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Non-contact tidal volume measurement through thin medium thermal imaging[☆]

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ABSTRACT

Tidal volume (TV) is frequently measured by pulmonologists to assess the breathing ability and respiratory behaviors of a patient. The most common method of measuring tidal volume, spirometry, generally requires the patient to breathe through a tube while wearing a nose clip. This method of measurement is uncomfortable for the patient, and alters their natural breathing behaviors. In this paper, we describe and implement a new approach to respiration monitoring and tidal volume estimation that preserves patient comfort while maintaining measurement accuracy. In this method, a patient breathes onto a thin medium placed perpendicular to the patient's exhaled airflow while a thermal camera records the heat signature on the opposite side of the medium. Measurements such as tidal volume, respiration rate, and nose to mouth distribution are extracted from these thermal images, correlated with ground-truth measurements and trained into a recurrent network model using TensorFlow. This method is comfortable for the patient, works for a variety of different body types and ages, and can be used in the comfort of an out-patient office.

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1. Introduction

Tidal volume (TV), the volume of air inhaled and exhaled during normal breathing, is an important measurement taken during respiration monitoring. Abnormal tidal volume measurements can be an indicator of a variety of medical problems, such as asthma, pneumonia, or chronic obstructive pulmonary disease (COPD). The most common methods of tidal volume measurement provide reliable results at the cost of patient comfort, while methods that provide a better patient experience are more error-prone. Current methods generally favor either accuracy or comfort, with virtually no middle ground.

Methods of tidal volume measurement can be divided into two categories: contact methods and non-contact methods. Contact methods require placing sensors directly on the patient's body, whereas non-contact methods monitor the respiration of the patient using remote sensors. Contact methods can be further divided into invasive and non-invasive methods. As the name implies, invasive methods are the most uncomfortable for the patient, requiring the patient to wear apparatus such as a mask covering their face, or a tube in their mouth while wearing nose clip. Non-invasive methods place sensors elsewhere on the body, such as the chest or around the nose or mouth.

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Contact methods tend to give much more accurate results than their non-contact counterparts. Spirometry, an invasive method, is the gold standard in respiratory volume measurements. Although spirometry can accurately measure the air volume passing through a pipe, this device has a significant clinical flaw in that discomfort caused by the apparatus can alter patient breathing behaviors. Additionally, spirometers can only be used for minutes at a time. Both of these factors contribute to *white gown syndrome*, where a patient's physiological data is altered due to the psychological effect of being in a clinical environment.

Breathing behavior is subtle and sophisticated, and can be easily altered by various external influences. Allowing a patient to breathe naturally without any device attached to their face for a relatively long period of time would help to alleviate adverse effects related to invasive methods. Conversely, non-contact methods measure respiration remotely, and do not interfere with the natural breathing of the patient. These methods are more com- fortable than contact methods, but because they do not measure respiration directly, they are more error-prone. One study proposed using a Microsoft Kinect to measure the rise and fall of the patient's chest over time (Transue, Nguyen, Vu, & Choi, 2016). While this method does not touch the patient, the compressibility of the air and the physical characteristics of the patient cause errors in the results. For these reasons, an alternative to current methods that can measure respiration in a reasonably accurate and comfortable way over a longer period of time is desired by the medical community.

In this paper, we present a novel method of tidal volume measurement that strikes a balance between accuracy and comfort by measuring respiration directly, yet remotely. In this method, the patient exhales onto a thin medium while a thermal camera records the heat signature on the opposite side. By integrating the captured thermal images over time, tidal volume measurements can be extracted from the collected data. In previous studies, it has been shown that this method is also capable of capturing other valuable respiration metrics, including breathing rate, nose to mouth distribution, and breathing strength (Schoun, Transue, & Choi, 2017; Schoun, Transue, Halbower, & Choi, 2018). This method is impervious to body type and can be used with a variety of patients, and it can be used for a much longer period of time than many contact methods. Our aim is to find a middle ground between measurement accuracy and patient comfort, and to provide a holistic understanding of overall breathing behavior, such as the correlation between tidal volume and breathing rate, speed, strength, and consistency.

2. Related work

The most common and most accurate methods of measuring tidal volume are invasive methods. Spirometers are the most frequently used device in a clinical setting, and measure breathing volume by having the patient breathe through a tube while wearing a nose clip, or by having the patient wear a mask. The apparatus causes both physical and psychological discomfort, which alters natural breathing and significantly reduces the amount of time that it can be used (Askanazi et al., 1980; Gilbert, Auchincloss, Brodsky, & Boden, 1972). Patients' breathing pattern through the device is also quite different from natural breathing, since they tend to blow harder through it intentionally. A less invasive method is whole-body plethysmography, where the patient sits in a pressure-controlled chamber that measures respiratory volume by pressure changes within the chamber (Goldman, Smith, & Ulmer, 2005). This method is more comfortable for the patient, but is less cost-effective than using a spirometer, and requires a large amount of space. In addition, the patient has to be inside of a glass chamber, which will not be suitable for patients with certain health conditions. Other contact methods such as inductive plethysmography, fiber-optic plethysmography and using a strain-gauge transducer or accelerometers measure respiratory volume by placing sensors on the patient's body to monitor the rise and fall of the chest wall (Folke et al., 2003). These methods are dependent on patient body type, and because everyone breathes differently, they are also dependent on the position of the sensors placed on the patient's body and require additional signal processing.

A few non-contact methods measure the rise and fall of the chest wall remotely. One such method uses a Microsoft Kinect to reconstruct a 4D deformation model of the subject's chest over time (Transue et al., 2016), but requires appropriate clothing. Doppler radar methods measure the rise and fall of the chest (Massagram, Lubecke, & Boric-Lubecke, 2009) to also correlate chest movement with tidal volume. Both of these methods are affected by the body composition of the patient, as the ratio between chest movement and tidal volume varies based on body size, shape, and the distribution of muscle and fat. Additionally, since air is highly compressible and internal organs' deformation characteristics that absorb external chest movement varies among patients in different disease groups, measuring tidal volume through chest movement includes a lot of room for data interpretation, and is therefore prone to precision errors. Doppler radar is even more problematic because it only measures one point on the chest, and it is extremely difficult to choose the correct measurement point (Figs. 1, 2).

A method similar to our own has previously been proposed to examine the nasal cycle. This method requires a patient to exhale through their nose onto a thermochromatic liquid crystal sheet while a film camera photographs the heat signature on the opposite side (Canter, 1986). Though the method is similar in concept, this research pre-dates many advancements in modern technology that make real-time processing of large amounts of data possible. Similar methods have also been used to visualize gases for other purposes, such as visualizing gas from air diffusers (Cehlin, Moshfegh, & Sandberg, 2002), and viewing the temperature distribution of air moving through cooling passages (Wang, Ireland, & Kohler, 1996).

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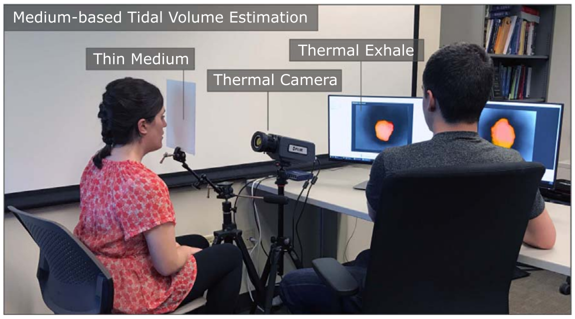

Fig. 1. Thin-medium respiratory analysis using thermal imaging. The patient exhales onto a thin medium while a thermal camera records the heat signature on the opposite side. Exhale data is correlated with tidal volume using machine learning.

3. Method

In the proposed method, a patient breathes onto a thin medium while a thermal camera records video of the opposite side as shown in Fig. 1. The medium heats up as the patient exhales, and cools as the patient inhales, producing the results illustrated in Fig. 2. These thermal signatures represent cross-sectional projections of exhale volume that can be reconstructed into a tidal volume estimate over time.

Images from the thermal camera are reduced to a continuous signal that can be correlated with a known ground-truth measurement from a spirometer. This correlation is generated through the use of a Long-Short-Term-Memory (LSTM) neural network and used as a predictive model for tidal volume esti- mates. We then analyze the validity of the predicted waveform given the exhale characteristics of the subject's breathing patterns and the known exhale flow and tidal volume as measured by a spirometer.

To generate the thermal projection for tidal volume estimation, the subject sits in front of a thin medium (at distance d_p) placed perpendicular to the exhaled airflow. A thermal camera is mounted on the other side of the medium (at distance d_c) that records heat signatures as the subject breathes. The thermal image of the medium forms a collection of pixels $p_{i,j}$ that correspond to the thermal energy of material points $m_{i,j}$ within the medium shown in Fig. 3. These cross-sectional areas are then used to represent an instantaneous measurement of the exhale flow onto the medium during the standard measurement process.

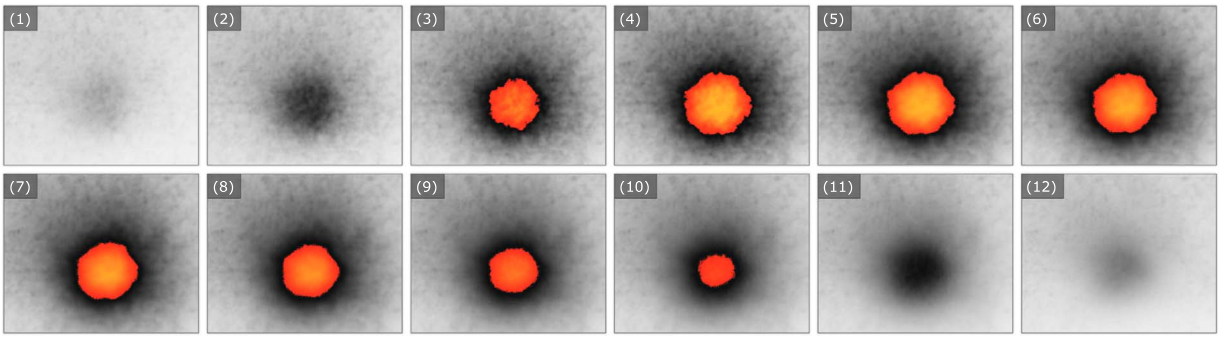

Fig. 2. Medium-based thermal exhale image sequences for tidal volume estimation from the spirometer syringe. The thermal exhale pattern imposed on the thin medium illustrates the link between the exhale behavior and our proposed volume estimation model. The (top) sequence illustrates the exhale portion of the breathing cycle and the (bottom) sequence displays the dissipation behavior of the medium as it loses thermal energy and returns to its equilibrium state.

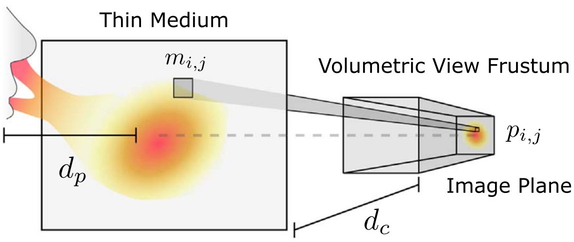

Fig. 3. Experimental setup. This setup is based on two dis-tances: (1) the distance between the subject and medium d_p and (2) the distance between the thermal camera and medium d_c. Pixel $p_{i,j}$ represents the thermal energy of the medium at point $m_{i,j}$.

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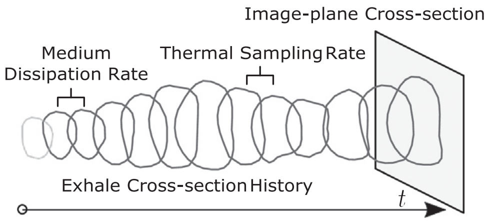

Fig. 4. Thermal signature to tidal volume measurements based on cross-sectional areas. Cross-sectional distributions indicate slices of the observable flow rate over time. Cross-section values are used to define the tidal volume waveform predictions.

3.1. . Exhale tidal volume estimation

The projected thermal signature imparted on the medium surface is only capable of capturing respiratory behavior during the exhale duration of each breath. Therefore, the premise of our approach is that, through accurately modeling the thermal exhale characteristics of each breath, we can still obtain a total tidal volume estimate using cross-sectional measurements. During each exhale, each frame captured by the thermal camera provides a measurement of the thermal intensity of the medium at a specific instance in time (defined by the thermal sampling rate). This generates a 1D time-sequence of scalar cross-section measurements that describe the level of thermal energy imparted to the medium due to the exhale shown in Fig. 4.

3.2. Thin medium

The choice of medium material is critical to the success of this method. Therefore, several different thin medium materials (cloth, paper, and acrylic) were analyzed with respect to capturing an accurate representation of an individual's exhale. Since the material needs to be thin in order to dissipate heat quickly and provide a clear representation of the respiratory signal on the medium, we evaluated each of the medium materials based on the ideal characteristics. The material must (1) provide ideal temperature signatures, (2) minimize heat retention, (3) be thermally opaque, and (4) be inexpensive, easy to obtain, easy to replace, and sterile.

The medium should ideally be a readily-available and inexpensive material that can easily be replaced between uses. To capture the thermal signal, the medium should be large enough to capture the entire heat signature from the exhaled airflow and prevent pollution of the thermal signature due to the patient's face behind the medium (thermally opaque). Additionally, since the application domain of this technique is within clinical respiratory monitoring, the ease-of-use, cost, and interchangeability of the medium are nearly as important as the ability to capture the exhale behavior. The final most critical component of the medium material properties is that its heat retention does not interfere with the continuous waveform generated for the tidal-volume estimate described in detail in Section 4. After analyzing several materials, we chose standard copy paper as our medium material. Copy paper has a thickness of 0.1[mm], and is industrially standardized, ensuring consistency between sheets.

3.3. Correlated tidal volume

The proposed method of measuring tidal volume through heat signatures does not directly provide an accurate estimate due to factors such as breathing strength, distance-to-medium and other factors detailed in Section 4.1. With the introduction of chaotic airflow and thermal distributions within the medium, a direct and accurate measurement of this quantity becomes in- tractable. Therefore we introduce a correlation that forms a behavioral relationship between exhale thermal signatures and a ground-truth tidal volume estimation provided by a spirometer. In the ideal case, the thermal signature on the medium should appear as a circular gradient, with the gradient continually growing and shrinking as the subject breathes. At each time step during an exhale, the medium increases in temperature and the circular gradient expands to cover a larger area. The heat signature at each time step during the exhale is the accumulation of heat over time, or the accumulated integral of the exhaled airflow. Once the subject inhales, the medium loses heat at each time step due to the material properties of the medium, and the circular gradient area shrinks. This corresponds to a cyclical time series based on the transfer of thermal energy to the medium and rapid dissipation. This relationship can then be used to form a predictive model that can estimate tidal volume measurements using our medium-based approach without assistance from existing measurement techniques. To implement this model we utilize TensorFlow (Abadi et al.) with a predictive neural network model trained on spirometer and thermal distribution values obtained from our experimental setup.

3.4. Long-Short-Term-Memory (LSTM) network

To generate the correlation between ground-truth volume measurements and thermal distributions, we utilize a Long Short-Term Memory (LSTM) neural network. We use the LSTM model from Keras (Chollet et al., 2015) with the back-end implementation TensorFlow to implement a predictive model that can estimate a tidal volume waveform that describes flow and volume over time. This allows us to reformulate our thermal image-based approach into a continuous time series that can be trained and evaluated with respect to our ground-truth measurements provided by a spirometer.

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Based on the collected thermal time series and the simultaneously collected ground-truth measurements, we for-mulate the form of our training model set as: $T(t, s)$ where the thermal data t is the input value, and the spirometer data s is the expected value. Since our input is a single dimensional regression, the network structure (1,4,1) is used for obtaining this correlation and is defined as: a single input, 4 node LSTM layer, and single output node. This network is then used to generate the predictive model: $P(t) = s^{j}$ that estimates the resulting exhale volume based on this correlation established within our trained model. For training our model, we use a batch size of 32, a 10% validation split of the training samples, and 100 epochs for each training sample.

4. Data acquisition and signal processing

As the primary data generation method, we use generic thermal imaging cameras to record the thermal distribu-tions exhaled onto the medium. Since this method only considers the heat distribution on the surface, any thermal imaging camera can be used. Additionally, since we primarily consider the change in the center circular gradient of the image, the resolution of the device is not critical to the success of this method. In our experimental setup we use a FLIR A6788sc (640*x*512) @ 30[*f ps*]. Presented images are generated with the A6788. As our ground-truth device, we use a Vernier Spirometer that provides flow [*L/s*] and tidal volume [*L*] measurements. For our method validation, we use a spirometer calibration syringe with a known volume of 1.0[*L*] 12[*mL*]. However, the proposed method is independent from the ground-truth device used in this paper, and can be replaced with other devices.

4.1. Experimental parameters

Several variables need to be considered in order for this method to be successful. Choosing an appropriate and constant distance between the patient and the medium (d_p) is necessary for the success of this method due to three factors: (1) the maximum exhale distance that will reach the medium is limited, (2) the exhale should be visible within the center of the medium, and (3) the patient must remain stationary. If the medium is too close to the patient, it causes the exhaled air to hit the medium with more force and to spread further across the medium and delay dissipation, causing overlap errors. Close distances can also cause discomfort for the patient and they may naturally move away from the medium. If the medium is too far from the patient, the heat in the exhale may completely dissipate by the time it hits the medium, leaving no reliable trace of the breath. We assume the patient remains at a constant 10 20[*cm*] away from the medium and is instructed to minimize movement and breathe through their mouth. The distance between the patient and the medium can also be guaranteed by having the patient place their chin on a chin rest, similar to those used during eye exams, to limit patient movements during each measurement.

The velocity of the exhale is another variable that needs to be accounted for in both speed and direction. Direction plays an obvious role in evaluating the thermal signature on the medium, so we assume that the patient is perpendicular to the medium for generating ideal cross-sections of the exhale. Additionally, when the patient breathes through their nose as opposed to their mouth, the airflow direction is greatly affected. For speed, breaths from a wider mouth opening will be hotter and less turbulent and breaths from a smaller mouth opening are cooler and more turbulent. Both of these factors contribute to how the thermal signature is formed. Since our primary objective is to provide a reliable and natural solution for respiratory monitoring over times that would become strenuous using a spirometer, we collect samples ranging from 30 [*s*] to 2[*min*] to compare the experience of using our setup versus breathing through a spirometer.

4.2. Thermal imaging

To extract a value from each frame that represents the area of the thermal signature at that moment in time, we simply take the average pixel value of each frame. This is in order to avoid thresholding at an arbitrary value, and to take into account the thermal energy values of each pixel.

This also helps alleviate the interference of the material texture within the generated signal. The images in Fig. 5 illustrate the raw form of the thermal images that are used to generate the thermal waveform.

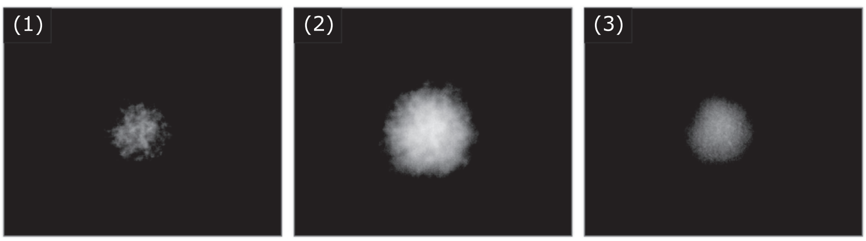

Fig. 5. Thin medium thermal images for exhale begin (left), exhale peak (center), and dissipation (right). These images represent the input to the processing stream for extracting the value that will be used to generate the correlation model for tidal volume.

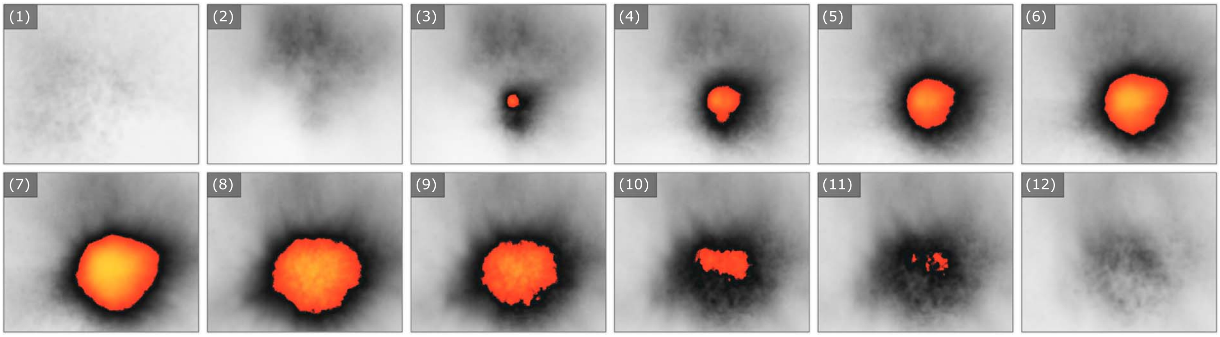

Fig. 6. Medium-based thermal exhale image sequences for tidal volume estimation from normal human breathing. The chaotic flow of natural breathing introduces noise within the images. These sequences are used to train the human-based model for tidal volume estimation. We assume that the training set is composed of mouth exhale behaviors, directed at the center of the image, reflecting similarity to the images in Fig. 2.

These thermal average values plotted over time results in a waveform resembling a sine wave with an irregular baseline. The baseline linear trend is generally upwards, due to heat on the medium accumulating faster than it can dissipate. This is heavily dependent on the choice of medium material, as a more thermally conductive material could dissipate the heat completely after each exhale. We remove this baseline trend using a Butterworth high-pass filter and a detrending algorithm.

When simultaneously taking spirometer and thermal data for training and testing purposes, we compare the thermal data to the spirometer data in two ways. In the first method, the thermal signal is compared to the cumulative integral of the spirometer data. This provides a volume estimation for each breath by subtracting each valley in the signal from the peak that immediately follows. In the second method, the thermal signal is compared to the original spirometer signal, which allows us to estimate exhale flow. Since we do not expect to get detailed information about respiratory flow from the thermal images, this processing method is expected to be less accurate than the exhale volume estimation. In both of these methods of processing, we use cross-correlation to approximate the delay between the thermal signal and the spirometer signal, and shift the data accordingly. The illustrated result of the exhale medium image sequence used to compute the tidal volume (with the exhale region highlighted by temperature) for a human trial is shown in Fig. 6.

4.3. Predicted waveform formulation

The collected thermal signatures corresponding to the pa- tient's exhales represents a *discontinuous* representation of the actual respiratory cycle. This is due to the inability to detect any thermal impact on the medium due to the patient inhaling. Therefore, for each complete inhale-exhale cycle, we can only obtain a valid portion of the flow estimate corresponding to the exhale region of the cycle. During the inhale portion, the wave-form is characterized purely by the material properties of the selected medium. We explicitly make this distinction between exhale and material property in the predicted waveform as part of our continuous recurrent model shown below in Fig. 7.

The key observation that we build on is that, while we can-not measure or infer inhale tidal volume, we can still effectively measure the volume through the duration of the exhale through our acquired thermal signature. To address the discontinuity problem for both the waveform and training, we allow the thermal dissipation of the exhale to describe the remaining portion of the waveform. Since this portion of the waveform only depends on the medium's material properties, we identify them as *follow-through regions* that only support continuity of the waveform.

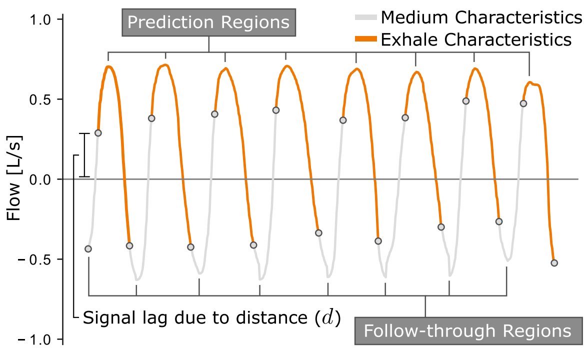

Fig. 7. Predicted waveform formulation. Exhale contributions are illustrated in (bold maxima) and the portions of the waveform characterized by the medium's material properties are shown by the regions containing the (minima) values. Tidal volume is estimated based on the differences of the maxima/minima values determined by peak detection.

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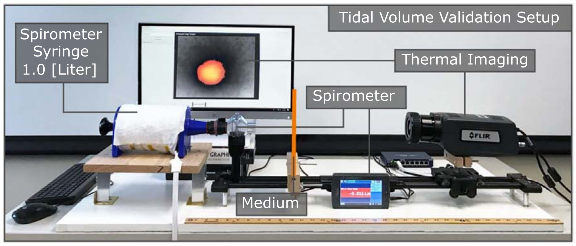

Fig. 8. Tidal volume validation setup. This setup validates the thermal-to-volume relationship based on a fixed 1.0[L] spirometer syringe. Dis-tances between the thermal camera, medium, and syringe are fixed.

The assumption is that the selected medium can approximate a reasonable dissipation rate so the next exhale can be captured without significant overlap from the current exhale. Additionally, the distance to the medium and exhale velocity determine the phase shift of the signal that is recorded on the medium compared to that recorded from the spirometer (lag due to travel distance from spirometer mesh to medium). From the remaining valid portion of the waveform, we can predict flow values based on the minimally overlapping thermal signature of each breath. We do this while identifying the regions defined by exhale contributions and those defined by the material properties.

Due to the cyclic nature of the signal and our objective of predicting exhale behavior and exhale volume, we take this phase shift into account within our signal processing and predict a continuous waveform that represents an accurate tidal volume estimation. Based on the objective of this prediction, this continuous waveform is valid for measuring exhale flow during the expiration and the total tidal volume of each breath. This is accomplished by taking the difference in the maxima and minima values for each period of the waveform.

5. Experimental design

5.1. Calibrated syringe experimental setup

Spirometer calibration syringes are used to calibrate the measured airflow to a known volume enclosed within an air-tight cylinder that can be used to simulate exhale behaviors. Using a spirometer attached to the flow direction provided by our heated syringe, we simulate controlled exhales to measure the thermal energy imparted in the medium while simul-taneously recording the spirometer reading in liters per second as shown in Fig. 8.

Using this approach provides a basis for establishing the correlation between the thermal signature imparted on the medium and the known airflow through the spirometer. Within this controlled experimental setup, we formulate an accurate model that can be trained to measure the known syringe volume while recording the heat exchange on the medium. We use this setup to generate an initial model of spirometer syringe predictions that verify our approach and establish error factors that may impact our results based on this method.

5.2. Human experimental setup

The human experimental setup consists of two configurations: (1) the initial training phase where the patient breathes through the spirometer onto the medium to train the correlation network and (2) the use phase where the patient breathes normally onto the paper. This allows for per-patient breathing pattern training, however it is not explicitly required by our technique. This is because the exhale patterns imparted onto the medium are not patient specific. That is, for each patient the exhale characteristics on the medium do not drastically vary between users. Therefore, with an established training database, our method can be used without prior training. However, if this is the case, care must be taken to ensure that reasonable environmental conditions are ensured: no airflow, reasonable room temperature (75[F] or 24[C]), and the dis-tance to medium is maintained at an optimal range.

The patient must remain still and breathe normally while trying to maintain a constant distance of 4.0[cm] 8.0[cm] to the medium. Currently this distance is maintained by a fixed chair and a stationary posture. This ensures that the exhale thermal signal will be visible and distinct from the environmental temperature. If the environment and medium have a higher ambient temperature, the thermal signature on the medium will become less prominent. For adjustability of the setup for different individuals, we used two simple camera tripods to hold both the thermal camera and the medium with an attachment arm. Visual results of the exhale thermal pattern due to breathing directly on the medium (without the spi-rometer present) are shown in the image sequence presented in Fig. 2.

It is important to note that during this process, we assume the patient breathes on the center of the medium consistently, as illustrated in Fig. 9. This provides a thermal signature similar to that used within the training process based on the amount of heat transferred to the medium. The thermal signature (on the left monitors) presented within Fig. 9(left) can be compared to the thermal signature presented within Fig. 9(right).

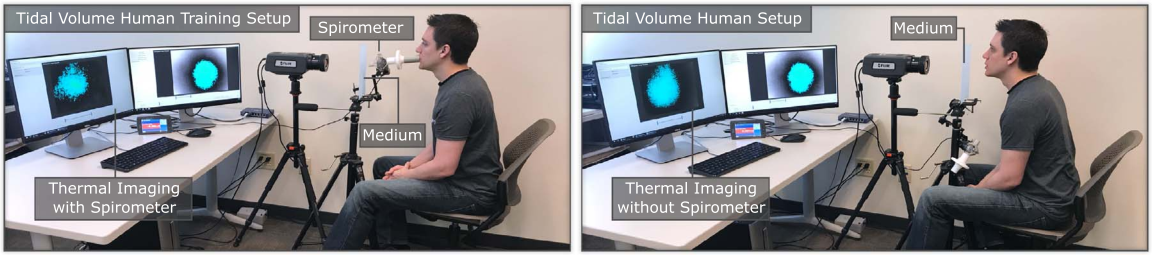

Fig. 9. Human trial tidal volume training setup (left). The patient breathes through the spirometer onto the medium to provide both the known ground-truth measurement and the thermal distribution to create the training sets used for generating the estimation model. Human trial tidal volume validation setup (right). The patient breathes normally and uninhibited onto the medium to generate the input to the trained estimation model. This allows us to predict tidal volume accurately while the patient breathes without a spirometer with the reference signature (used as a training guideline) as shown on the right monitor in both cases, the result remains similar. This allows us to train on spirometer calibrated data for training and use a natural exhale pattern for long term monitoring. Due to the potential of the patient to drift or breathe in different directions, we try to provide a natural and comfortable setup for prolonged monitoring durations. This partially accounts for the patient's tendency to move during monitoring, causing the distance between them and the medium to increase.

From the ability to breathe naturally onto the thin medium, the monitoring process is significantly less strenuous than breathing through a spirometer for long durations. Furthermore, fatigue due to spirometer use (mouth tube, filter, holding the device), make its use burdensome for long monitoring durations. In our approach we assume that the patient remains still and breathes on the medium, but the airway is not restricted, which is a major influence on the patient's comfort levels during the experiment.

6. Results

The results of this technique are presented with respect to the two experimental setups proposed. These include (1) the simulated exhale volume of the calibrated syringe as a fixed heated volume used to verify our volume measurement approach and (2) the human experiments that validate this approach for actual exhale behaviors recorded without the use of a spirometer. Furthermore, we demonstrate that this technique can be used independent of an existing tidal volume estimation and still provide reasonable estimates while maintaining patient comfort. This allows the technique to be used for longer periods of time and allows for natural respiratory behaviors.

6.1. Calibrated syringe results

We collected 10 samples of simulated exhale data using the calibrated syringe. Each sample is 30 s long, and consists of information collected from both the thermal camera and spirometer simultaneously. The thermal images are reduced to average values and compared with the spirometer waveform. To test the accuracy of our method, we iterated through each of the 10 samples, predicting the waveform of each sample using a network trained with the other 9 samples. The accuracy was assessed by calculating the Root-Mean-Square Error (RMSE) of the predicted and spirometer waveform. We use two different methods to process the data. In the first method, the thermal data is compared to the cumulative integration of the spirometer data in order to determine exhale volume per breath. Fig. 10 shows a comparison of the thermal signal and the cumulative integration of the spirometer signal from one sample, as well as the predicted waveform from the neural network. The average RMSE of the 10 samples is approximately 8.43%. The exhale volume for each breath can be determined

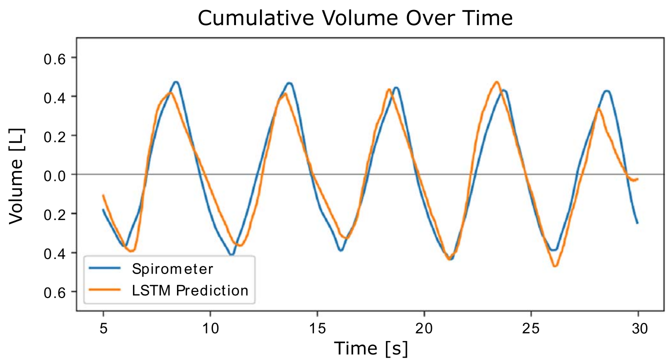

Fig. 10. Exhale volume prediction results. The plot illustrates the thermal signal and the cumulative integration of spirometer data as the estimated tidal volume.

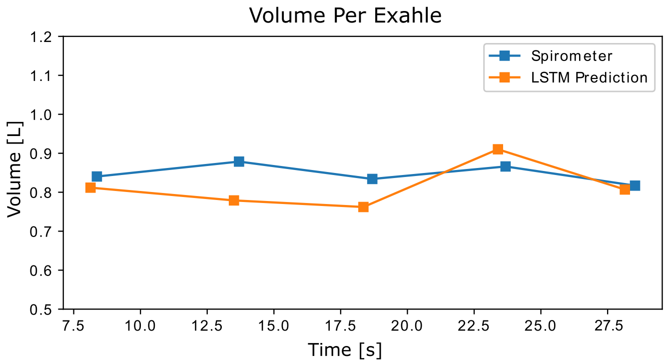

Fig. 11. Volume of each exhaled breath from the spirometer compared with the estimated volume of each breath from the thermal data. Measured as maxima - minima from Fig. 10.

by subtracting the valley of each cycle in the waveform by the peak that immediately follows. Fig. 11 shows the exhale volume for each breath from the spirometer compared with the estimated exhale volume for each breath as determined by the neural network and thermal data.

In the second processing method, the LSTM neural network is trained on raw spirometer data and thermal data, and predicts respiratory flow from thermal data. Fig. 12 compares the original spirometer data and the LSTM predicted waveform from the neural network. This method shows an error of approximately 19.10%.

As discussed in Section 4.1, we expect a lower accuracy with this method than we do with the first method since we do not expect to get fine-grained respiratory flow detail from the thermal images. This is due in part to the material properties of the medium and the rate at which it dissipates heat in relation to the fine-grained flow measurement provided by the spirometer. Using a larger amount of data to train the neural network may help to increase the accuracy of our flow-based measurement, and additional medium materials that better capture flow behaviors could be evaluated. However, since our general interest is in reducing the total error related to tidal volume, we leave improvement of this accuracy as a secondary objective.

6.2. *Human results*

We collected samples from five healthy normal human subjects. Each subject provided 10 samples by breathing through a spirometer onto the medium for 30 second intervals. Each person was instructed to breathe in and out of the spirometer through their mouth during data collection. These results are shown in Fig. 13. In order to determine the accuracy of the human results, we iterated through each sample and predicted the spirometer data for that sample using an LSTM neural network that had been trained with the other 9 samples. Fig. 13 and 14 show the output of the cumulative volume processing for samples from the five different subjects. As mentioned previously, we used RMSE to calculate the error for each sample, which showed an average error of approximately 10.61%.

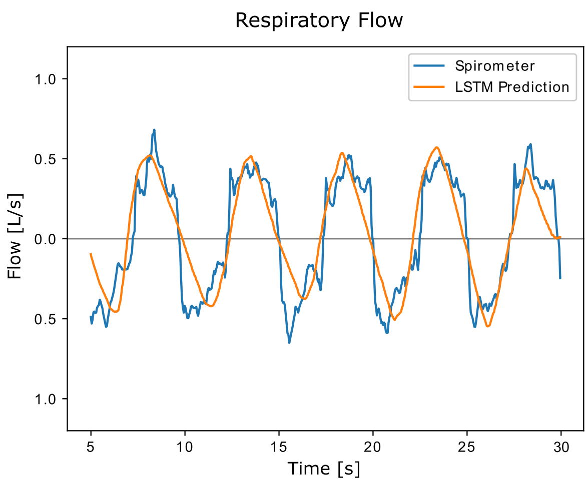

Fig. 12. Respiratory flow measured by the spirometer compared with raw thermal data and the predicted waveform from the validation experiment.

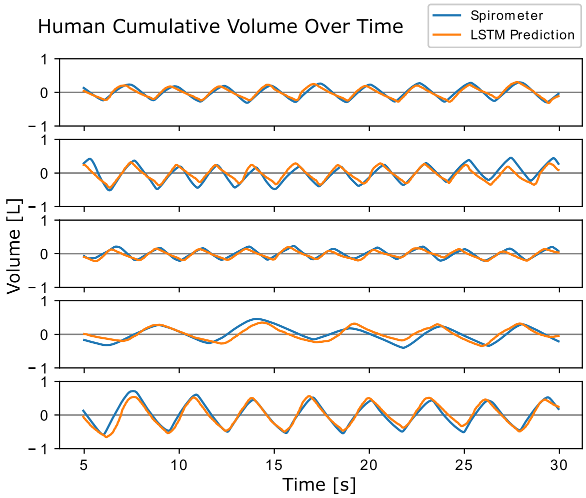

Fig. 13. Exhale volume prediction results from human tests, plotted against the cumulative spirometer data for five human subjects.

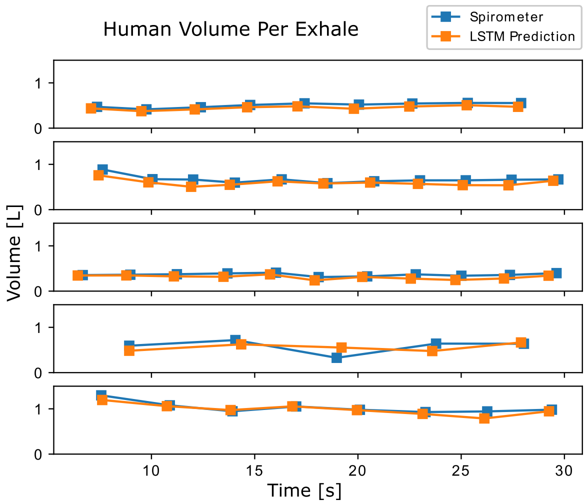

Fig. 14. Comparison of spirometer exhaled volume and estimated exhaled volume from the thermal data for five human subjects.

We also compared the thermal signal to the raw spirometer flow signal, as described in the previous section. Fig. 15 shows a plot of the spirometer data and the predicted respira-tory flow for samples from the five test subjects. Using RMSE, we calculated an error of 21.81%. We expect a reduced accuracy for the human results compared with the syringe due to extraneous movement, as well as the more chaotic nature of exhaled breath from a human. This error could possibly be remedied by using more data to train the network.

7. Evaluation and discussion

7.1. Inhalation estimation

As stated previously, this method only provides information about a person's exhale. The medium's cooling period corresponds to the duration of the inhale of the individual, but doesn't provide any additional information about a person's inspiration characteristics. Therefore, the inhale portion of tidal volume measurements are characterized by the material properties of the thin medium rather than direct measurements of the patient's exhale. While additional inhalation metrics such as Inspiratory Reserve Volume (IRV) and Inspiratory Capacity (IC) cannot be measured directly, these values can be inferred using exhale measurements.

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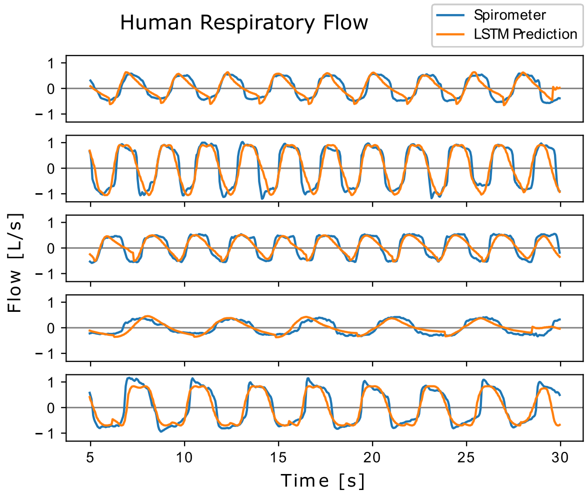

Fig. 15. Human respiratory flow compared with the waveform predicted by the neural network for five human subjects.

7.2. Movement and irregularities

The accuracy of the proposed technique is highly dependent on the movement of the patient and their breathing direction. Due to the current planar shape of the medium, the patient must remain at a constant distance and angle to the medium. This makes this technique less applicable to other forms of respiratory monitoring such as long-term studies related to sleep apnea. To mitigate the effect of the patient moving while breathing, the medium can be curved to provide flexibility in the direction and distance the patient must maintain during the monitoring process. The shape of the mouth and velocity of the exhale can also impact the results of this method and will require further investigation, as a larger mouth opening will create a larger, hotter thermal signature, and a smaller mouth opening will create a smaller, cooler thermal signature. Another irregularity is how the moisture of your natural breath may effect the medium we have selected, but since the medium is inexpensive, we can exchange it between uses. Further investigation on optimal arrangement is necessary, such as using a chin rest to keep a constant distance between the patient and the medium, whether a sitting posture or lying posture is preferable, and if a curved medium will provide more robustness against patient movement.

7.3. Training to runtime image discrepancy

There is a large difference between the thermal distributions generated while using the spirometer (through a tube) and the test set that is generated from a patient naturally breathing on the medium (without a tube). This is because the airflow through the tube has similar behavioral characteristics to a laminar flow. Natural exhale airflow is behaviorally chaotic, which leads to different thermal projections on the medium. Additionally, our test setup does not validate nose breathing (since the spirometer syringe has only one flow passageway), but this is not a limitation of the human trial setup. For nose breathing, an appropriate training set can be established to identify the tidal volume due to the downward thermal distribution projected on the medium due to breathing only through the nose. Another factor would be simultaneous nose and mouth breathing, which would also require additional training.

It is important to note that our proposed method can be trained to other ground-truth methods besides spirometry; training our method against another method such as a whole-body plethysmograph chamber may eliminate uncertainty related to spirometry and breathing mode. Regardless of the ground-truth device, training can be improved with varied initial conditions, such as varying the shape of the mouth and exhale force. Extension of the training model and accommodated exhale behaviors with these variants allows for the clinical feasibility and deployment of our method.

7.4. Material error factors

An ideal material for the medium would fulfill the requirements outlined in Section 3.2 while providing an ideal imaging surface. However, when using paper as a medium, it is important to consider the varying surface textures of different types of paper. Copy paper in particular contains a relatively coarse texture when viewed through a thermal camera, introducing additional signal noise to the processed images as shown in Fig. 16(left). A paper material with a finer texture may alleviate this problem.

Heat retention is also a primary error factor due to the accumulation of thermal energy between breaths as shown in Fig. 16 (center, right). This effect will lead to higher tidal volume estimates due to the prolonged intensity values remaining from the prior exhale. To alleviate this problem, we modify the scaling on the processed images to provide a reliable baseline between breaths (ideally the medium thermal energy returns to zero). However, for rapid breathing, alternative medium

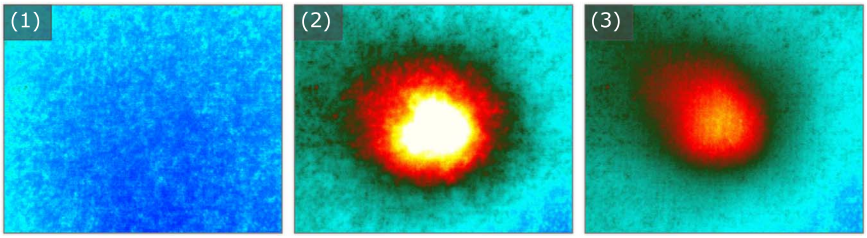

Fig. 16. Thin medium surface texture. Surface texture from the selected medium introduces additional error due to the non-uniformity of the thermal signature in room temperature (left), exhale (center), and dissipation portions of the monitoring process.

materials may be considered. An ideal material would provide immediate dissipation, but due to the practical requirements of deploying the system within a clinical setting, this would require a more expensive material that is less suited for immediate replacement.

7.5. Future direction

Though the system currently trains on each person individually, we plan to collect a large amount of data from healthy normal individuals and those with pulmonary issues so that the LSTM can be trained from multiple scenarios. By collecting a large amount of data, we can train the system to accurately determine breathing volume without having the individual provide training data themselves, and potentially build a classifier to determine whether the individual being tested has pulmonary issues. Training could be done for additional metrics besides tidal volume, such as Expiratory Reserve Volume (ERV), by collecting data from forceful exhales. Clinical testing is required in order to determine the device's applicability to pulmonological assessment, and whether this method is accurate enough for clinical deployment.

8. Conclusion

Tidal volume measurement methods have previously been unable to provide a comfortable experience for the patient while producing reliable results. Our proposed method demonstrates a novel approach to tidal volume measurement that finds a middle ground between accuracy and comfort, and provides numerous other benefits. This method can be used for longer periods of time than spirometry without fatiguing the patient, and because it is not impacted by body composition, it can be used to monitor a variety of patients. Additional metrics beyond tidal volume can be measured using this method, such as respiration rate, nose to mouth distribution, and exhale strength.

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Conflict of interest

We wish to draw the attention of the Editor to the following facts which may be considered as potential conflicts of interest and to significant financial contributions to this work.

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