based techniques required only the filling of a sterile bag with cold water and, in the insulated variant, the addition of a neoprene layer, which could be applied or removed within seconds. Pre-cooled thermal pads were equally easy to position without fixation

or adjustment. However, to maintain the intended cooling temperature, these pads should be applied immediately after removal from a cold storage unit maintained at –10 °C. This necessitates access to a nearby freezer. Nonetheless, both the neoprene-insulated water-based technique and the pre-cooled pad technique required less attention during application than the standard technique, where manual effort is often needed to position the cooling element in a way that minimizes uncooled creases. Consequently, the need for operator training is reduced. Moreover, all necessary materials were readily available through commercial suppliers at low cost. These characteristics support the integration of these techniques into routine surgical workflows with minimal burden in terms of time, complexity, or resources.

An important consideration highlighted by this study is that a brief or minimal cooling duration may theoretically result in high cooling uniformity by reducing temperature gradients across the skin surface. However, such an approach may not sufficiently enhance the visibility of perforators, which depend on distinct temperature contrasts following cooling. Another limitation of this study is the use of a uniform cooling duration across all techniques and identical cooling temperatures across all water-based techniques. While this design choice ensures consistency and comparability, it also constrains the ability to assess the varying intrinsic cooling capacities of the different techniques. This implies that the applied conditions may not represent the optimal performance settings for each individual technique, potentially leading to an overestimation or underestimation of their true efficacy. Therefore, the relationship between cooling duration, cooling intensity, and perforator visibility warrants further systematic investigation. Future research should explore optimal combinations of cooling parameters that strike a balance between uniform cooling and sufficient temperature contrast to enable reliable perforator identification.

Several limitations of this study should be acknowledged. Firstly, artifact analysis relied on qualitative visual inspection without a standardized or semi-quantitative scoring system, introducing potential observer bias. Future work should consider implementing objective or graded criteria to enhance reproducibility. Secondly, all cooling techniques were applied by a single individual to reduce variability in positioning, timing, and pressure. While this approach enhances internal consistency and strengthens the validity of intra-study comparisons, it does not account for potential variability across different users. Future research should examine inter-operator reproducibility. Finally, no comparison was made with established imaging modalities such as CTA or magnetic resonance angiography (MRA). Consequently, the diagnostic accuracy of DIRT, including sensitivity, specificity, and false-positive rates, remains to be validated against clinical gold standards.

Beyond these considerations, alternative strategies may further enhance DIRT performance. Approaches such as advanced image processing algorithms, including automated artifact detection and correction, as well as artificial intelligence-driven image enhancement techniques, represent promising directions for future investigation. These methodologies could further enhance perforator detection accuracy and complement improvements achieved through optimized cooling protocols.

Conclusions

This study systematically compared eleven cooling techniques for their application in DIRT during DIEP flap planning and provided preliminary clinical validation in a small patient cohort. Among the tested techniques, water-based cooling with neoprene insulation emerged as the most effective in the experimental setting and demonstrated comparable performance in pilot clinical cases. These results highlight the feasibility and clinical potential of this technique as a reliable and practical tool for improving perforator identification. While promising, these findings warrant further validation in larger, more diverse patient populations before broader implementation in clinical practice can be recommended.

CRediT authorship contribution statement

Conceptualization, Clarys W., Thiessen F., Steenackers G.; methodology, Clarys W., Thiessen F., Steenackers G., Hummelink S.; investigation, Clarys W.; data curation, Clarys W.; writing—original draft preparation, Clarys W.; writing—review and editing, Clarys W., Verspeek S., Verstockt J., Hummelink S., Thiessen F., Steenackers G.; visualization, Clarys W.; supervision, Verspeek S., Steenackers G., Thiessen F. All authors have read and agreed to the published version of the manuscript.

Ethical approval

Ethical Statement: the authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Ethical approval has been obtained from ethics committee. Belgian registration number: B3002024000116.

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Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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