

Artificial Intelligence–Driven Analysis of Infrared Thermography for Noninvasive Diagnosis of Low Cardiac Output in Critically Ill Patients

Análisis de termografía de infrarrojos mediante inteligencia artificial para diagnóstico no invasivo de bajo gasto cardíaco en pacientes críticos

ANDRÉS N. ATAMAÑUK^{1,2}, IGNACIO J. GANDINO², HORACIO E. FERNÁNDEZ³, RENZO E. MELCHIORI³, LUIS E. GÓMEZ², JORGE BILBAO³, NICOLÁS A. TORRES³, GUSTAVO ROSS QUAAS⁴, SERGIO J. BARATTA³

ABSTRACT

Background: Skin blood flow plays a key role in thermoregulation and is impaired in hemodynamic shock. Infrared thermography offers a noninvasive method for mapping peripheral temperature and analyzing its performance in patients with hemodynamic instability.

Objective: The aim of this study was to evaluate facial thermal behavior in critically ill patients undergoing invasive hemodynamic monitoring using an infrared camera and to establish the diagnostic value of artificial intelligence-driven analysis for diagnosing low cardiac output.

Methods: We conducted a cross-sectional study of critically ill patients undergoing pulmonary artery catheter monitoring. Facial thermal images were obtained using an infrared camera simultaneously with measurements of hemodynamic parameters obtained via invasive monitoring. Six predefined facial regions were analyzed, and individual and average temperatures and thermal gradients were calculated. Thermal data were processed using machine learning to predict a cardiac index < 2.5 L/min/m².

Results: A total of 35 monitoring sessions were performed on 18 patients (age 60 ± 14 years, 70% male). Sixty percent were in shock, and 40% were in the postoperative period following cardiovascular surgery; 54% were receiving ≥ 2 vasoactive drugs. Most infrared facial thermography analyses had a significant association with cardiac index, and the thermal gradient (TG) was the variable with the strongest correlation ($r = -0.45$; $p = 0.010$). The neural network model achieved an area under the ROC curve of 0.75 for predicting low cardiac output.

Conclusions: In this proof-of-concept study, facial thermography identified regions and gradients with a significant correlation with cardiac index. Its integration with artificial intelligence demonstrated a promising biological signal for detecting low cardiac output, emerging as an alternative to noninvasive hemodynamic monitoring in the critical care setting.

Key words: Thermography - Artificial intelligence - Hemodynamics - Critical care - Shock - Heart failure - Monitoring

RESUMEN

Introducción: El flujo sanguíneo cutáneo desempeña un papel clave en la termorregulación, y se ve alterado en estados de shock hemodinámico. La termografía infrarroja ofrece un método no invasivo para mapear la temperatura periférica y analizar su comportamiento en pacientes con inestabilidad hemodinámica.

Objetivo: Evaluar el comportamiento térmico del rostro de pacientes críticos bajo monitoreo hemodinámico invasivo, mediante el uso de cámara infrarroja. De manera secundaria, por medio de inteligencia artificial, establecer el valor diagnóstico de dicho método para bajo gasto cardíaco.

Material y métodos: Estudio transversal en pacientes críticos bajo monitoreo con catéter de arteria pulmonar. Se obtuvieron imágenes térmicas faciales con cámara infrarroja simultáneamente a la realización de mediciones hemodinámicas invasivas. Se analizaron seis regiones faciales predefinidas y se calcularon temperaturas aisladas, promedios y gradientes térmicos. Los datos fueron procesados mediante *machine learning* para predecir un índice cardíaco $< 2,5$ L/min/m².

Resultados: Se realizaron 35 monitoreos en 18 pacientes (edad 60 ± 14 años, 70 % hombres). El 60 % presentaba shock y el 40 % estaba en posoperatorio cardíaco; 54 % recibía ≥ 2 drogas vasoactivas. La mayoría de los análisis térmicos faciales mostraron correlación significativa con el índice cardíaco (mejor correlación, gradiente térmico (GT): $r = -0,45$; $p = 0,010$). El modelo de redes neuronales alcanzó un área bajo la curva ROC de 0,75 para predecir bajo gasto.

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Correspondence: Andrés Nicolás Atamañuk. E-mail: nicoatama@hotmail.com

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¹ Heart Failure and Heart Transplantation Section, Hospital Universitario Austral, Pilar, Buenos Aires, Argentina.

² Department of Cardiology, Hospital General de Agudos Juan A. Fernández, Ciudad Autónoma de Buenos Aires, Argentina.

³ Cardiovascular Critical Care Unit, Hospital Universitario Austral, Pilar, Buenos Aires, Argentina.

⁴ Artificial Intelligence Center of the University of Mexico and Panamerican University.

Conclusiones: En esta prueba de concepto, la termografía facial identificó regiones y gradientes con correlación significativa con el índice cardíaco. Su integración con inteligencia artificial exhibió una señal biológica prometedora para la detección de bajo gasto cardíaco, perfilándose como una alternativa a explorar para el monitoreo hemodinámico no invasivo en el entorno crítico.

Palabras clave: Termografía - Inteligencia artificial - Hemodinamia - Cuidados críticos - Shock - Insuficiencia cardíaca - Monitoreo

INTRODUCTION

Hemodynamic monitoring is an essential component for the management of critically ill patients, and cardiac output (CO) is recognized as one of the primary indicators of circulatory status. Throughout history, Fick's method and thermodilution via a pulmonary artery catheter (PAC) have been considered the gold standard. Their invasive nature entails significant risks, including arrhythmias during insertion (ranging from 12.5% to over 70%). Clinically significant ventricular arrhythmias occur in less than 1%. Catheter-associated bacteremia is another complication occurring in approximately 1.3%–2.3% of cases. (1,2) These limitations have driven the development of less invasive or noninvasive alternatives for assessing hemodynamic status.

Among minimally invasive methods, transpulmonary thermodilution—as represented by devices such as PiCCO— (3,4) uses a central venous catheter and an arterial catheter, although it has limitations in patients undergoing extracorporeal therapies or with intracardiac shunts. Transpulmonary lithium dilution, (5,6) available in systems such as LiDCO, requires the injection of lithium chloride and an arterial sensor, which limits its use in patients undergoing lithium therapy or exposed to certain muscle relaxants. Arterial pressure waveform analysis using the FloTrac/Vigileo or MostCare systems is another alternative that estimates beat-by-beat stroke volume without requiring calibration in some systems. Nevertheless, the accuracy of this analysis may be reduced in states of vasoplegia or in the presence of ventricular assist devices. (7-9) The accuracy of these methods may be limited in patients with pacemakers, pulmonary hypertension, or severe valvular regurgitation. (10,11) Transthoracic and transesophageal Doppler echocardiography provide information on blood flow and cardiac morphology, but require specific training and exhibit interobserver variability. In addition, esCCO system, based on pulse oximetry, electrocardiography, and peripheral pulse wave analysis, has demonstrated a favorable correlation with thermodilution in selected studies. (9-12) However, the evidence regarding these techniques is characterized by significant methodological heterogeneity, small sample sizes, and limited safety information, although the incidence of adverse effects appears to be low. (12) Furthermore, costs are variable, ranging from esophageal Doppler—an affordable option—to PiCCO, one of the most expensive minimally invasive alternatives. (9-12)

In this context, infrared thermography emerges as a promising, fully noninvasive, and low-cost tool that captures infrared radiation from tissues and helps

identify abnormalities in peripheral perfusion. Its clinical potential has been evaluated in heart failure, where recent studies have shown that, when combined with artificial intelligence (AI) algorithms, it can differentiate patients with acute decompensated heart failure from controls, with an interesting sensitivity and an area under the ROC curve of 0.82. (13) Similarly, ocular surface temperature, measured using thermography, has shown a correlation with core body temperature (14,15) and an association with cardiovascular outcomes, such as acute myocardial infarction and long-term prognosis in animal models. (16) This evidence suggests that infrared thermography could become a diagnostic and clinical monitoring tool applicable in critical care settings and telemedicine contexts, providing a safe and accessible alternative to current hemodynamic strategies.

METHODS

We conducted a cross-sectional study in the Critical Care Cardiology Unit of two tertiary hospitals. We included patients consecutively admitted and undergoing invasive PAC monitoring, indicated by clinical criteria independent of this protocol. Patients with a history of facial surgery or trauma, severe facial edema, active infections, ocular or facial devices, and any condition that could alter anatomy or thermal patterns were excluded from the study. The study protocol was approved by the institutional review board and complied with the Declaration of Helsinki. (17)

For each patient, three serial facial thermal images were obtained using a portable infrared camera (FLIR ONE®, FLIR Systems Inc.) with a resolution of 160 × 120 pixels and a spectral range of 8–14 μm . The photos were taken simultaneously with three hemodynamic measurements obtained using the PAC, and the values were averaged for analysis. The photos were taken in the supine position, 10 cm from the face in a room with controlled environmental temperature, avoiding the influence of external heat sources or drafts.

The images were analyzed using specialized thermography software. A blinded evaluator selected six facial regions of interest: forehead, right cheek, left cheek, nose, and the inner corners of both eyes. Three types of variables were calculated in these regions: 1) individual temperatures per region (T), 2) average temperatures across different regions (AT), and 3) thermal gradients between regions (TG) (Figure 1). Subsequently, a second blinded evaluator compared the thermal parameters with the hemodynamic variables obtained via the PAC.

Thermal data were processed using machine learning to identify the optimal predictive model for a cardiac index (CI) < 2.5 L/min/m², defined as low cardiac output.

Qualitative variables are expressed as numbers and percentages and quantitative variables are expressed as mean and standard deviation. The association between categorical variables was explored using the chi-square test or Fisher's test, while the Student's t test or the Wilcoxon rank sum test was used for quantitative variables. The Pearson or Spear-

man correlation coefficients were used to measure the relationship between quantitative variables. A p -value < 0.05 was considered statistically significant. Discriminative ability was evaluated using ROC curves and calculating the area under the curve (AUC), along with sensitivity, specificity, and predictive values. The study protocol was approved by an institutional review board. Patients' identities were protected because the characteristics of the thermal images do not allow for facial identification.

RESULTS

A total of 18 patients underwent 35 hemodynamic monitoring sessions, with 9 patients undergoing 2 or more monitoring sessions. Mean age was 60 ± 14 years and 70% were men. The causes of hospitalization were heart failure in 50% of cases, postoperative care following cardiovascular surgery in 39%, and non-cardiovascular causes in 11% of cases. The indication for hemodynamic monitoring was shock in 60% of cases, and postoperative complications following cardiovascular surgery in 40%. Seventeen (94.4%) patients required vasoactive drugs; 2 drugs or greater were used in 19 (54.3%) monitoring sessions. These agents included dobutamine and norepinephrine in more than 50% of cases, milrinone in 27%, and epinephrine and nitroglycerin in $< 10\%$.

During hemodynamic monitoring with the PAC,

CO was calculated using the thermodilution method in 31 measurements (88.6%). Low cardiac output occurred in 18 cases (51.4%), with the following values: mean arterial pressure (MAP), 74.5 ± 7.8 mmHg; heart rate (HR), 95.7 ± 21.2 beats/min; mean pulmonary artery pressure (MPAP), 26.2 ± 8.7 mmHg; pulmonary capillary wedge pressure (PCWP), 12.2 ± 4.9 mmHg; central venous pressure (CVP), 7.3 ± 4.2 mmHg; cardiac index (CI), 2.6 ± 0.6 L/min/m²; systemic vascular resistance (SVR) 1123.3 ± 260.1 dyn·s·cm⁻⁵; and pulmonary vascular resistance (PVR), 168 ± 87.4 dyn·s·cm⁻⁵. Twenty-five percent of patients were on mechanical ventilation.

A total of 105 thermographic images were obtained. The thermal data that showed the strongest correlation with the CI were, respectively: T1, 35.55 ± 1.84 °C ($r = 0.42$, $p = 0.010$); T3, 34.48 ± 2.45 °C ($r = 0.37$, $p = 0.021$), T4, 35.74 ± 1.48 °C ($r = 0.41$, $p = 0.012$), AT1 (average between T1 and T4), 34.99 ± 1.47 °C ($r = 0.43$, $p = 0.014$) and GT (gradient between T1 and AT1), 1.32 ± 0.59 °C ($r = -0.45$, $p = 0.010$). There were also some significant correlations between SVR and CVP (Table 1), but not with PCWP, HR, MPAP and MAP. Except for T2, all thermal measurements correlated with CI, and the best value was obtained with TG (Figure 2).

Fig. 1. Facial thermographic image of a patient acquired with an infrared camera (FLIR ONE). The regions measured are indicated: T1 (glabellar region), T2 (inner corner of the eyes), T3 (nasal root), and T4 (alar groove). The color scale indicates temperature variations in °C.

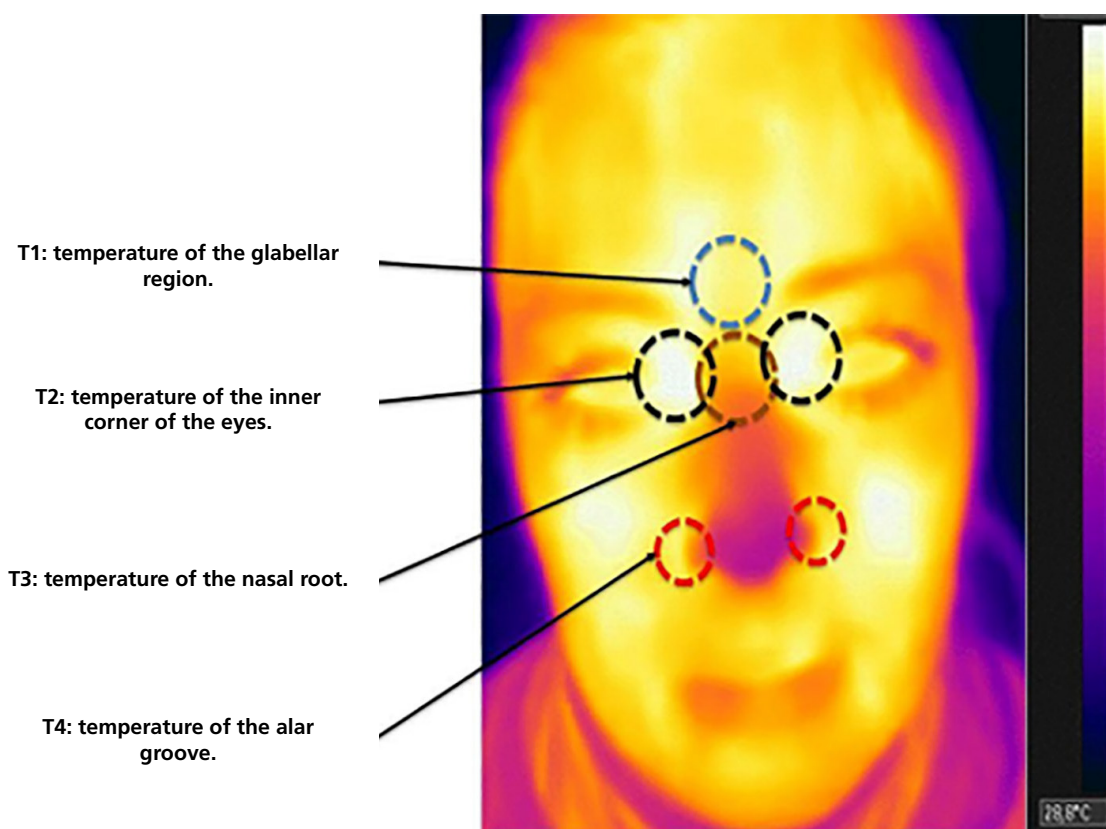
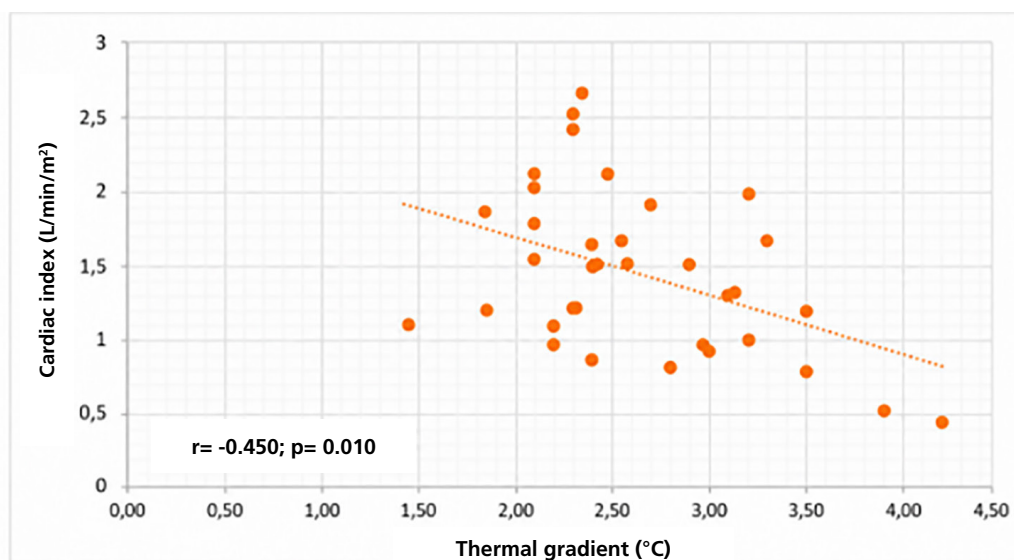


Table 1. Thermal values and their correlation with cardiac index.

Hemodynamic variable	T1	T2	T3	T4	AT=1	AT=1
CVP	r = 0.42; p = 0.010	r = 0.32; p = 0.506	r = 0.37; p = 0.020	r = 0.35; p = 0.033	r = 0.4; p = 0.010	NS
MPAP	NS	NS	NS	NS	NS	NS
PCWP	NS	NS	NS	NS	NS	NS
MAP	NS	NS	NS	NS	NS	NS
HR	NS	NS	NS	NS	NS	NS
CI	r = 0.42; p = 0.010	NS	r = 0.37; p = 0.021	r = 0.41; p = 0.012	r = 0.43; p = 0.010	r = -0.45; p = 0.010
SVR	r = -0.36; p = 0.030	NS	r = -0.35; p = 0.041	r = -0.44; p = 0.010	r = -0.41; p = 0.010	NS
PVR	NS	NS	NS	NS	NS	NS

CI: cardiac index; CVP: central venous pressure; HR: heart rate; MAP: mean arterial pressure; MPAP: mean pulmonary artery pressure; NS: non-significant; PCWP: pulmonary capillary wedge pressure; PVR: pulmonary vascular resistance; SVR: systemic vascular resistance; T: individual temperature by region; TG: thermal gradient; TP: average temperature.

Fig. 2. Correlation between facial thermal gradient (TG) and cardiac index (CI). A significant inverse association is observed ($r = -0.45$; $p = 0.01$).

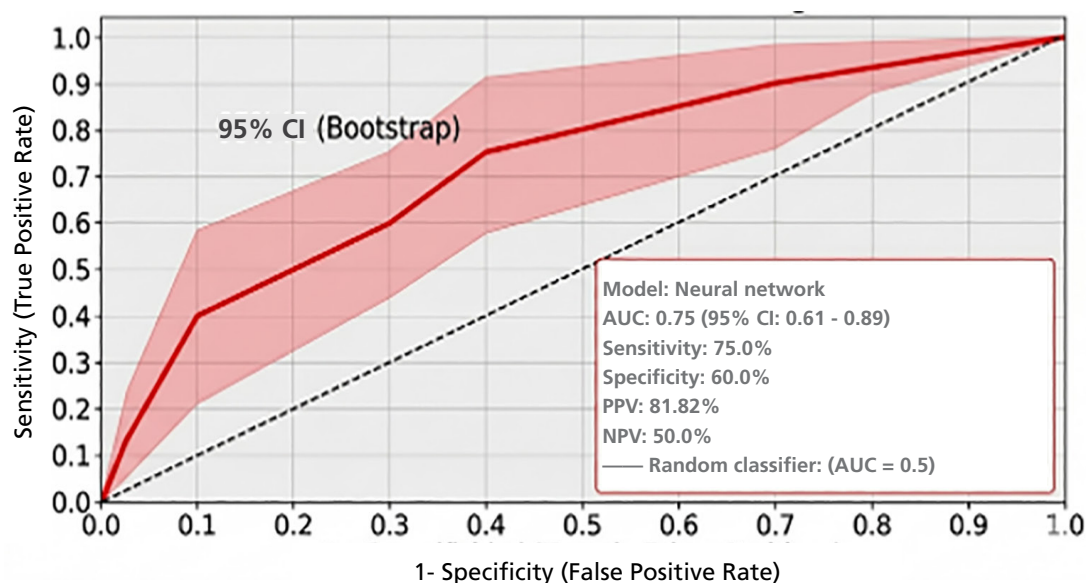
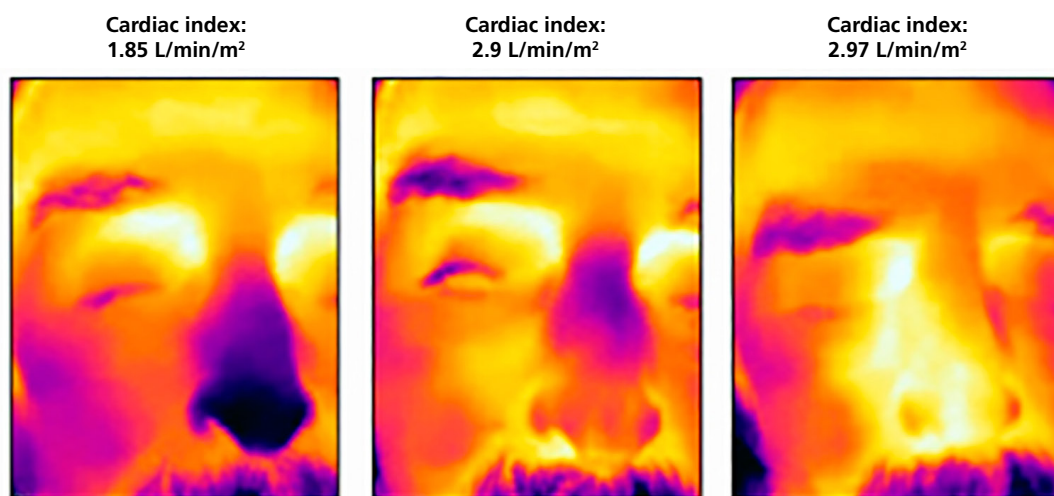
The best model to predict low cardiac output with the use of AI was a neural network with an AUC-ROC of 0.75 (95% CI 0.61–0.89), sensitivity of 75.0%, specificity of 60.0%, positive predictive value of 81.82%, and negative predictive value of 50.00% (Figure 3).

DISCUSSION

This study demonstrates that infrared facial thermography, integrated with AI, can identify significant correlations with CI, particularly through thermal gradients. These findings are consistent with previous evidence demonstrating that thermography had a sensitivity of 84% and a specificity of 52% to detect

acute decompensated heart failure. (13) Additionally, recent studies describe how skin thermoregulation is abnormal in heart failure, with a slower and reduced thermal response during exercise, particularly in patients with reduced ejection fraction. (18,19) This thermal dysfunction reflects impaired peripheral perfusion and progression toward advanced stages of the disease.

It is worth noting that the correlation between peripheral temperature and CI is not a novel finding. (19,20) In 1969, Joly and Weil published a pioneering study demonstrating that hallux temperature was a sensitive marker of peripheral hypoperfusion and cor-

Fig. 3. ROC curve for predicting CI <2.5 L/min/m², using a neural network model based on facial thermography.**Fig. 4.** Facial thermographic images of a patient with cardiogenic shock across three distinct hemodynamic states. From left to right, a progressive improvement in cardiac index (1.85, 2.9, and 2.97 L/min/m²) is observed, with the corresponding thermal changes on the color scale (white = higher temperature, black = lower temperature).

related with cardiac output in patients with shock. (21) That paper laid the physiological basis for considering skin temperature as an indirect reflection of circulatory status, predating modern applications of thermography by several decades. Our results extend this observation to facial thermal analysis, further incorporating AI algorithms to optimize diagnostic capability.

The strength of this study lies in a standardized protocol using simultaneous thermal imaging with invasive CI monitoring in critically ill patients, regional

facial analysis, and AI-driven processing. This enabled robust correlations with CI, providing a novel diagnostic approach. This is the first report to combine facial thermography, simultaneous invasive monitoring, and AI-driven analysis, offering a fully noninvasive, rapid, and cost-effective tool with potential applications in telemedicine and critical care.

However, some limitations should be considered. The modest sample size and clinical heterogeneity—with a high proportion of patients presenting with

shock or post-cardiac surgery— restrict the generalizability of the results. Furthermore, the predictive ability of the AI-driven model, with an AUC of 0.75, is promising but requires external validation in larger and more homogeneous cohorts. It is not yet known whether these thermal patterns vary among specific subtypes of heart failure (based on ejection fraction, among other factors). Additionally, the temporal evolution of thermal patterns following hemodynamic interventions was not evaluated—although individual patient analyses revealed thermal–hemodynamic concordance (Figure 4)— nor was its utility explored in outpatient or remote monitoring.

In line with recent reviews, medical thermography has multiple valid applications, such as the early detection of vascular or inflammatory changes, and detection of subtle thermal variations that precede structural abnormalities. (14) However, it is essential to remember that thermography is a complementary physiological tool and does not replace conventional structural methods, such as echocardiography or cardiac catheterization, among others. As such, thermography could serve as a novel complementary diagnostic tool in critical care, and its integration with AI offers clear advantages over current alternatives due to its noninvasive, rapid, and cost-effective nature.

CONCLUSION

Infrared facial thermography showed an association with cardiac index in critically ill patients, with the thermal gradient being the variable with the strongest correlation. Integration with artificial intelligence enabled the identification of a physiological signal with potential utility for detecting low cardiac output.

Given the exploratory nature of the study, the limited sample size, and the absence of external validation, these findings should be interpreted with caution. Prospective studies with a larger number of patients and robust analytical method are needed to confirm the diagnostic value and define the applicability of this method.

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Conflicts of interest

None declared.

(See authors' conflict of interests forms on the web).

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