Contribution ID: **99** Type: **Poster**

Next-Gen Respiratory Safety: Synchronizing Thermal Imaging and AI for N95 Leak Assessment

Infrared thermography (IR) combined with deep learning offers a promising approach for accurately detecting and localizing leaks in N95 masks, a critical concern in respiratory protection research. This study aims to develop and validate a real-time system that not only identifies leak occurrences but also pinpoints their exact location on the mask perimeter. By leveraging a novel workflow incorporating IR imaging, transfer learning, and correlation-based signal analysis, we address the limitations of conventional fit-testing procedures, such as qualitative saccharin and quantitative PortaCount® methods, which are not designed for continuous monitoring nor do they provide precise spatial localization of leak sites.

Methods: A controlled test bench was first established using a mannequin head, where a mechanical ventilator simulated breathing by pushing warm, humid air through an N95 mask. Small, artificially induced leaks of known dimensions were introduced at different locations around the mask perimeter to create a high-fidelity benchmark dataset. Infrared cameras capture thermal data throughout each respiratory cycle, providing temperature variations that reflect exhaled air escaping from leak points. These IR recordings were then transformed into spectrograms using the Fast Fourier Transform (FFT), highlighting the unique frequency signatures of exhaled breath. A two-stage classification pipeline was developed: first, deep features were extracted with a ResNet50 model fine-tuned via transfer learning, and second, an SVM classifier was employed to discriminate between leak and no-leak conditions. Once the system confirmed a leak, a correlation-based localization method subdivided the mask contour into Regions of Interest (ROIs). Each ROI's spectrogram was compared against a reference respiratory signal from the mask centre, enabling robust localization by identifying which ROIs exhibited the highest correlation with the breathing frequency.

Results: Under controlled conditions, the method achieved a leak-detection accuracy exceeding 95%, outperforming traditional image-based classification approaches in both precision and recall. The correlation-based localization exhibited a sub-millimetre-level resolution in pinpointing leak sites, demonstrating minimal false positives even when multiple leaks were present. The system was evaluated in a human subject study following these promising results. Participants wore standard N95 masks, and their natural respiration and head movements introduced additional variability. Leveraging a segmentation approach—combining a custom U-Net model with the Segment Anything Model (SAM2)—the framework dynamically tracked the mask boundary in real-time. The correlation method consistently identified leaks for participants whose quantitative fit factor (FF) indicated poor sealing. Participants with high FF values showed negligible correlated ROIs, corroborating minimal leakage.

Conclusion: These findings highlight the potential of IR imaging and deep learning for advanced respiratory fit evaluations. The proposed system surpasses traditional fit-test solutions that lack continuous monitoring or precise leak mapping capabilities by delivering real-time leak alerts and detailed spatial localisation. This innovation paves the way for safer clinical, industrial, and public health applications, ensuring that protective masks are worn correctly and effectively. Future work will include scaling the platform for wearable edge devices and investigating adaptive thresholding methods to counter variations in ambient temperature and humidity. Overall, the proposed approach provides a scalable, non-invasive tool for improving respiratory protection and safety in high-risk environments.

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