Predicting Hemodynamic Shock from Thermal Images using Machine Learning

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Proactive detection of hemodynamic shock can prevent organ failure and save lives. Thermal imaging is a non-invasive, non-contact modality to capture body surface temperature with the potential to reveal underlying perfusion disturbance in shock. In this study, we automate early detection and prediction of shock using machine learning upon thermal images obtained in a pediatric intensive care unit of a tertiary care hospital. 539 images were recorded out of which 253 had concomitant measurement of continuous intra-arterial blood pressure, the gold standard for shock monitoring. Histogram of oriented gradient features were used for machine learning based region-of-interest segmentation that achieved 96% agreement with a human expert. The segmented center-to-periphery difference along with pulse rate was used in longitudinal prediction of shock at 0, 3, 6 and 12 hours using a generalized linear mixed-effects model. The model achieved a mean area under the receiver operating characteristic curve of 75% at 0 hours (classification), 77% at 3 hours (prediction) and 69% at 12 hours (prediction) respectively. Since hemodynamic shock associated with critical illness and infectious epidemics such as Dengue is often fatal, our model demonstrates an affordable, non-invasive, non-contact and tele-diagnostic decision support system for its reliable detection and prediction.

Shock is a clinical state of mismatch between the demand and supply of cellular oxygen. It is most commonly associated with fluid loss (hypovolemia), inefficient pumping (cardiogenic) or infections (septic) that cause redistribution of fluids within the body. All three mechanisms contribute, often in combination, to shock in the intensive care unit (ICU). Shock affects almost 30% of ICU patients¹ with mortality rates as high as 34% especially in the developing countries². Although reversible in initial stages, delay in detection leading to ineffective management of shock often leads to rapid deterioration of tissue function, failing organs (lungs, liver, kidney, gut) and eventually death. The 2014 consensus update on shock has recommended a more aggressive approach to hemodynamic assessment including response to fluids and sequential evaluations³. Aggressive management that has been shown to improve outcomes⁴–⁶. While continuous assessment is vital, many of the recommended procedures involve invasive monitoring which substantially contributes to hospital-acquired infections. The non-invasive methods, such as cuff-based BP monitoring and ultrasonography are not continuous and additionally require skin-contact which is a risk factor for infections especially in neonates and infants⁷. Importantly, hemodynamic compromise is not only prevalent in the ICUs but also in the community in developing countries with low doctor-to-patient ratio and high rate of infections such as dengue and diarrhea that often lead to shock. Hence, a non-invasive, non-contact modality for monitoring hemodynamic status is highly desirable for guiding shock management.

Here we report a non-invasive, non-contact modality constructed using a combination of thermal-imaging, machine-learning and longitudinal data analysis for detection and prediction of shock in patients admitted to a pediatric intensive care unit (PICU). We had earlier reported the feasibility of such recordings on a small number of images by using an affordable device attached to Android Smartphone⁸ and its potential value for shock-detection using a hand-calculated feature, central-to-peripheral temperature difference, a known feature of shock⁹,¹⁰. In this paper, we expand the feasibility study to detect and predict (forecast) shock up to 12 hours in

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advance using a fully automated computer vision and machine-learning pipeline (Fig. 1). We do this by training random forest classifiers for ROI extraction using shape features extracted from thermal images. Shock-index, defined as the ratio of heart rate and systolic blood pressure is one of the important measures of hemodynamic instability\textsuperscript{11,12} and guided the model learning as an outcome variable. A longitudinal data modelling approach using generalized linear mixed-effects model for detection and prediction of binary shock-index is tested. Hence the aim of this study was to construct a robust, non-invasive, non-contact, automated and affordable pipeline for shock prediction using machine learning and this is demonstrated through superior model prediction indices. The potential to scale beyond the intensive care settings to emergency rooms and the community make this study especially valuable for decision making for shock in resource-limited settings.

**Results**

**Patient demographics.** Cohort characteristics and statistical differences in shock versus non-shock groups are shown in Table 1. Shock and Non-shock were defined on the basis of Shock Index Pediatric Age-adjusted calculation. As expected, pulse rate (and heart rate) showed the most significant difference between the two groups, followed by age.

**Center-to-periphery difference achieved 75% accuracy in detecting and predicting shock.** A representative thermal image with manual extraction of center-to-periphery difference (CPD) is shown in Fig. 1 (top-right), clearly demonstrating a difference in intensity between abdomen and foot (open dots). CPD was calculated along the lines (green) joining the abdomen and foot and was used as a predictor in the generalized mixed model for detection and prediction of binary shock index (response variable). The non-linear, U-shaped dip present in most images corresponds to the diaper worn by the children and may be ignored. Figure 2 shows the area under the ROC curve for detection (0 hr) and prediction (3 hr) generalized linear mixed effects models. A test set accuracy of 75% in detection and 3 hr prediction were achieved (Table 2; AUC = 79%, sensitivity = 0.69, specificity = 0.79), thus validating the non-contact, non-invasive potential for CPD. Similar accuracies were obtained at 3 hr, 6 hr and 12 hr post-imaging models (Table 2). This result encouraged us to construct automated pipelines for shock detection and prediction without minimal manual intervention as a next step.

**Histogram of oriented gradients combined with random forest achieved 99% and 94% AUC for abdomen and foot segmentation.** Thermal images are often noisy as the IR radiation is diffuse. Thus, these lack sharp features and may be contaminated by ambient thermal noise. Since we could not use texture or color for recognition of ROIs, a pipeline relying upon shape features was designed. Figure 3 illustrates the steps of this pipeline which included image processing, HOG feature generation and Random Forest classifiers for foot and abdomen detection. The classifiers constructed a bounding box and an ROI (lower right), which were then evaluated against the human-labeled ground truth. Scale-invariance of detection was achieved by using an adaptive window size while detecting the foot and abdomen, with a resultant AUC of 99% for abdomen detection.
and 94% for foot detection evaluated against the human annotated ground truth (Fig. 4). The median intensity of
the ROIs were taken forward for constructing longitudinal models for detection and prediction of shock.

Topical subheadings are allowed.

### Shock detection using automated difference.

The ROI’s around foot and abdomen were used for further automation of shock detection using the automated CPD. Generalized mixed effects model using repeated patient samples as random effects and age, pulse rate as covariates achieved 0 hr detection accuracy of 73% (sensitivity = 0.58, specificity = 0.81), Table 3. The ROC curve for automated shock detection is shown in Fig. 4A. Since our model does not include the prior history of shock status in a patient, it can be used for classification of shock/no-shock from a snapshot alone.

### Shock prediction using automated difference.

The SAFE-ICU resource allowed us to mine time-stamped shock indices at 3 hr, 6 hr and 12 hr from the time of imaging. Similar models using mixed effects were constructed for these time points as well to evaluate the predictive potential of automated CPD. Interestingly, the models were able to predict the binary shock-index status, especially at 3 hours from imaging with an accuracy of 73% (PPV 75%, NPV 74%) (Table 3, Fig. 5B). In an ICU where patients may rapidly decompensate and end up in failure, a lead time of up to 3 hours can make a considerable difference in saving lives and in preventing organ failure which contributes to major human and economic morbidity in ICU survivors. Since the models were evaluated upon 10 repeated partitions, we could assess and compare the stability of AUC between manual and automated shock prediction models (Supplementary Figure S1). As expected, the manual and automated

| Variable                              | Non-shock Images n = 147 | Shock Images n = 106 | Statistical Test |
|---------------------------------------|--------------------------|---------------------|-----------------|
| Age (months)                          | 33.23 (46.76)            | 58.33 (53.84)       | 5.97E-07 (W)    |
| Mean Arterial Blood pressure, mm Hg   | 71.66 (19.33)            | 63.45 (16.69)       | 0.002162 (W)    |
| Arterial Systolic Blood pressure, mm Hg | 97.55 (21.81)            | 88.97 (21.62)       | 0.004605 (W)    |
| Arterial Diastolic Blood pressure, mm Hg | 57.64 (16.63)            | 50.55 (14.87)       | 0.009395 (W)    |
| Heart rate, per min                   | 120.75 (24.53)           | 136.16 (22.78)      | 5.83E-07 (t)    |
| Respiratory rate, per min             | 34.14 (14.12)            | 33.43 (17.96)       | 0.289486 (W)    |
| Oxygen saturation (SpO2)%             | 92.26 (9.16)             | 92.79 (8.48)        | 0.852786 (W)    |
| Pulse Rate, per min                   | 118.65 (24.55)           | 135.91 (23.03)      | 4.78E-08 (t)    |
| Shock Index                           | 1.32 (0.44)              | 1.63 (0.52)         | 1.03E-05 (W)    |
| Abdomen Intensity                     | 164.24 (21.53)           | 161.82 (17.73)      | 0.69571 (W)     |
| Foot Intensity                        | 144.69 (20.16)           | 136.43 (24.16)      | 0.003386 (W)    |
| Difference between pixel intensities of abdomen and foot | 19.56 (23.48) | 25.39 (28.88) | 0.042471 (W) |

Table 1. Cohort characteristics of the control (no-shock) and affected (shock) group. p-values for difference were computed using Wilcoxon (W) rank sum test (non-parametric) or Student’s t-test (t) (parametric) after testing for the normality assumption.
AUC’s follow each other closely. The manual models performed slightly better at 0 hr and 3 hr whereas the automated pipeline demonstrated slightly superior performance at 6 hr and 12 hr of shock prediction. In this result as well, the model was agnostic to prior history of the patient’s shock status, hence useful for forecasting of shock using a snapshot alone, without the need for capturing repeated images.

**Discussion**

This study presents a machine-learning algorithm trained upon thermal images for continuous, non-contact detection and prediction of shock in the PICU. Resource-constrained settings motivated the use of an affordable and compact thermal array coupled to an Android smartphone, thus ensuring hardware scalability and potential for ER and community use beyond ICUs. Further, we intentionally kept the models lean to avoid the need for a graphics processing unit (GPU), making our study especially relevant for developing countries with low doctor-to-patient ratio and lack of skilled professionals. Artificial intelligence and machine-learning are expected to disrupt healthcare and bring novel understanding to disease mechanisms and delivery of healthcare. Several recent studies have shown that advanced artificial intelligence methods such as deep-learning can out-perform doctors at specific tasks such as skin cancer detection, arrhythmias and retinal disease detection. However, we took an alternative approach to leverage physiological hypothesis in order to keep the hardware and models lean. Body surface thermal gradients are known to exist in shock and we developed the machine learning pipeline around it. Skin-surface is a key area for evaluating the perfusion status of body as its temperature is correlated with blood flow. However, the potential for surface body temperature patterns using machine learning and computer vision for hemodynamic status has been under-explored. Most common sensors available in the ICUs measure temperature at a single point and fail leverage temperature gradients. Our study demonstrates that affordable and compact thermal imaging can effectively capture the CPD gradient that may inform shock diagnosis and prediction. Since manual annotations are expensive, repetitive, time-consuming and a hindrance to automation,

| Time-point, (NS, S) | Coef | AUC Mean(SE) | Accuracy Mean(SE) | Sensitivity Mean(SE) | Specificity Mean(SE) | PPV Mean(SE) | NPV Mean(SE) | Cut-off Mean(SE) |
|-------------------|------|--------------|-------------------|---------------------|---------------------|-------------|-------------|----------------|
| 0 hr (detection), (146, 107) | 0.03 | 0.79 (0.02) | 0.75 (0.02) | 0.69 (0.05) | 0.79 (0.05) | 0.72 (0.05) | 0.8 (0.03) | 0.47 |
| 3 hr (prediction), (141, 107) | 0.01 | 0.79 (0.04) | 0.74 (0.04) | 0.72 (0.05) | 0.78 (0.07) | 0.73 (0.06) | 0.81 (0.03) | 0.45 |
| 6 hr (prediction), (129, 109) | 0.01 | 0.65 (0.04) | 0.66 (0.02) | 0.48 (0.09) | 0.81 (0.06) | 0.72 (0.07) | 0.71 (0.05) | 0.62 |
| 12 hr (prediction), (131, 118) | 0.01 | 0.7 (0.03) | 0.69 (0.02) | 0.67 (0.03) | 0.68 (0.04) | 0.65 (0.06) | 0.7 (0.03) | 0.41 |

Table 2. Performance of Model predicting binary shock index using manually calculated CPD. (Coeff—Model coefficient of difference percent, AUC—Area Under the curve, PPV—Positive predictive value, NPV—Negative predictive value, Cut-off—Average Threshold of Ten Folds, NS—Non-shock, S—Shock).

Figure 3. Illustration of steps in the automated detection of abdomen and foot ROIs using Random Forest based classifier on HOG features. Each classifier was trained using positive (e.g. foot) and negative (e.g. not foot) samples and adaptive window sizes were slid over the image to achieve scale-invariance of detection. Median of intensity over the detected ROIs was taken and their difference was used as a predictor (CPD). Relative CPD (percent normalized to abdomen) was used to make the feature more robust to ambient thermal variations.

AUC’s follow each other closely. The manual models performed slightly better at 0 hr and 3 hr whereas the automated pipeline demonstrated slightly superior performance at 6 hr and 12 hr of shock prediction. In this result as well, the model was agnostic to prior history of the patient’s shock status, hence useful for forecasting of shock using a snapshot alone, without the need for capturing repeated images.
our computer vision based machine learning pipeline classified the key central and peripheral areas in the human body. The recording of images needed minimal training or technical expertise, limited to handling the imager and taking precautions for reliable capture. Relative CPD percent added robustness against ambient thermal noise. We experimented with a wide range of features based upon intensity statistics, clustering and shape and found the shape-tailored features (HOG) to be a good fit for ROI detection in thermal images. Since machine learning algorithms are not yet mature for handling non-uniformly sampled longitudinal data, we applied generalized

![Figure 4](image). Quality evaluation of detected foot and abdomen using the computer-vision automated-detection pipeline. Area under the ROC curve of 99% was achieved for the optimized abdomen classifier and 94% was achieved for the optimized foot classifier. Bounding boxes (C,E) for foot and abdomen in a non-shock and shock patient were constructed by the algorithm. The intensity gradient along the centers of these (D,F) recapitulated the manual gradient shown in Fig. 1, albeit without any manual intervention and was taken forward for longitudinal modeling.

| Time-point, (NS, S) | Coeff | AUC Mean(SE) | Accuracy Mean(SE) | Sensitivity Mean(SE) | Specificity Mean(SE) | PPV Mean(SE) | NPV Mean(SE) | Cut-off Mean |
|-------------------|-------|--------------|-------------------|---------------------|----------------------|--------------|--------------|--------------|
| 0 hr. (119,84)    | 0.03  | 0.75 (0.03)  | 0.73(0.03)        | 0.58(0.06)          | 0.81(0.06)          | 0.74(0.05)  | 0.75(0.03)  | 0.55         |
| 3 hr. (108,86)    | 0.02  | 0.77(0.04)   | 0.73(0.03)        | 0.65(0.06)          | 0.82(0.03)          | 0.75(0.04)  | 0.74(0.05)  | 0.49         |
| 6 hr. (100,88)    | 0.002 | 0.68 (0.03)  | 0.69 (0.02)       | 0.58(0.07)          | 0.74(0.06)          | 0.79(0.04)  | 0.64(0.02)  | 0.51         |
| 12 hr. (101,97)   | 0.01  | 0.69 (0.04)  | 0.67(0.03)        | 0.62(0.07)          | 0.73(0.07)          | 0.72(0.05)  | 0.69(0.04)  | 0.48         |

Table 3. Performance of Model predicting binary shock index using automated detection of CPD.(Coeff—Model coefficient of difference percent, AUC—Area Under the curve, PPV—Positive predictive value, NPV—Negative predictive value, Cut-off—Average Threshold of Ten Folds, NS - Non-Shock, S- Shock).
linear mixed effects models to leverage and account for repeated images from same subjects. Such models have been extensively used in statistical analysis of longitudinal clinical studies15. In an earlier study8, we had shown the correlation between lactate levels and the manually calculated CPD. However, in this study, we restricted ourselves to the most easily obtainable features such as age and pulse rate with the goal of non-invasive, continuous and scalable monitoring to ICUs, ERs and community health settings. Our models achieved reasonably useful (75% or higher) positive predictive and negative predictive values, the key indicators for clinical applicability for a machine learning model. AUROC, accuracy, sensitivity and specificity also demonstrated good performance of our models, nearly reaching the manual modeling of shock using CPD. We note that our model is generally more specific than sensitive and may have some value for ruling out shock. However, an omission of action in suspected shock, and critical care settings in general, may have drastic consequences, hence we do not advocate the use of our model for omission of fluid management decisions. Further studies on a larger scale may be necessary to explore the use in decisions involving fine-tuning of fluid management in shock. The expansion of our automated detection and prediction of shock beyond the intensive care and emergency room settings may be facilitated in the developing countries through rural support mechanisms such as the Accredited Social Health Activist (ASHA) workers, women who promote and educate health in the local rural Indian settings. With this end in mind, our model does not require prior history, thus able to classify and predict (forecast) shock from a snapshot in our settings. The results from our study encourage us to believe that lean development with state-of-the-art technology may be the most feasible solution for the developing world with low doctor-to-patient ratio and high disease prevalence. All our data and code for modeling are made openly available as per FAIR (findable, accessible, inter-operable and reusable) research guidelines (see Data availability section).

The current study has a few limitations. It was conducted on a small number of patients, owing to the requirement for the gold standard measurement of intra-arterial invasive BP monitoring. This was extracted from the SAFE-ICU resource that has been warehousing vitals, demographics, laboratory investigations and treatment charts since early 2016. In order to salvage more patient numbers, we tested whether the non-invasive BP can be used as a proxy for intra-arterial BP by constructing a model that predicts latter from the former. However, as per expectation, the intra-arterial BP had a consistent positive offset (intercept) and the model did not explain sufficient variance ($R^2$) to be useful (Supplementary Table S1). The other major limitation of this study is the lack of multiple clinical sites to validate the generalizability of the models. Ongoing work and partnerships with clinical and community organizations will address this limitation in future and the tele-diagnostic potential of the modality will be combined with models deployed on the cloud to offer decision support where adequate clinical expertise is not available. In conclusion, this study demonstrates the value of using thermal imaging, machine learning and generalized mixed effects models in conjunction for detection and prediction of shock with high AUC (76%) up to 3 hours and with a reasonable AUC (70%) up to 12 hours. This opens up a important window of opportunity to initiate early interventions such as fluid and vasopressor management before the downward spiral of irreversible organ damage sets in.

Methods
Cohort and Study Design. The study was carried out at the Pediatric Intensive Care Unit of All India Institute of Medical Sciences, a tertiary care hospital in New Delhi, India. Since thermal images only capture infra-red radiation, these don’t reveal patient identity and study did not involve any contact or change in routine patient care. Hence a waiver of consent was sought and granted by the Institute Ethics Committee (Ref. No. IEC/NP-211/08.05.2015, AA-2/09.02.2017). The period of the study was from May 2016 - September 2016 and from February 2017 - April 2017. Data were collected on all patients admitted during this duration (patients enrolled) and further limited to
include only patients with Arterial blood pressure recording (patients analysed). This was deliberately enforced to
train models against the gold standard for hemodynamic evaluation. The study design was prospective longitudinal
since multiple time points from each patient were recorded. A comparison of baseline characteristics in the shock
versus non-shock group was evaluated using a two-sample two-tailed Student’s t-test or a Wilcoxon’s rank sum test
after checking for the assumption of normality using Shapiro Wilk’s test for normality.

Thermal Imaging. A standard operating procedure was followed for the recording of thermal images in
order to minimize the effect of extraneous factors such as device handling, patient positioning, environment
etc (Supplementary Methods S1). Briefly, it was ensured that the ambient temperature was comfortable and the
patient was uncovered. Thermal images were clicked in a standard color-scale ensuring that the full body (in
infants) or at least abdomen and feet were exposed. A total of 253 thermal images from 51 children (27 male, 24
female), ages ranged between 0.2–144 months with and arterial line recordings available, were recorded using a
commercially available Android Smartphone attachment (Seek Thermal®). Images were acquired at different time
points (i.e. on different days), therefore, the same patient could have different values for shock-status on different
days which eliminates bias due to patient’s propensity characteristics (e.g. age and gender). An average of five
images was recorded for each child. Vitals corresponding to the time-stamp of image were extracted from the data
warehoused at 15 second intervals (SAFE-ICU®).

Manual extraction of the Central-to-peripheral difference in intensity. Central-to-peripheral
Difference (CPD) was manually extracted using FIJI18, an image processing software platform. CPD difference
percentage (diff-percent) was calculated as follows,

\[
\text{Difference percentage} = \frac{\text{Abdomen Intensity} - \text{Foot Intensity}}{\text{Abdomen Intensity}} \times 100
\]

Automated extraction of the Central-to-peripheral difference in intensity. The original
Red-Green-Blue (RGB) thermal images were (1108, 624, 3) dimensional matrices which were analysed using
an in-house computer-vision based pipeline (Fig. 3) written in Python19 using OpenCV20 version 3 library.
Abdomen/non-abdomen and foot/non-foot areas within images were cropped for training the classifiers. Images
were converted from RGB to grayscale. Pixel intensities were thresholded by the median of each image in order
to remove thermal noise. Contrast-limited adaptive histogram equalizer (CLAHE) was used to enhance contrast
for better detection of colder feet. Abdomen and foot images were padded and resized to (50, 50) and (100, 100).
Images were partitioned into a 70%-30% training and test sets. Histogram of oriented gradients21 (HOG) features
were extracted and random forest22 classifiers were constructed with 310 trees for abdomen and 160 trees for foot
(optimized using out-of-box error) using library sklearn23. The learned classifiers were evaluated on test set and
for further modeling.

\[
\text{Detected difference percentage} = \frac{\text{Detected Abdomen Intensity} - \text{Detected Foot Intensity}}{\text{Abdomen Intensity}} \times 100
\]

Detailed hyper-parameter tuning procedure for the number of trees and features is shown in supplementary
information (Supplementary Figure S2 and Supplementary Figure S3).

Outcome variable: Binary shock index. The SAFE-ICU initiative4 developed and described earlier has
warehoused over 3,00,000 patient-hours of monitoring data from the PICU and was used to extract time-stamped
data for corresponding patients at 0 hr, 3 hr, 6 hr and 12 hr blood pressure and heart rate recordings. Shock index
was calculated as the ratio of median heart rate and median arterial systolic blood pressure (both calculated over
30-minute straddling windows). Finally, age-specific binarized outcome (shock/no-shock) was computed for each
patient using shock-index pediatric age-adjusted (SIPA) guideline24.

Prediction time-points. The time-point for shock-detection model was 0 hr whereas and the time-points
for shock-prediction models were 3 hr, 6 hr, 12 hr from the time of imaging.

Modeling for shock detection and prediction. Generalized linear mixed effects (glmer) models25 were
constructed with Bound Optimization By Quadratic Approximation26 (bobyqa). The library lme427 in R28 (ver-
sion 3.4.3) was used. Age and pulse rate were included as covariates in the glmer model.

Model Evaluation. Repeated data were first partitioned patient-wise using patient IDs to avoid
cross-contamination between training and test sets. Ten random partitions with 70% training and 30% testing
sets respectively were then created for evaluation of stability and accuracy of the model using the caret29 library
in R28. Model performance was assessed using Area under the curve in the receiver operating curve (ROCs)
(AUROC). The standard measures of sensitivity, specificity, positive predictive value and negative predictive value
were obtained by taking threshold as Youden’s Index, \(J = \max(Se(c) + Sp(c) - 1)\).
Data Availability
All our data are made available on Open Source Framework (DOI 10.17605/OSF.IO/VP86J) and the code for modeling is open-sourced on GitHub and Zenodo (https://doi.org/10.5281/zenodo.1256486).

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Author Contributions
T.S. and R.L. conceptualized the study and designed the experiments, A.N., L.S.D., A.B. conducted the experiment(s), A.N. and T.S. analyzed the results. A.N., T.S., L.S.D. drafted the manuscript. All authors read and approved the final version of the manuscript.

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