Esquinas AM (ed): Applied Technologies in Pulmonary Medicine. Basel, Karger, 2011, pp 46–50

Thermal Infrared Imaging during Polysomnography: Has the Time Come to Unwire the 'Wired' Subjects?

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Abbreviations

ATHEMOS	Automated thermal monitoring system
BCI	Bayesian credible interval
κ (kappa)	Chance-corrected agreement
Pn	Nasal pressure – airflow monitoring device routinely used in polysomnography
REM	Rapid eye movement
RERA	Respiratory effort-related arousals
SDB	Sleep disordered breathing – encompasses a wide variety of disorders characterized by breathing abnormalities during sleep such as obstructive sleep apnea, central sleep apnea, etc.
TIRI	Thermal infrared imaging

Untreated SDB is a very prevalent problem and can cause daytime sleepiness as well as have far-reaching socioeconomic and health-related consequences. A summary of statistics from three pooled studies estimated that 20% of adults with a body mass index between 25 and 28 kg/m^2 have SDB based on an apnea-hypopnea index of ≥5 per hour [1]. Sleepiness is believed to have played a major role in causing disasters such as the Chernobyl and the Three Mile Island tragedies [2] and has been reported to be the most common cause of fatalities associated with motor vehicle accidents [3]. Untreated SDB is also associated with cardiovascular diseases [4].

Diagnosis of sleep apnea typically involves an overnight sleep study with simultaneous monitoring of airflow channels (Pn, oro-nasal thermistor), electrocardiogram, sleep staging by electroencephalography, electrooculography, and chin and leg electromyography in accordance with the Level 1 recommendations of the American Academy of Sleep Medicine [5]. However, conventional polysomnography has the potential to interfere with the 'usual' sleep pattern. A sizeable proportion of patients and normal volunteers who have never had a prior sleep study, experience the 'first night effect' characterized mainly by a decrease in sleep efficiency, prolongation of sleep-onset time, increase in REM sleep latency and a reduction in the total amount of REM sleep [6]. Additionally, it has been demonstrated that instrumentation during polysomnography affects body position during sleep [7] and thus impacts the diagnosis of SDB, the severity of which can increase during supine sleep. Moreover, bedside manipulation of sensors, in an effort to obtain high-quality data, may further disturb sleep and

hinder our ability to obtain a true representation of the patient's usual sleep pattern. Thus, decreasing subject contact with monitoring equipment and testing in the 'usual' sleep environment may help counteract polysomnography's interference with sleep and SDB.

American Academy of Sleep Medicine recommends the use of thermistor as the airflow sensor for the diagnosis of apnea and Pn for the diagnosis of hypopnea as well as RERA [5]. While Pn can overestimate pathological events, especially when subjects change from nasal to predominantly oral breathing, the thermistor on the other hand lacks the sensitivity as compared to Pn, to detect subtle flow abnormalities such as hypopnea and RERAs. Non-contact airflow monitoring technology such as TIRI has the capability to monitor airflow during sleep without subject contact. This concept can be extended to include both laboratory-based and home-based sleep studies.

Description of TIRI

The principle of operation of TIRI is close to that of the oro-nasal thermistor in that both these methods sense thermal radiation. However, it is important to note the following differences between the thermistor and TIRI:

(1) TIRI can sense thermal information at a distance (contact-free), while the thermistor needs to be physically placed and tethered to patient's oro-nasal area, in the proximity of the thermal signal.

(2) TIRI acquires thermal information through natural radiation from the source as opposed to the thermistor which acquires thermal information by conduction when placed in the path of airflow. Theoretically, conduction is bidirectional and has an associated measurement error based on where and when the measurements are made. The accuracy also depends on the intensity as well as the magnitude of change in the thermal signal that is being measured. This error can be detrimental to the detection of subtle airflow abnormalities. TIRI, on the other hand, is an array (imaging sensor) and not just a point sensor-like thermistor. Therefore, it can be used to obtain a thermistor-like signal across time by averaging the thermal signal from all the points in the cross-sectional area of the visible nares, as well as provide thermal information over an extended two-dimensional surface. Analysis of signal as an evolving two-dimensional surface across increases the sensitivity of TIRI and may increase its ability to detect subtle airflow-related phenomena.

Thus, on theoretical grounds alone, one would expect TIRI to be considered a 'virtual thermistor' to perform at least as good as the oro-nasal thermistor [8]. Despite these inherent advantages of TIRI as compared to the thermistor, the following significant challenges had to be overcome to realize the translation of this technology for airflow monitoring:

(1) *Virtual probing*: Since there is no physical probe involved in TIRI, a computational method is needed to segment the nostrils in the image, thus creating a 'virtual' probe, where the measurement can be performed. The difference in the temperature of inspired and expired air brings about a temporal variation in the thermal signature of the nostrils. This fluctuating thermal signal helps in the differentiation of the nostrils (or mouth, if the subject is mouth-breathing) from the rest of the facial tissue. The nostrils can thus be segmented from the face with the nasal cartilages forming 'colder' boundaries around the thermal signal (fig. 1).

(2) *Tracking*: Because there is no tethering and the subject is free to move, a computational method is needed to track changes in position, so that the virtual probe stays always in place and the accuracy of measurement is preserved. Functional imaging such as TIRI that maps randomly changing thermophysiological function in a non-restrained subject requires a collaborative network of particle filter trackers based on advanced statistics (coalitional tracking [9]) to compensate for subject movement.

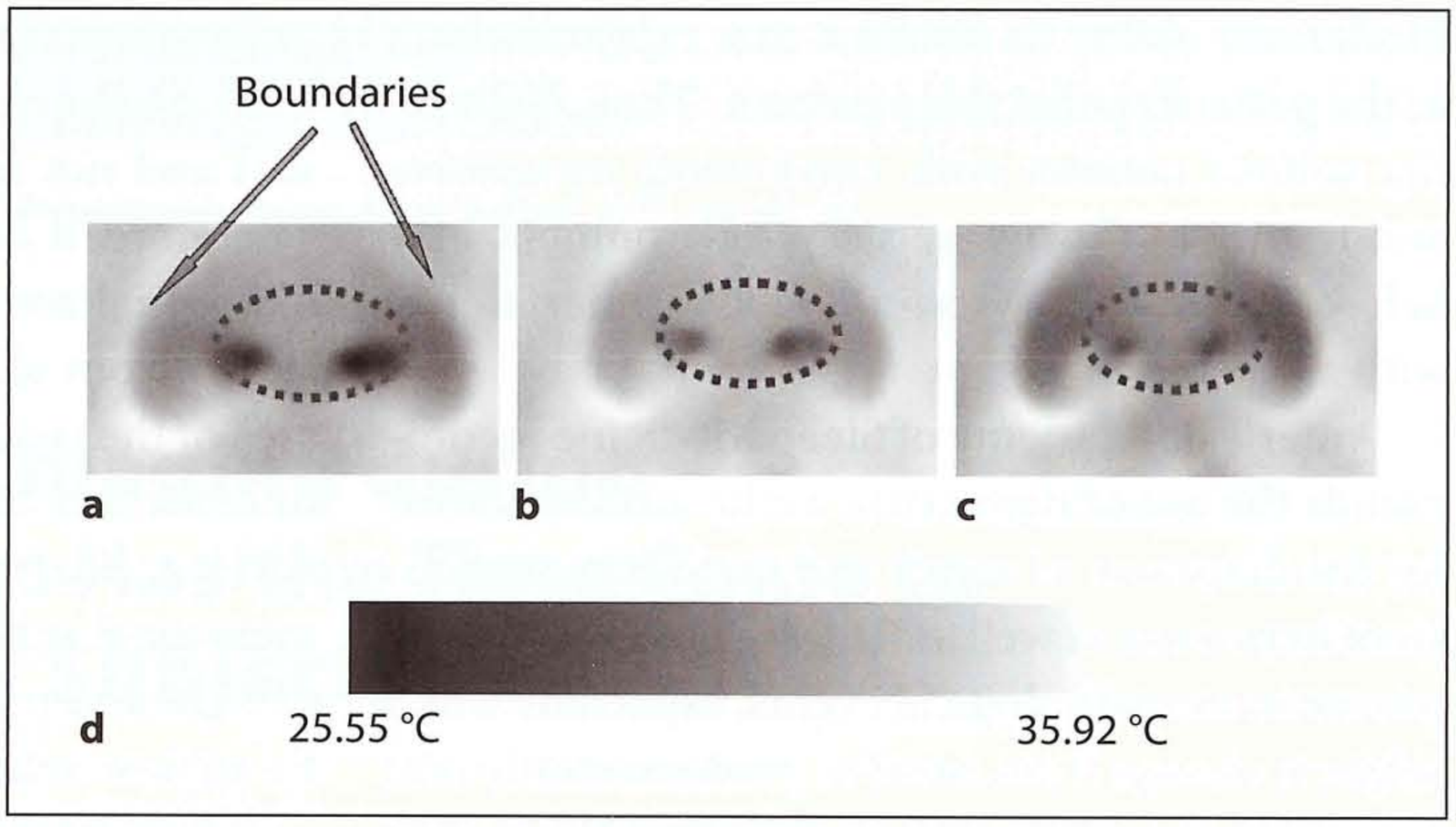

Fig. 1. Temporal variance of nostril region in thermal imagery during breathing: (**a**) inspiration phase, (**b**) transition phase, (**c**) expiration phase, and (**d**) thermal color map. Note the cold boundaries (labeled 'Boundaries') of the nasal cartilages that allow the segmentation of nostrils from the rest of the facial tissue.

(3) *Signal extraction:* Assuming that virtual probing and tracking work well, they create the opportunity for a good measurement, but not the measurement in itself. Since there is no physical transducer that can produce an electronic signal in response to thermal signal, the signal has to be computationally generated. This has been achieved by continuous wavelet transformation on the normalized thermal signal under the assumption that the breathing component is the strongest part of the varying thermal signal.

Integration of TIRI with Polysomnography

The integrated hardware and software system we used in our preliminary study [10] is called ATHEMOS. The thermal signal acquired by the infrared camera and processed by ATHEMOS as an airflow signal was recorded into an existing polysomnography system as an airflow channel, using a custom-made digital to analog converter. This allowed for easy display and comparison of all the airflow channels on a single screen. The camera was kept at about 2.45 m away from the patient during the recording.

Fourteen subjects (9 men and 5 women) without sleep apnea and 13 subjects (7 men and 6 women) with obstructive sleep apnea were studied for an average recording time of around 110 min. There was excellent κ (κ = 0.92, 95% BCI 0.86, 0.96; probability of κ being ≥0.70 [pκ] = 0.99) between TIRI and thermistor for the detection of apnea (defined as a ≥90% decrease in airflow for at least 10 s) and hypopnea (defined as a decrease in airflow signal by at least 50% from the baseline with a ≥4% oxygen desaturation from pre-event baseline). Likewise, there was a high degree of κ between TIRI and Pn (κ = 0.83, 95% BCI 0.70, 0.90; pκ = 0.98). When the performance of thermistor, Pn and TIRI was compared, the thermistor missed the most number of concordant events detected in the other two channels, while Pn missed the least. However, it is intriguing to note that TIRI missed only 3 concordant events detected by the thermistor and Pn while the thermistor missed 21 concordant events detected by TIRI and Pn. The better performance of TIRI as compared to the thermistor can be explained by the increased efficiency of detection of thermal signal by natural radiation, as opposed to conduction.

Discussion

There appears to be need to further advance the field of polysomnography with the use of non-contact-sensing methods in laboratory and home-

based sleep studies. The need to obtain a true representation the usual sleep pattern motivates this shift in paradigm. Non-contact-sensing methods such as TIRI have the potential to advance the field in this direction. However, this technology should be thoroughly tested prior to its widespread clinical use. Even though the results of our initial evaluation of TIRI appear to be optimistic, significant concerns in the study design, including a small sample and a limited monitoring period, remain. TIRI, to our knowledge, has never been evaluated during an overnight polysomnography. A study of this nature is of vital importance to establish the resilience and accuracy of thermal imaging as airflow-sensing method during routine nocturnal sleep studies. Even if contact airflow-sensing devices are replaced by non-contact technology, we still have to contend with the remaining contact sensors that may continue to interfere with sleep during polysomnography. On the other hand, the role of TIRI in conducting home sleep studies should be explored and validated. Since TIRI is currently a prototype, the expense associated with this technology is relatively high. However, with further development and widespread use of this technology, here is potential for cost reduction.

Analysis of thermal imaging signal using algorithms that preserve the array structure of the sensor may help in the detection of subtle airflow abnormalities such as RERAs. In such a situation, direct comparison of TIRI with Pn in scoring RERAs would be necessary to further validate this technology.

TIRI is the only technology that can perform signal acquisition in a retrospective manner since signal transduction is done computationally. The operator can redefine a new region of interest and computationally transduce the thermal signal. This concept can be expanded to simultaneously monitor airflow from the oro-nasal region and artificial airways such as tracheostomies. The current tracking algorithms automatically compensate for mild to moderate subject movement. In the event of a drastic change in subject position, signal acquisition can still continue if the nostrils are within the camera frame. In such a scenario, the operator can remotely change the camera position on a tilt-pan stand, redefine the region of interest and resume data collection. Extreme changes in body position can also be handled by interfacing multiple cameras at different positions in the room. Only when a subject buries his or her face into a pillow or pulls a sheet over the face, will the signal be lost. This scenario will need a technician intervention to instruct the patient appropriately. On a similar note, masks also interfere with thermal signal acquisition and thus TIRI cannot be used simultaneously with a continuous positive airway pressure titration at the present time.

TIRI has the potential to make a significant impact in pediatric polysomnography, where contact oro-nasal sensors are difficult to place and maintain. Sterilization of equipment or consumables is not necessary for TIRI to operate.

Future studies should validate TIRI in laboratory-based nocturnal polysomnography in adults and children. Since the accuracy of TIRI in the detection RERAs and its resilience during overnight polysomnography are still uncertain, this technology at the present time should only be used for investigational purposes.

Recommendations

- There is a need to develop non-contact-sensing modalities such as TIRI during polysomnography to not only improve patient comfort and experience, but also to obtain a representative sample of the subject's usual sleep.
- Even though the preliminary study with TIRI is encouraging, further validation is required before this technology can be used in a clinically meaningful way.
- TIRI has the potential to be used for medical applications beyond polysomnography where airflow monitoring in a non-contact manner is necessary.

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