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Non-Contact Comprehensive Breathing Analysis using Thermal Thin Medium

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Abstract— **Respiration monitoring methods that are both accurate and comfortable are highly sought after in the medical field. No existing method of respiration monitoring perfectly satisfies both of these criteria; each method is a trade-off between comfort and accuracy. Contact methods, which require placing sensors directly on the patient's body, provide reliable measurements, but are uncomfortable for the patient, which alters their natural breathing behaviors. Conversely, non-contact methods monitor respiration remotely and comfortably, but with lower accuracy. We present a method of respiratory analysis that is non-contact, but also measures the exhaled air of a human subject directly through a medium-based exhale visualization technique. In this method, we place a thin medium perpendicular to the exhaled airflow of an individual, and use a thermal camera to record the heat signature from the exhaled breath on the opposite side of the material. Breathing rate and respiratory behaviors are extracted from the thermal data in real time. Our proposed respiration monitoring technique accurately reports breathing rate, and provides other information not obtainable through other non-contact methods. This method can be implemented as a small low-cost device for ease of use in a clinical environment.**

I. Introduction

Respiration monitoring techniques that are both accurate and comfortable for the patient are sorely lacking from the medical field. The most accurate methods of respiration monitoring, such as placing ECG electrodes on the patient's body [8], putting thermistors in the patient's nose [12], having the patient wear an abdominal strain-gauge transducer [9], or monitoring multiple biophysiological parameters concurrently with polysomnography [5], all involve place sensors directly on the patient's body. These direct measurements have a high rate of accuracy, but cause discomfort and alter the natural breathing of the patient. This problem is the driving force behind ongoing research into innovative methods that measure respiration remotely and preserve patient comfort. Proposed non-contact methods of respiration monitoring utilize remote sensors such as cameras [13] [1] [6] [16], volumetric sensors [14], microphones [10], and radar [7]. These methods are more comfortable for the patient, but are less reliable and more error-prone than contact methods. These methods are also limited in the information that they can provide; most non-contact methods only provide breathing rate measurements, though a few provide tidal volume estimates indirectly through chest movements and machine learning techniques. However, these volume estimates are prone to individuality, and the learning algorithm requires a large accumulation of sample data.

We propose a new method of non-contact respiratory analysis that combines the accuracy of contact methods and the comfort of non-contact methods. We place a thin medium in the path of the exhaled air of the patient, and record the resulting thermal signature on the medium with an infrared camera. We use image processing techniques to extract information from the thermal data, and then display the resulting metrics. By measuring respiration both directly and remotely, we can obtain higher measurement accuracies without causing discomfort to the patient. This system is capable of measuring breathing rate, as well as other metrics not obtainable through other respiration monitoring methods such as nose to mouth distribution. Additionally, this method gives insight into respiration characteristics such as exhale strength, flow, and pattern, and can also be used to generate a 3D reconstruction of exhales over time. Since this method works independently of the physical characteristics of the patient, it can be used to monitor individuals of various ages and sizes, including young children that are unable to use certain contact methods. This image-based analysis algorithm is hardware independent and can be used with inexpensive thermal sensors, and can be deployed as a stand-alone measurement device for easy clinical use. Overall, this method provides medical professionals with a tool to comprehensively analyze breathing activities, and can be used for various clinical applications.

II. Related Work

Several non-contact respiration monitoring methods exist. There are many camera-based methods that infer breathing rate, such as using a camera to monitor the motion of the patient's chest [13] [1], and using a thermal camera to measure the change in temperature of the patient's skin underneath their nose [6] [16]. Some methods are able to estimate tidal volume in addition to breathing rate, such as one method that uses a Microsoft Kinect to measure the rise and fall of the patient's chest [14], or another method that uses Doppler radar to measure chest movement [7].

Our proposed method has the ability to provide other information not attainable by the aforementioned methods, such as nose to mouth distribution and exhale strength. The technique proposed in this paper has been used to study the nasal cycle by comparing the thermal signature of each

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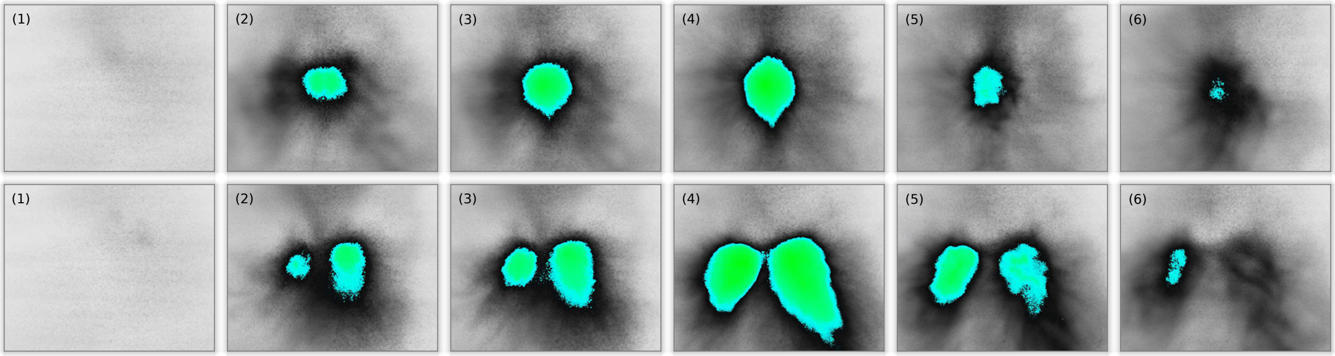

Fig. 1. Medium-based thermal exhale image sequences. The image sequence illustrates the thermal exhale distributions of the mouth (top row) and nose (bottom row). The segmented regions represent the highest thermal intensity, illustrating distinct exhale pattern distributions over a single exhale.

nostril [2]. In this method, patients exhale through their nose onto a thermochromatic liquid crystal film, and images are taken of the opposite side. The film needs to be placed close to the patient's face so that the film can be sufficiently influenced by exhale force. Our method improves upon this technique by using a thermal camera and image processing techniques, neither of which were available at the time the initial experiment was conducted. Our technique also works without close contact with the patient's face, and extracts more metrics than the previous experiment. The proposed technique has also been used to visualize gases for other applications, such as visualizing airflow from air diffusers [3] and examining the temperature distribution of air coming out of cooling passages [15].

III. Method

Our proposed method takes advantage of the temperature difference between human breath and the surrounding environment by projecting an individual exhale onto a projection *medium* that is used to visualize the thermal distribution of the exhale as shown in Figure 1. The resulting heat signature is preserved on the medium only for a short period of time, but it remains long enough for a conventional thermal sensor to capture the information. This medium-based method allows us to capture thermal exhale behaviors before the exhaled air dissipates, and then analyze the respiratory behaviors based on the resulting thermal distribution.

A. Experimental Variables

The success of this experiment relies heavily on the choice of medium material. The material should be highly emissive, very thin and thermally opaque, and have specific thermal properties that retain heat long enough for the camera to capture the image, but allow for dissipation of the heat between breaths. When choosing a medium material, we tested copy paper, cotton, and linen under identical conditions. Copy paper performed the best out of the three materials, and was chosen as our medium material [11].

Other variables that impact this method's performance are distance between the subject and the medium, and the exhale characteristics of the subject. If the medium is too far away from the subject's face, the exhale may have mostly dissipated before making contact with the medium. This situation could be overcome by a strong exhale, but is exacerbated by light exhales. Conversely, if the medium is close to the subject's face and the subject forcefully exhales, the airflow will hit the surface of the medium and spread in multiple directions. Through experimentation, we chose a distance of 3 inches between the subject's face and the medium for our setup. This distance is close enough to obtain a strong signal, but far enough that it minimizes the impact of turbulent flows, and is still comfortable for the patient. We also assume that the patient is always facing the medium and that varied distance effects result quality. This method is not currently intended for unmonitored use in sleep studies.

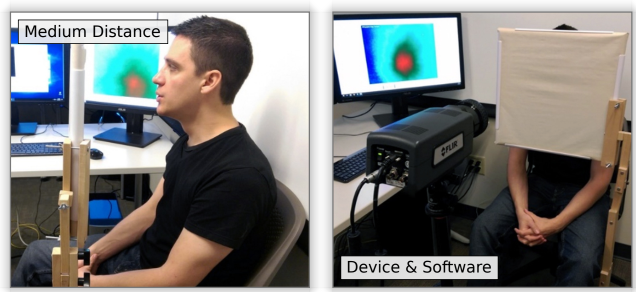

Fig. 2. Experimental setup. The subject sits in a chair and breathes onto a medium while a thermal camera records the medium heat signature.

B. Data Processing and Visualization

Projecting exhales onto a medium allows us to extract different respiratory characteristics of an individual, as well as monitor the patient for abnormal breathing behavior. Some metrics and exhale characteristics that can be extracted from our medium-based exhale monitoring technique include:

1) Breathing Rate: Breathing rate is extracted from this method by calculating the difference between the current and previous image, summing the positive values from the difference image, and then performing a windowed fast Fourier transform (FFT) to convert data from the time domain to the frequency domain. The highest peak in the FFT data is the breathing rate in hertz, which can then be converted to breaths per minute (BPM).

2) Breathing Pattern: The positive difference image values over time from the breathing rate calculation provides useful insight into the exhale patterns of the individual. Breathing pattern abnormalities, such as several breaths in rapid succession over a short period of time, are lost after condensing the data into a single breathing rate value. However, these abnormalities are made visible as a plot of increasing difference sums over time.

3) Respiration Mode: The thermal signature on the medium can be used to determine whether a patient is breathing nasally, orally, or oronasally. Each of these modes of respiration show a unique thermal signature pattern on the medium that can be identified by their size, shape, location and flow direction. To segment the thermal signature into separate exhale sources, we filter out the regional maxima, threshold the image, and then use pixel clustering.

4) Nose to Mouth Distribution: After identifying individual exhale sources from the thermal signature, the contribution from the mouth and each nostril to the surface area of the heat signature can be determined by the pixel sum per thermal region. From this information, we can calculate the nose-mouth distribution ratio or between each nostril.

5) Breathing Strength: The strength of an individual exhale can be estimated by the rate of expansion of the thermal signature on the medium. Stronger exhale heat expands farther after hitting the medium surface than that from a less forceful exhale. To estimate exhale strength, we use optical flow to estimate surface heat flow across the medium.

IV. Results

In our experiments, we use a custom FLIR A-series camera that produces 640x512 images at 33 frames per second. Previous experiments were conducted using an inexpensive FLIR C2 camera with a low frame rate and image resolution [11]. Our proposed breathing analysis algorithms are reasonably independent from the resolution and frame rate of the sensor device, but as one would expect, high resolution devices provide more detailed results. However, because the system can be implemented using a cost-effective sensor, this method can be deployed on independent battery-powered hardware for easy deployment in clinical applications. Our chosen medium is a large sheet of newsprint attached to a 17”x17” frame. The medium is positioned 3[in] away from the face and centered to the nose and mouth. Each subject is asked to provide 30 second samples of nasal breathing, oronasal breathing, alternating breathing strengths, and breathing with interspersed abnormalities (Figure 3).

A. Breathing Rate and Pattern

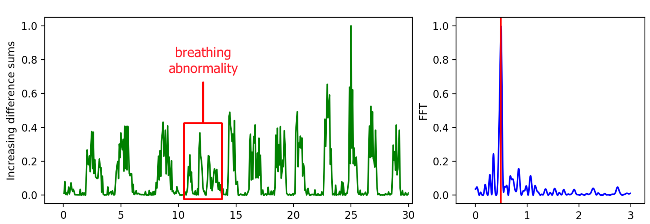

Fig. 3. Plot of breathing rate pattern with one episode of abnormal breathing (top) and the FFT of the breathing rate pattern (bottom).

In a previous experiments [11], simulated exhaled airflows generated using a programmatically controlled fan have been used to define a constant known breathing rate. The results of this experiment demonstrated that breathing rate could be extracted using a medium-based technique with reasonable accuracy. To determine if exhale pattern abnormalities could be identified using this technique, we asked participants to exhale in rapid, short breaths to simulate a breathing pattern abnormality. Figure 3 shows a plot including the abnormality and the associated FFT from one of these trials. A clear difference can be seen in the abnormal signal region in the left subplot. The ability to see changes in exhale pattern in real-time can alert medical professionals to subtle breathing difficulties that may be missed by a rate measurement.

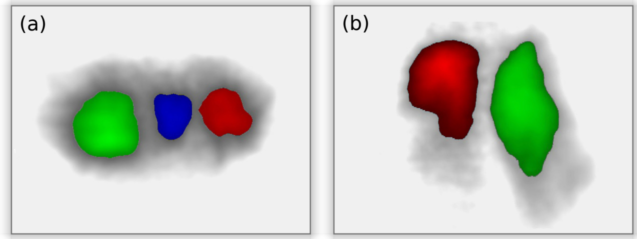

Fig. 4. Images of exhaled heat signatures after segmentation. The images above illustrate (a) oronasal breathing and (b) nasal breathing.

B. Nose and Mouth Separation

Oral, nasal, and oronasal breathing result in different thermal signature medium patterns. Generally, oral breathing results in one circular or elliptical gradient, nasal breathing looks like two similarly shaped gradients with a similar flow direction, and oronasal breathing results in three gradients on the medium that are a combination of circular and elliptical gradients, two with a similar shapes and flow direction. To determine the exhale sources and the distribution between the nose and mouth, each image is filtered and thresholded to reduce noise, and the thermal signatures are segmented using a watershed algorithm. Figure 4 shows the results of this processing method for oronasal breathing (left) and nasal breathing (right). The Horn-Schunck optical flow algorithm is used to determine the flow of each exhale source to aid in classifying the source of each segment [4]. After classifying each segment, we can convert the pixel counts for each region into an area measurement based on the width and height of the medium visible in the image. Figure 5 shows a plot of the surface area contributed from each nostril and the mouth.

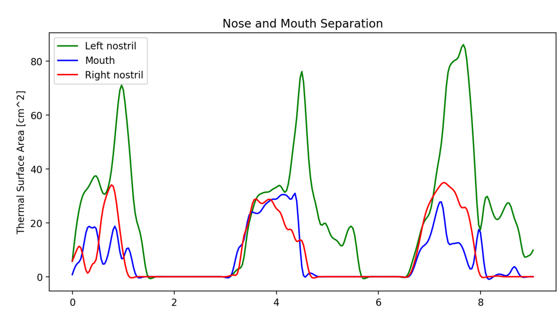

Fig. 5. Exhale contribution from each nostril and the mouth. This correlates with the distributions shown in Figure 4.

C. Breathing Strength

When participants change their breathing strength over time, this results in a visible difference in the thermal signature on the medium and a difference in amplitude in exhale pattern over time [11]. The size of the mouth opening of the patient dictates how the thermal signature will appear on the medium. Stronger exhales from a wide mouth opening have a slower rate of change in diameter due to decreased turbulence, and the center of the gradient is hotter from prolonged and concentrated exhaled air contacting the medium. The opposite is true for a small mouth opening; more turbulent exhaled air increases the rate of change in the diameter of the heat signature, and gradient center is cooler. Figure 6 shows an image sequence processed using the Horn-Schunck optical flow algorithm to determine the flow direction and magnitude of the exhaled air [4].

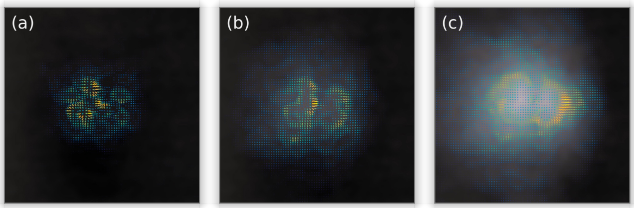

Fig. 6. Images from one exhale with optical flow vectors showing the spread (a-c) of the heat signature across the surface of the medium.

Building on the temporal relationship between signature image intensity and flow, we can generate a 3D reconstruction of the exhale by stacking image frames as shown in Figure 7, which illustrates the rotation of the exhale. 3D projections of the distributions provide insight on other metrics such as distribution behaviors and tidal volume.

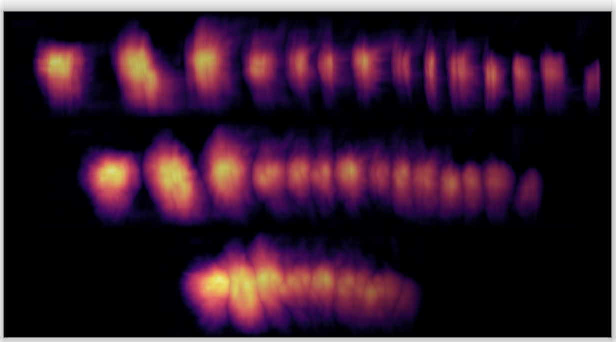

Fig. 7. 3D projection of the medium thermal signature images. Each level shows a y-axis rotation of the exhale in 3D space.

V. Evaluation and Discussion

This method is useful for a variety of clinical applications, such as identifying patients with chronic nasal obstruction that would benefit from treatment. Based on our results, we can accurately analyze respiratory behaviors in a comfortable environment for the patient. This method can be implemented for use in various clinical scenarios, and the data provided can be used to monitor and identify many different ailments. Clinical trials are needed to further assess this method.

A. Medical Significance

This method of respiration monitoring has many implications for the medical field. Nasal obstruction, a common respiratory dysfunction leading to sleep apnea, swallow dysfunction, sinus infection, and permanent dental and facial bone developmental abnormalities can be easily classified with this technique. This method can also measure airflow obstruction in children too young to use traditional medical devices, allowing them to be seen non-invasively in the comfort of an outpatient office. Classification of the nose-mouth distribution of airflow will accurately identify people with abnormal breathing patterns, indicating those requiring medical or surgical intervention for treatment of sleep apnea.

VI. Conclusion

In this paper, we have described a method of non-contact respiration rate monitoring that measures respiration directly. This method accurately measures breathing rate, and provides other valuable information not obtainable through other non-contact methods, such as breathing mode, nose to mouth distribution, nasal distribution, and breathing strength. Since this method works independently of the physical characteristics of the person being monitored, this method can also be used to monitor the respiration of a wide variety of individuals, including children and infants. The proposed technique represents a novel approach to non-contact respiration monitoring, providing a low-cost, accurate and comprehensive analysis of breathing behavior, while keeping the patient comfortable and preserving natural breathing.

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