pii: jc-18-00708 https://dx.doi.org/10.5664/jcsm.7880

JCSM
Journal of Clinical Sleep Medicine

SCIENTIFIC INVESTIGATIONS

Use of a Transformed ECG Signal to Detect Respiratory Effort During Apnea

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Study Objectives: To evaluate the ability of a transformed electrocardiography (ECG) signal recorded using standard electrode placement to detect inspiratory bursts from underlying surface chest wall electromyography (EMG) activity and the utility of the transformed signal for apnea classification compared to uncalibrated respiratory inductance plethysmography (RIP).

Methods: Part 1: 250 consecutive adult studies without regard to respiratory events were retrospectively reviewed. The ECG signal was transformed with high pass filtering and viewed with increased sensitivity and channel clipping to determine the fraction of studies with inspiratory burst visualization as compared to chest wall EMG (right thorax). Part 2: 445 consecutive studies were reviewed to select 40 with ≥ 10 obstructive and ≥ 10 mixed or central apneas (clinical scoring). Five obstructive and 5 central or mixed apneas were randomly selected from each study. A blinded scorer classified the apneas using either RIP or a transformed ECG signal using high pass filtering and QRS blanking. The agreement between the two classifications was determined by kappa analysis.

Results: Part 1: Inspiratory burst visualization was noted in the transformed ECG signals and chest wall EMG signals in 83% and 71% of the studies ($P < .001$). Part 2: The percentage agreement between RIP and transformed ECG signal classification was 88.5%, the kappa statistic was 0.81 (95% CI 0.76 to 0.86) and interclass correlation was 0.84, showing good agreement.

Conclusions: A transformed ECG signal can exhibit inspiratory bursts in a high proportion of patients and is potentially useful for detecting respiratory effort and apnea classification.

Keywords: apnea, diaphragmatic EMG, respiratory effort

Citation: Berry RB, Ryals S, Dibra M, Wagner MH. Use of a transformed ECG signal to detect respiratory effort during apnea. *J Clin Sleep Med.* 2019;15(7):991–998.

BRIEF SUMMARY

Current Knowledge/Study Rationale: Recording a diaphragmatic/chest wall electromyography (EMG) signal using surface electrodes detects inspiratory effort facilitating accurate apnea classification. However, the signal is not routinely recorded in many sleep centers and may not exhibit inspiratory bursts in many patients.

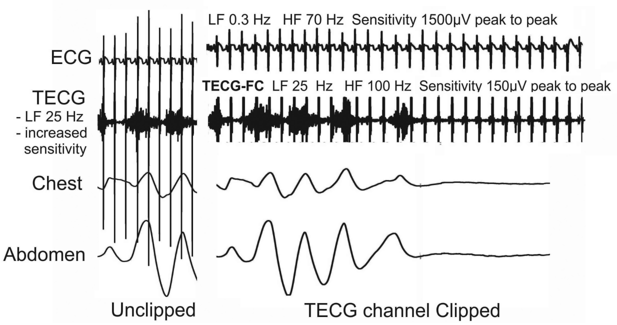
Study Impact: Transformation of the signal from routinely placed electrocardiography (ECG) electrodes reveals underlying inspiratory EMG activity. The transformed ECG signal can reveal EMG bursts when they are not clearly seen in the chest wall EMG signal and complements respiratory inductance plethysmography belt detection of respiratory effort improving the accuracy of apnea classification.

INTRODUCTION

Respiratory effort belts may fail to clearly demonstrate signal deflections during obstructive apnea resulting in misclassification of the apnea as central.[1–4] Recording of a diaphragmatic/chest wall electromyography (EMG) signal using surface electrodes typically placed on the right lower chest wall has been used to detect respiratory effort and quantify the magnitude of effort.[4–7] The signal may detect respiratory effort when effort belts fail to do so and complements the information from the effort belts.[4] However, diaphragmatic/chest wall EMG electrodes are not routinely placed in many sleep centers and when placed, the signal may fail to clearly demonstrate inspiratory bursts of activity during apneas or contain excessive 60 Hz artifact making the signal unusable.[4,7]

According to The AASM Manual for Scoring Sleep and Associated Events: Rules, Terminology and Technical Specifications (AASM Scoring Manual)[8] a modified lead II is recommended for electrocardiography (ECG) monitoring during polysomnography (PSG) with the negative electrode below the right clavicle and the positive electrode on the left torso below the heart. The AASM Scoring Manual states that the electrodes should be "aligned and parallel to the right shoulder and left hip."[8,9] The exact position of the positive electrode is not specified relative to the intercostal spaces, but is typically placed in the fifth, sixth, or seventh left intercostal space near the anterior axillary line. The recommended filters for recording the ECG signal include a low filter setting of 0.3 Hz and a high filter setting of 70 Hz. Given that the positive ECG electrode is placed on the left lower thorax near the anterior axillary line, this electrode could potentially detect inspiratory chest wall EMG bursts (diaphragm and other muscles). However, the ECG signal is relatively strong at this location and an attempt to record a surface EMG with low and higher filter settings of 10 and 100 Hz shows the ECG signal without EMG activity. However, in many patients one can visualize inspiratory bursts

Figure 1—Visualization of inspiratory bursts in a transformed ECG signal.



The effect of transformation of the ECG signal with filtering, increased sensitivity, and channel clipping (TECG-FC) is shown. Chest and abdomen channels are uncalibrated respiratory inductance plethysmography. Inspiratory bursts vanish with the onset of absent deflections in the chest and abdomen respiratory inductance plethysmography effort belt signals. Note the much higher sensitivity (lower peak to peak voltage) used for the transformed ECG signal. ECG = electrocardiography, TECG = transformed ECG signal, TECG-FC = transformed ECG signal with filtering and channel clipping.

of activity in the ECG signal[10] using a low filter setting (high pass filter) that reduces the ECG amplitude but allows visualization of the underlying EMG signal (low filter setting of 25 to 40 Hz, high filter setting 100 Hz). With suitable filtering of the ECG signal (to increase the relative magnitude of the underlying EMG components), an increase in sensitivity, and clipping of the channel (to allow visualization of the lower amplitude EMG component), a transformed ECG signal (TECG-FC) often exhibits inspiratory bursts due to the underling inspiratory EMG activity (**Figure 1**).

We hypothesized that using this technique to transform the ECG signal would allow visualization of inspiratory EMG bursts in a significant fraction of patients undergoing sleep studies. We further hypothesized that applying a QRS blanking technique to a suitably filtered ECG channel would result in a useful signal to detect inspiratory effort without significant ECG artifact. The signal after QRS blanking has several advantages including elimination of the need for channel clipping as well as facilitating the ability to derive a rectified and integrated signal exhibiting the amplitude of the EMG bursts. The blanking technique removes the portion of the filtered ECG signal containing the QRS complex and replaces it with a copy of a portion of the adjacent signal. The blanking technique was developed for removing ECG artifact from EMG signals but can also be applied to the ECG signal filtered to minimize the ECG relative to the underlying EMG components.[11,12]

The first goal of the current investigation was to determine how often simple transformation of the ECG signal (**Figure 1**) using filtering and channel clipping (TECG-FC) can reveal underlying inspiratory bursts relative to the ability of a simultaneously recorded chest wall EMG signal on the right thorax using typical electrode placement. The second study goal was to compare the ability of the filtered and QRS blanked ECG signal (TECG-FB) to classify apneas compared to traditional respiratory inductance plethysmography (RIP) belts.

METHODS

Consecutive adult sleep studies recorded over a 3-month period at the UF Health Sleep Center were retrospectively reviewed. The retrospective analysis was approved by the institutional review board of the University of Florida.

Part 1: Visualization of EMG Bursts With TECG-FC (Filtering and Channel Clipping)

For the first part of the study, the first 250 consecutive adult sleep studies (diagnostic, split, and positive airway pressure [PAP] titration) without concern for the presence or absence of respiratory events were analyzed for the ability to visualize inspiratory bursts in the TECG-FC signal for over two-thirds of the study. The ability to visualize inspiratory bursts in the simultaneously recorded chest wall EMG signal (routinely recorded in the sleep center) was also determined. The chest wall EMG signal was recorded as previously described[4] using a bipolar AC amplifier and two adhesive patch electrodes placed 2 cm apart in the eighth intercostal space at the right midaxillary line. Both the TECG-FC signal and the chest wall EMG signal were recorded using the Grass Comet Digital PSG system (Natus Neurology, Warwick, Rhode Island) and displayed using the same channel width with a high pass filter (low filter) of 25 Hz, channel clipping, and a sensitivity of up to 100 to 25 μV peak to peak (adjusted for visualization of inspiratory activity) using Twin software (Natus Neurology, Warwick, Rhode Island). The fractions of studies showing inspiratory bursts in both signals, the TECG-FC signal alone, the chest wall EMG signal alone, and neither of the signals were determined. The proportions of sleep studies with the chest wall EMG versus TECG-FC allowing visualization of inspiratory bursts were compared using the McNemar test for proportions (MedCalc Software bvba, Ostend, Belgium).

Part 2: Apnea Classification With TECG-FB (Filtering and ECG Blanking)

A second analysis was performed to compare the ability of the filtered and QRS blanked transformed ECG signal (TECG-FB) to classify apneas compared to dual uncalibrated RIP belts. The first 40 adult studies (diagnostic or split study) meeting the following criteria based on clinical technologist scoring of the entire study were analyzed:

a. Age older than 18 years
b. At least 10 central or mixed apneas
c. At least 10 obstructive apneas
d. Chest and abdominal RIP belt signals were of adequate technical quality.
e. The ECG signal using electrodes as recommended by the AASM Scoring Manual (including one on the left lower chest) exhibited prominent inspiratory bursts after transformation using a low frequency filter of 25 Hz when the gain was increased to 100 to 25 μV peak to peak and the ECG channel was clipped for at least two-thirds of the study.

A total of 445 consecutive adult sleep studies (diagnostic or split night) were reviewed to select the required number for analysis.

Of these studies 49 (11%) fulfilled respiratory event criteria and RIP belt criteria (a–d). However, 9 studies did not have a filtered and clipped ECG signal showing inspiratory bursts of activity for the majority of the study. Thus 81.6% of studies that met respiratory event criteria had an ECG signal showing inspiratory bursts after filtering, sensitivity increase, and channel display clipping. These 40 studies were analyzed in detail using QRS blanking of the filtered ECG signal and comparison with dual channel uncalibrated RIP classification of apneas. Adequate chest wall EMG bursts were not required for this analysis.

Polysomnography

Standard PSG techniques were utilized with recording of frontal, central, and occipital electroencephalogram and left and right eye movement derivations (E1-M2, E2-M2), and chin derivations as recommended by the AASM Scoring Manual.[8] Airflow was detected using an oronasal thermal sensor and nasal pressure (diagnostic study) or PAP device flow signal (PAP titration). Uncalibrated chest and abdominal respiratory inductance plethysmography signals were used to detect respiratory effort. Pulse oximetry (SpO_2) and right and left anterior tibial EMG signals were recorded. An ECG signal using electrode placement as recommended by the AASM Scoring Manual was also recorded. A chest wall EMG signal was recorded as described in a previous section. The Grass Comet Digital PSG system was used for PSG. Signals were acquired with a 200 Hz sampling rate and viewed using Twin software.

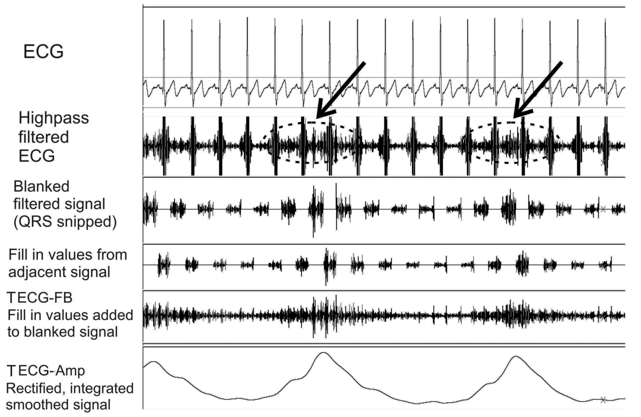
Transformation of the ECG Signal With Blanking

PSG signals of the 40 selected studies were exported in the European Data Format (EDF) using the Twin software. The EDF data was then imported into LabChart (a signal acquisition and analysis program, ADInstruments, Dunedin, New Zealand) for processing of the ECG signal. A modification of the algorithm developed by ADInstruments for blanking of ECG artifact in EMG signals[11] using built in LabChart functions was applied to the filtered ECG signal.

An overview of the process is depicted in **Figure 2**. The ECG signal first was high pass filtered (low filter 40 Hz, high filter 100 Hz). This reduced the amplitude of the QRS relative to the underlying EMG signal. Next the QRS segments were identified and removed from the signal (the blanked signal). A segment of the signal adjacent to the snipped portion was snipped, time shifted, and added to the blanked signal. This produced a signal (TECG-FB) representing the underlying surface EMG component of the ECG signal. This transformed signal was then rectified (absolute value function), integrated, and smoothed using built in functions in LabChart to provide an amplitude signal (TECG-Amp) reflecting the magnitude of the inspiratory bursts. The TECG-FB and TECG-Amp signals were the derived ECG signals used for apnea classification.

The resulting TECG-FB and TECG-Amp signals were exported along with EEG, EOG, chin EMG, ECG, nasal pressure and oronasal thermal flow (or PAP flow), chest and abdominal RIP effort signals, and oximetry (SpO_2) signals to another EDF file. The EDF file was imported into the G3 software (version 3.7.4, Philips Respironics, Murrysville, Pennsylvania) and workspaces showing either airflow signals and chest and abdomen respiratory effort signals or airflow signals and the derived ECG signals (TECG-FB and TECG-Amp) were created.

Figure 2—A summary of the QRS blanking process.



One can visualize the underlying EMG signal (arrows) obscured by QRS activity in the second channel surrounded by dashed ellipses. The QRS activity was snipped and replaced with adjacent signal activity. The TECG-FB signal was then processed to produce a signal reflecting the amplitude of inspiratory activity (TECG-Amp). ECG = electrocardiography, TECG-FB = transformed ECG signal with filtering and QRS blanking.

Event Selection

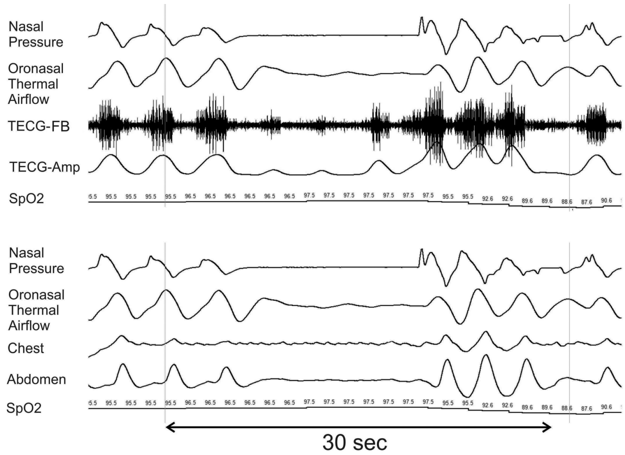
In each study, 5 central or mixed apneas and 5 obstructive apneas were randomly chosen. The random number function in Excel 365 (Microsoft, Redmond, Washington) was used to select an epoch number. The next event with technically adequate tracings was selected until the required number of events were identified. If the random epoch number selected an epoch after the last respiratory event, another random number was generated.

Screen shots showing EEG, EOG, chin EMG, and ECG, derivations along with arterial oxygen saturation, nasal pressure and thermal airflow (or PAP flow) with either chest and abdominal RIP channels or the transformed ECG signals were created. The screen shots were de-identified and copied into Power Point 2016 (Microsoft, Redmond, Washington) for viewing. These screen shots showing either chest/abdominal RIP or the transformed ECG signals for each apnea were presented to a single blinded observer for classification of apneas as obstructive, mixed, or central. Only one individual was responsible for blinded review of all data. For each apnea event the screen shots of the two methods were presented in different files so that the scorer could not compare the appearance of the two methods for a given apnea. Classification of apneas as obstructive, mixed, or central followed the rules of the AASM Scoring Manual.[8] An example showing only the respiratory signals from the two methods is illustrated in **Figure 3**.

Analyzing Agreement (Apnea Classification)

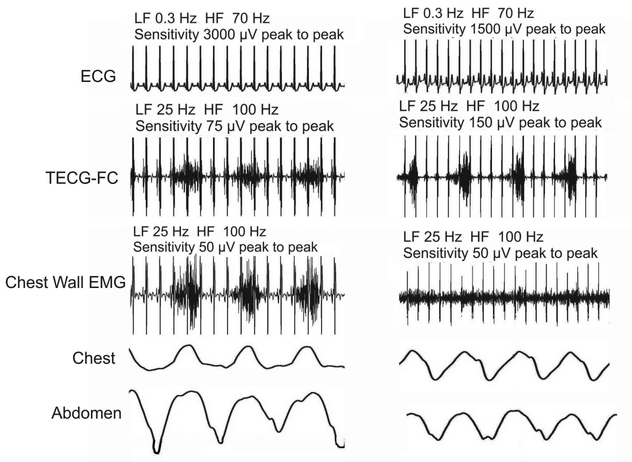
The agreement between methods for apnea classification was determined by both kappa analysis and intraclass correlation. Statistical software was used (Med Calc, Bvba, Ostend, Belgium). The percentage agreement was computed as: (number of pairs with agreement × 100) / total number of pairs.

Figure 3—Tracings for apnea classification.



Examples of respiratory signals using the transformed ECG signals (group 1: top 5 channels) or RIP signals (group 2: bottom 5 channels). For apnea classification the blinded scorer viewed only one group of signals at a time. In the flow signals inspiration is upward. Chest and abdomen are respiratory plethysmography signals. In this example the apnea was classified as obstructive by the transformed ECG signals but central by the RIP signals. ECG = electrocardiography, RIP = respiratory inductance plethysmography, SpO_2 = arterial oxygen saturation, TECG-Amp = rectified, integrated, smoothed TECG-FB, TECG-FB = transformed ECG signal with filtering and QRS blanking.

Figure 4—Visualization of inspiratory bursts in the chest wall EMG or transformed ECG signals.



Left: Tracings from a study with inspiratory burst visualization in both the transformed ECG (TECG-FC) and chest wall EMG (right thorax) is depicted. Right: A study with inspiratory bursts clearly visible only in the transformed ECG signal. Chest and abdomen are uncalibrated respiratory inductance plethysmography signals. ECG = electrocardiography, EMG = electromyography, TECG-FC = transformed ECG signal with filtering and channel clipping.

RESULTS

Part 1: Frequency of Visualization of EMG Bursts With TECG-FC

The demographic information of the 250 studies analyzed for the ability to visualize inspiratory bursts after a simple transformation of the ECG signal (TECG-FC) is displayed in **Table 1**. For split studies the apnea-hypopnea index (AHI) and events from the diagnostic portion were used in the calculations. The mean AHI was in the moderate to severe range. The frequency of EMG burst visualization for the TECG-FC and the chest wall EMG signals is shown in **Table 2**. The percentage of studies showing inspiratory bursts in the transformed ECG signal was greater than the percentage of studies showing bursts in the chest wall EMG signal. If both signals were considered (chest wall EMG only, transformed ECG only, or both), inspiratory bursts were visualized 91.6% of the time. Examples of studies showing inspiratory bursts in both chest wall EMG and TECG-FC signals or only the TECG-FC signals are illustrated in **Figure 4**.

Table 1—Demographics of group for inspiratory burst visualization (n = 250).

Age (years)	52.8 ± 15.1
BMI (kg/m^2)	34.1 ± 9.1
Sex (male/female)	128/122
AHI (events/h)	24.7 ± 23.1
Obstructive apneas (% total events)	21.4 ± 22.1
Mixed apneas (% total events)	2.4 ± 8.3
Central apneas (% total events)	10.5 ± 17.6
Hypopneas (% total events)	65.2 ± 28.2

Values are presented as mean ± standard deviation. For split studies the AHI and respiratory events are from the diagnostic portion. Event classification by clinical scoring. AHI = apnea-hypopnea index, BMI = body mass index.

Table 2—Frequency of inspiratory burst visualization (n = 250).

Inspiratory bursts with TECG-FC	83.0%*
Inspiratory bursts with chest wall EMG	71.0%*
Inspiratory bursts with chest wall EMG only	5.6%
Inspiratory bursts with TECG-FC only	20.0%
Inspiratory bursts with both	66.0%
Inspiratory bursts with at least one	91.6%

*TECG-FC versus chest wall EMG ($P < .0001$ McNemar Test). EMG = electromyography, TECG-FC = transformed ECG signal with filtering and channel clipping.

Part 2: Comparison of Apnea Classification (TECG-FB Versus RIP)

The demographic information for the study population for apnea classification is shown in **Table 3**. For split studies the AHI and respiratory events were for the entire night as the entire night was used for event selection. The patients were middle aged or older with an increased body mass index. The AHI was in the moderate to severe range. The percentages of event types are for the entire night (not the events selected for detailed analysis). By design, studies with a significant percentage of the apneas that were central or mixed apneas were selected (based on clinical sleep technologist scoring).

Table 3—Demographics for apnea classification (n = 40).

Age (years)	55.0 ± 16.5
BMI (kg/m²)	34.4 ± 7.5
Sex (male/female)	33/7
AHI (events/h)	38.1 ± 18.1
Obstructive apneas (% total events)	27.8 ± 18.8
Mixed apneas (% total events)	8.6 ± 14.5
Central apneas (% total events)	27.5 ± 24.1
Hypopneas (% total events)	36.1 ± 20.4

Values are presented as mean ± standard deviation. For split studies the AHI and respiratory events are for the entire night. Event classification by clinical scoring. AHI = apnea-hypopnea index, BMI = body mass index.

Table 4—Agreement table for apnea classification.

		TECG-FB			
		OA	MA	CA	Total
RIP	OA	182	12	4	198
	MA	8	74	4	86
	CA	11	7	98	116
	Total	201	93	106	400

CA = central apnea, MA = mixed apnea, OA = obstructive apnea, RIP = respiratory inductance plethysmography, TECG-FB = transformed electrocardiography signal with filtering and QRS blanking.

Event Agreement

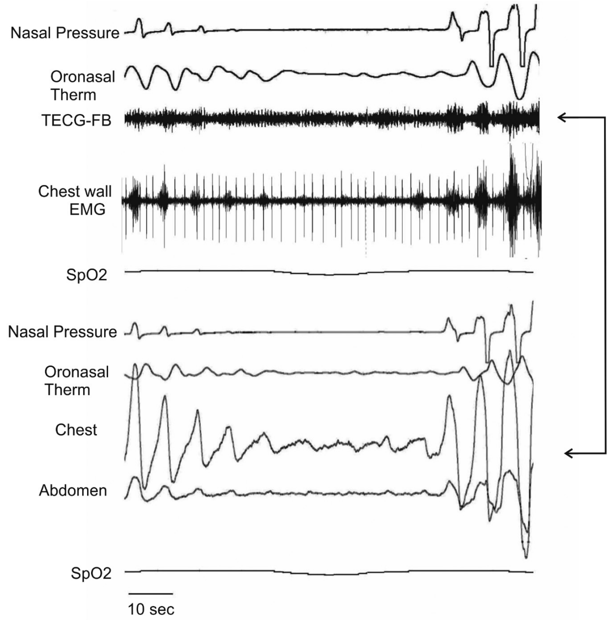
The event classification with the two methods (TECG-FB versus RIP) is shown in **Table 4**. The diagonal represents event agreement. The percentage of agreement was 88.5%. The kappa statistic was 0.81 (95% confidence interval: 0.76 to 0.86), consistent with good agreement. The intraclass correlation (for absolute agreement) was 0.84 (95% confidence interval: 0.81 to 0.87).

Events With Disagreement Between the Methods

Using RIP bands there were 116 apneas classified as central. Of these 18 (15.5%) were classified as obstructive or mixed by the transformed ECG signals. An example of an apnea classified as central by RIP but obstructive by TECG-FB is illustrated in **Figure 3**. Using the transformed ECG signals there were 106 apneas classified as central but 8 were classified as obstructive or mixed by RIP. An example of such an event is illustrated in **Figure 5**. In this event inspiratory bursts in the TECG-FB signal are clearly present in non-obstructive breaths but not during apnea. Although not used for apnea classification the simultaneously recorded chest wall EMG signal included in the figure does show inspiratory bursts.

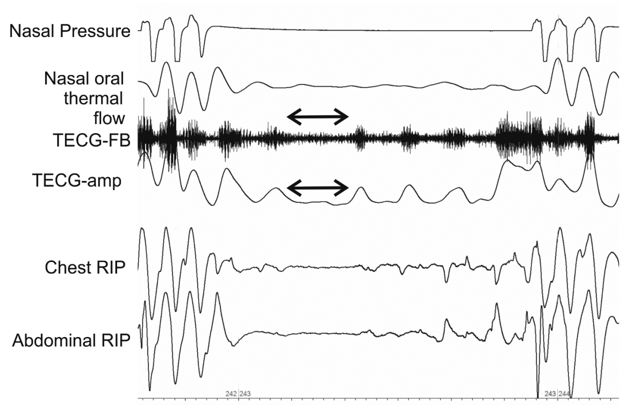
The other apnea classification disagreements were when one method classified an apnea as mixed while the other classified the apnea as obstructive. In many of these apneas with mixed versus obstructive apnea classification disagreement, the presence or absence of a short central portion was ambiguous in one or both signals (**Figure 6**). In other apneas, the transformed ECG signal did not clearly display small amplitude inspiratory efforts at the start of an event because of high background activity (scored as mixed) while inspiratory effort was identified using the RIP signals (scored as obstructive).

Figure 5—Classification disagreement (central versus obstructive).



An apnea classified as central by TECG-FB and obstructive by RIP. Inspiratory bursts in the TECG-FB signal are well visualized when flow was present but not during apnea. Note that the chest wall EMG signal did show inspiratory bursts (not visible when the apnea was classified by the TECG-FB signal). Chest and abdomen are uncalibrated RIP signals. EMG = electromyography, RIP = respiratory inductance plethysmography, TECG-FB = transformed electrocardiography signal with filtering and QRS blanking.

Figure 6—Classification disagreement (obstructive versus mixed).



This apnea was classified an obstructive by TECG-FB signals and mixed by RIP signals. The "central" portion was shorter in the TECG signals (double arrows) than the RIP signals. For easy comparison only one set of flow signals is shown and the TECG and RIP signals are combined in one figure. The blinded scorer saw only one group of effort signals. RIP = respiratory inductance plethysmography, TECG = transformed electrocardiography signal, TECG-Amp = rectified, integrated, smoothed TECG-FB, TECG-FB = transformed electrocardiography signal with filtering and QRS blanking.

DISCUSSION

The first main finding of this study is that a transformed ECG signal recorded using standard electrode positions exhibited inspiratory bursts of activity in a significant fraction of consecutively reviewed routine clinical sleep studies. We also found that when a chest wall EMG signal (right thorax) is recorded, the transformed ECG signal may show inspiratory bursts when the chest wall EMG signal does not (or is faulty). The second main finding is that there is a high degree of agreement between apnea classification with dual channel RIP effort belts and a filtered and blanked ECG signal (TECG-FB). In addition, of the apneas classified as central by RIP, 15% were classified as obstructive or mixed by the transformed ECG signal. Thus, transformation of a routinely recorded ECG signal can potentially provide useful information concerning classification of apneas and complements information from RIP effort belts.

The most important potential use of the chest wall EMG signal is to identify events falsely labeled as central by RIP bands. If unambiguous inspiratory bursts are identified in the transformed ECG signal, this is strong evidence for the presence of respiratory effort. In a previous study[4] comparing apnea classification between a chest wall EMG signal and RIP, 26 of 249 events classified as central by RIP were classified by the chest wall EMG as obstructive or mixed. However, the study also found a few events classified as central by chest wall EMG that had definite chest and abdominal RIP signal deflections. Thus, the RIP and chest wall EMG signals provide complementary information.

One may question the clinical significance of misclassifying a few respiratory events as central in a patient with primarily obstructive apnea. However, most sleep centers routinely encounter patients with a significant proportion of central apneas or studies with ambiguous effort belt deflections during reductions in airflow. For these reasons, a number of sleep centers routinely use diaphragmatic/chest wall EMG to assist with apnea classification. In those centers the value of an additional method to detect respiratory effort is believed to justify the extra effort needed to record the signal.

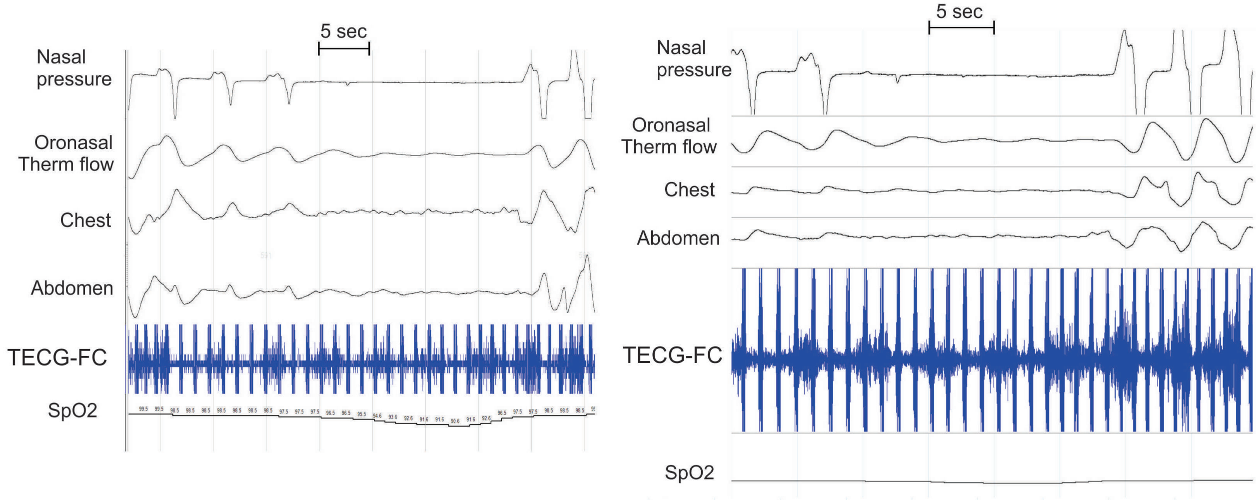
A chest wall EMG signal is not routinely recorded in many sleep centers and if recorded the signal is sometimes not useful due to artifact from a faulty electrode or inability to visualize inspiratory bursts during respiratory events. This proof of concept study was initiated after the observation that with proper filtering and transformation the routinely recorded ECG signal allows visualization of inspiratory bursts from the underlying EMG activity at the site of the ECG electrode on the lower left thorax. A retrospective review of 250 consecutive studies in which a chest wall EMG signal was recorded found that inspiratory bursts from transformed ECG signal could be visualized at least as often as in the chest wall EMG signal. In addition, sometimes visualization was possible in the transformed ECG signal when not seen in the chest wall EMG signal. Utilizing both the transformed ECG signal and the chest wall EMG signal inspiratory bursts could be identified in 91% of the studies.

Our study has several limitations. First, relevant to use of the TECG-FC signal, not all sleep computer programs have a low frequency 25 to 40 Hz filter available in ECG channels or the ability to clip channels. Thus, using this simple transformation may not be an option in all PSG computer software. With respect to apnea classification, we did not compare classification between the transformed ECG signal and the gold standard for respiratory effort detection (esophageal manometry). We were able to evaluate a large number of clinical studies using a signal that is routinely recorded during PSG. Stoohs and coworkers[5] compared esophageal manometry and surface diaphragmatic EMG in patients with obstructive sleep apnea. The ECG artifact in the EMG signal was minimized by a gating technique, the signal was rectified, and a moving time average was determined. During obstructive events, changes in the EMG signal closely tracked the esophageal pressure signal in most patients. Over the course of the obstructive events the increase in esophageal pressure deflections and the EMG signal were similar as a percentage of baseline. This suggests that the surface EMG signal is an acceptable surrogate for esophageal pressure deflections to detect respiratory effort. It could be argued that the presence of unequivocal inspiratory bursts in the TECG-FB signal is strong evidence for the obstructive nature of events. However, we cannot eliminate the possibility that apneas classified as central by both the TECG-FB and RIP methods might be classified as obstructive by esophageal manometry.

Another limitation of our study was the retrospective nature. To minimize selection bias, we reviewed consecutive studies selecting those meeting our study selection criteria and within each study randomly selected events for analysis. However, it is possible, the retrospective nature may have affected our results. In addition, for the apnea classification analysis we eliminated studies when the transformed ECG signal did not clearly show inspiratory bursts. Our analysis of a large group of patients in the first part of the study found that the TECG-FC signal displayed inspiratory bursts in only about 83% of patients while the corresponding value for the chest wall EMG signal was about 71%. Therefore, these signals complemented but could not replace the RIP signals. In a previous study[4] we found that only 76% of 79 studies otherwise meeting selection criteria for analysis had technically adequate chest wall EMG signals. This is very similar to our current analysis of a much larger group of consecutive studies analyzed for chest wall EMG visualization of inspiratory bursts. When both the transformed ECG and chest wall EMG signals were considered at least one allowed inspiratory burst visualization in 91% of the studies. This suggests that using both signals will increase the chance of obtaining useful information. Of interest, at least in the current analysis, the fraction of studies with visualization of inspiratory bursts was slightly higher using the transformed ECG signal than the chest wall EMG signal. Some studies of diaphragmatic activity surface EMG have used a more anterior position (anterior axillary line rather than midaxillary line) or higher intercostal space than is routinely uses in our sleep center.[4] Certainly, a more anterior position for chest wall EMG electrodes should be tried if inspiratory bursts are not seen using a midaxillary position.[13]

Another significant limitation of our study is that the method of ECG blanking used in this study was labor intensive. Techniques such as adaptive filtering[14] typically used to remove ECG artifact from EMG signals may not work well when the

Figure 7—An event from a patient visualized using two different polysomnography software programs.



The tracings have ambiguous respiratory effort RIP signals (chest and abdomen) and might be scored as central apneas. The TECG-FC shows inspiratory bursts and therefore the event is an obstructive apnea. The panel on the left is using Sleepware G3 (Philips Respironics) and the panel on the right in using RemLogic (Natus Neurology). In both, a high pass filter of 30 or 40 Hz was used with increased gain and channel clipping. RIP = respiratory inductance plethysmography, TECG-FC = transformed electrocardiography signal with filtering and channel clipping.

ECG signal itself must be transformed. However, investigators have used computational subtraction techniques[10,12,15] that might be easier to use than our method of QRS blanking. To use the built-in functions in LabChart for ECG blanking we had to import the PSG signals. The LabChart program is not designed to display sleep study data in traditional views; therefore, the signals were exported to another program that could easily select the channels to be viewed in 30- and 60-second pages. The G3 program was used for EDF import and subsequent display of the signals as EDF import is very difficult in Twin software. The major advantage of a signal with QRS blanking is that channel clipping is not necessary. The low amplitude EMG signal can be visualized at an appropriate gain without the associated much larger QRS component that intrudes into other channels (without clipping). The blanked transformed ECG signal can then be rectified and integrated to provide a useful amplitude signal reflecting the EMG burst magnitude. However, a transformed ECG signal can still be useful without the complexity of QRS blanking. A simple transformation of the ECG signal as shown in **Figure 1** and **Figure 4** may suffice to classify apneas when the RIP signals are equivocal. This simple option would require the availability of a suitable ECG channel filter in the computer program being used as well as some type of channel clipping or the ability to set the voltage range displayed in the channel. While Twin software was used for the first part of our investigation, many other standard PSG software programs can be used. In **Figure 7**, EMG bursts are visible in a transformed ECG signal in two other standard PSG programs that are widely available. It is worth noting that an ECG montage with one electrode on the lower left chest is essential for the method to work and the AASM Scoring Manual-recommended ECG electrode positions were used in this study.

In a previous study[7] the utility of a rectified and integrated chest wall EMG signal for hypopnea classification (central versus obstructive) was evaluated. The current study was confined to apnea classification given the increased complexity of hypopnea classification which requires an accurate measure of airflow. Diagnostic studies using nasal pressure and oronasal thermal flow do not reliably provide an accurate measure of airflow. Apnea classification was also addressed because most sleep centers using an EMG signal for respiratory effort do so mainly for apnea classification. Future investigations are needed to document the utility of a transformed ECG signal for hypopnea classification.

In summary, in this proof of concept study a simple transformation of the ECG signal was able to display inspiratory bursts from underlying EMG activity in a large proportion of patients. Analysis of a group of randomly selected apneas designed to contain an appreciable number of central and mixed apneas found that there was good agreement between apnea classification by RIP effort belts and the transformed ECG signal derived by filtering and QRS blanking. The best potential uses of a transformed ECG signal to detect respiratory effort would be in patients when a chest wall EMG signal was not recorded or does not show reliable inspiratory bursts of activity and the RIP belts do not show evidence of respiratory effort during apnea. Further study is needed to determine the clinical utility of a transformed ECG signal.

ABBREVIATIONS

AASM Scoring Manual, The AASM Manual for Scoring Sleep and Associated Events: Rules, Terminology and Technical Specifications
AHI, apnea-hypopnea index
ECG, electrocardiography
EMG, electromyography
PSG, polysomnography

RIP, respiratory inductance plethysmography
TECG-FB, transformed ECG signal with filtering and QRS blanking
TECG-FC, transformed ECG signal with filtering and channel clipping

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SUBMISSION & CORRESPONDENCE INFORMATION

Submitted for publication November 18, 2018
Submitted in final revised form March 2, 2019
Accepted for publication March 8, 2019

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DISCLOSURE STATEMENT

All authors have seen and approved the manuscript. The authors report no conflicts of interest.