Transcutaneous Carbon Dioxide Monitoring and Capnography During Pediatric Polysomnography

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INTRODUCTION

PEDIATRIC OBSTRUCTIVE SLEEP APNEA (OSA) IS ASSOCIATED WITH SEVERAL SIGNIFICANT COGNITIVE, BEHAVIORAL, AND MEDICAL SEQUELAE INCLUDING school failure, concentration difficulties, irritability, cor pulmonale, failure to thrive, hypersomnolence, and developmental delay.1-9 Recent work has revealed a spectrum of severity in pediatric sleep disorders, ranging from snoring due to partial obstruction of the upper airway with no associated hypoxemia, hypercarbia, or apparent sleep disruption, to continuous episodes of complete upper airway obstruction with one or more of these associated consequences.1-5 The shared clinical features across this continuum of severity make it increasingly difficult to reliably establish the diagnosis of OSA through clinical assessment alone. Thus, current recommended practice includes the use of overnight laboratory polysomnography (PSG) to investigate and confirm suspected OSA in children.6,7

A key variable in PSG for the successful evaluation of pediatric OSA is the continuous monitoring of arterial CO$_2$. Although the absolute measure is arterial blood sampling and blood gas analysis, this technique is impractical within a sleep study setting, due to associated morbidity, intermittent measurements, and cost.8 Therefore, two noninvasive surrogate measures have been widely adopted for use during pediatric and adult PSG: capnography or end-tidal CO$_2$ (PETCO$_2$) monitoring and transcutaneous CO$_2$ (PtcCO$_2$) monitoring. PETCO$_2$ monitoring has been validated as an accurate predictor of arterial CO$_2$ level in endotracheally intubated patients10 and has been reported to be a useful screening tool in OSA.11 The accuracy of PETCO$_2$ monitoring during adult sleep studies has been shown to be inconsistent under conditions in which supplemental oxygen or positive airway pressure are being used.12 PtcCO$_2$ monitoring has been shown to be a valid and interpretable measure of arterial CO$_2$ in children during sleep.13,14

Situations in which PtcCO$_2$ monitoring may not be interpretable include patients with perfusion problems, skin diseases, edema, or hypovolemia, all of which are uncommon in the pediatric sleep study population.13,15,16

To date, only one study has been reported on PETCO$_2$ and PtcCO$_2$ monitoring during pediatric PSG.15 In this study, a constant and close relationship was found between both measurement tools. However, the study involved the analysis of only 15 pediatric PSG evaluations. A thorough comparison of PETCO$_2$ and PtcCO$_2$ monitoring using a large patient population has yet to be performed. Thus, we elected to review our experience using PETCO$_2$ and PtcCO$_2$ monitoring techniques in 609 children with respect to the total amount of time interpretable signals could be obtained from both devices during overnight PSG and the agreement between the 2 outputs. We hypothesized that there would be close agreement in this population.

METHODS

Patient Selection

In this retrospective study, diagnostic PSG studies taken from a consecutive sample of children aged 0.1-18.4 years were reviewed. Nondiagnostic PSG evaluations and those done during
periods of PSG equipment malfunction were omitted from this study. All subjects were referred for evaluation of a possible sleep disorder to the Pediatric Sleep Service at the Alberta Children’s Hospital by community general practitioners, pediatricians, or otolaryngologists between June 28, 2000 and October 27, 2003. The legal guardian for each subject signed a consent form agreeing to the review and reporting of anonymous PSG data for quality control and research purposes. Ethics review of the project prior to data collection was not possible, however, no concerns regarding publication were identified when the internal scientific and ethics review board was notified.

Laboratory Polysomnography Studies

Computerized laboratory PSG (Sandman NT, Nellcor Puritan Bennett, Ottawa, ON) was performed according to American Thoracic Society guidelines. Monitoring included electroencephalogram (C4-A1, C3-A2, O1-A2, O2-A1) electrooculogram, submental electromyogram, electrocardiogram, oxygen saturation monitoring (Nellcor Puritan Bennett, N200 Ottawa, ON), chest, abdominal wall, and sum channel movements using respiratory inductance plethysmography (Respitrace Plus, Sensormedics Corporation, Yorba Linda, CA), bilateral tibial electromyograms, nasal/oral airflow using a thermistor device (EdenTec Model 3170 Sleep Lab Airflow Cable, EdenTec Corporation, Eden Prairie, MN), nasal pressure (Ultima Airflow Pressure Sensor Model 0580 Braebon Medical Corporation, Carp, ON), end-tidal carbon dioxide monitoring (Model 1265 Novametrix Medical Systems Inc, Wallingford, CT), and transcutaneous carbon dioxide monitoring (Radiometer Compact Combined pCO₂/pO₂ Monitoring system-TCM3 Radiometer Medical, Copenhagen).

Sleep architecture was determined using standard criteria. Registered PSG technicians manually scored the studies and eliminated all CO₂ data that was not interpretable based on predetermined criteria of acceptable values and PETCO₂ waveform clarity (patient intolerance, signal artifact, calibration signals and movement). Total “uninterpretable data” time was calculated for both channels. Respiratory events were defined as follows:

- Apnea was defined as an 80% or greater decrease in amplitude on the respiratory inductive plethysmographic sum channel. Mixed and obstructive events were counted as significant if greater than 2 breaths in duration, whereas central apneas were counted only if accompanied by a decrease in SaO₂ ≥ 4% from baseline or if ≥ 20 seconds in duration. Ancillary surrogate measures of airflow included nasal pressure and thermistor signals.

- Hypopnea was defined as at least a 50% decrease in amplitude associated with ≥ 4% drop in SaO₂ from baseline on the respiratory inductive plethysmographic sum channel and/or evidence of cortical arousal.

- Central, mixed/obstructive, and total apnea/hypopnea (AHI) indices were calculated as number of events per hour of sleep.

PETCO₂ monitoring was performed using nasal cannulae with a sampling rate of 4 Hz. Numeric values and waveform were displayed in real time on the PSG epoch and data was eliminated if a clear plateau was not identified on the waveform signal. PtCO₂ monitoring was also sampled at 4 Hz and displayed in numeric and waveform formats. As per our standard laboratory procedure, transcutaneous probes were placed on the subject’s trunk unless excess subcutaneous tissue was noted (obese children in which case the probe was placed on the forearm. In children under one year of age, the transcutaneous transducers were calibrated and re-sited every 2 hours or more as needed. In all other children, the transducer was moved only as needed to recalibrate. Typically, a single site was adequate for approximately 7 hours under normal conditions (absence of excess sweating and/or movement). Probe and cannulae replacements were performed as needed during periods of slow wave sleep in order to minimize subject disturbances.

Mean and maximum values were computer generated following the manual elimination of bad data by the sleep technicians on an epoch by epoch basis during scoring and were based on total recording time. Agreement between the 2 methods was considered good if within 4 mmHg.

Data Analysis

The average total recording time (TRT) and mean duration of ‘uninterpretable data’ per study were used to determine an average time of interpretable data obtained from both channels. The agreement between the two outputs was examined by comparing the mean CO₂ and maximum CO₂ values obtained by the two channels in each PSG evaluation. The data were analyzed using the Bland-Altman technique. This technique involves plotting the difference between measurements obtained using 2 measuring tools (one of which is considered a gold standard) against the average value between the 2 measurements. The mean difference between the values, and the standard deviation (SD) of the differences, are calculated to provide the levels of agreement. A positive difference indicates a value exceeding the gold standard comparison value, whereas a negative difference indicates reported values less than the comparison tool. Identification of how tightly and consistently the 2 techniques agree is obtained by calculating the mean and limits of agreement (+/- 2SD) and analyzing the distribution of data points in the Bland-Altman plot. To determine whether clinical severity affects the agreement between the 2 methods, statistical analysis was performed on groups of data separated on the basis of the number of respiratory events per hour of recording time (AHI).

RESULTS

Within the selected period of study, 609 children (363 males), mean age 7.9+/-.6 years (range 0.1-18.4) met study inclusion criteria. The PSG findings are summarized in Table 1. The group mean AHI and sleep efficiency were 9.6+/-.15.8/hour and 84.5%+/-.15.9% respectively. The mean total recording time (TRT) was 454.7+/-.61.2 minutes (range 62.4-556.5). Interpretable PETCO₂ and PtCO₂ data were available for 61.8%+/-.35.1% and 71.5%+/-.25.2% of TRT respectively. In 407 (67%) and 499 (82%) of the 609 studies, interpretable PETCO₂ and PtCO₂ data were available for 50% or more of TRT respectively. No PETCO₂ data were available in 39/609 (6.4%) of studies, although PtCO₂ data were available in all but one of these. Conversely, there were 2 studies (0.3%) in which only PETCO₂ data were available.

In 61.8% of the studies, PETCO₂ and PtCO₂ maximum values differed by only +/- 0.1 mmHg. Mean CO₂ values using the two techniques showed even closer agreement with a difference of only +/- 0.6 mmHg in 71.5% (Table 2). For maximum recorded levels, PtCO₂ exceeded PETCO₂ values by more than 4 mmHg.

SLEEP, Vol. 29, No. 12, 2006

Tc CO₂ vs ETCO₂, in Children—Kirk et al
in 103 (16.9%) and were lower than PETCO2 max values by more than 4 mmHg in 135 (22.1%) of studies. In comparison, mean values differed less with the PtcCO2 values exceeding PETCO2 values by more than 4 mmHg in 64 (10.5%) PSG studies and underestimated the PETCO2 values by more than 4 mmHg in 108 (17.7%) of studies. In general, more variability between the two measurement tools was seen in the subjects with a higher AHI (Table 3). In children under 5 years of age (n=201), reliable signal data were obtained less frequently using both measures (41.5% and 68.7% of total recording time, PETCO2 and PtcCO2 respectively) compared with those aged greater than 5 years (70%-73% of total recording time using either tool).

The data from subjects with an AHI < 5/hr (n=318) were looked at separately to see if the additional CO2 data added any clinically significant information. The mean CO2 values were greater than 50 mmHg in 37 (11.6%) and 38 (11.9%) using PETCO2 and PtcCO2 data respectively. Effects of adipose tissue on interpretable data time was examined by subgroup analysis of subjects noted by the sleep technicians to be obese (14.3% of the total group). At the time of data collection, our laboratory forms did not include height, weight or body mass index information. A physical examination/technician observation form was completed for each subject which included an assessment of overall size (thin, normal, mildly overweight, obese). No significant differences were identified. Reliable data was available for a mean of 61.8% (PETCO2) and 71.5% (PtcCO2) of total recording time in this group, as well.

Mean and maximum CO2 values in REM and NREM sleep were also examined for potential variances related to sleep stage. Agreement between the 2 methods was slightly better during NREM sleep (median difference 0.7 mmHg) compared with REM sleep (1.7 mmHg), however, the agreement remained very close in all sleep stages.

**Measures of Agreement**

Overall, the mean and max CO2 data from both methods showed good agreement with narrow limits of agreement (95th percentiles) shown on the Bland-Altman analyses (Figure 1). Subgroup analysis suggested that the means and limits of agreement between PtcCO2 and PETCO2 values were the closest for subjects with an AHI < 10 (Figure 2) compared to those with more severe OSA (Figure 3). Visual inspection of all the Bland-Altman plots (Figures 1-3) showed close clustering along the x-axis regardless of AHI, which is indicative of good agreement with no systematic bias between the two methods. Several outliers were noted, and review of the technician notes indicated the presence of either obesity with low/presumably inaccurate transcutaneous readings and/or tachypnea associated with low/inaccurate end-tidal readings.

**DISCUSSION**

This study has 2 key findings which demonstrate the usefulness of PtcCO2 and PETCO2 monitoring techniques for pediatric PSG.

The first major finding is that both methods provided interpretable signals for the majority of subjects. In circumstances where the subject had an AHI < 10, both techniques provided near equal maximal and mean CO2 values for approximately the same amount of time (Table 1). In subjects with moderate to severe respiratory abnormalities (AHI ≥ 10), the time that interpretable PETCO2 signals were available declined by approximately 15% while the PtcCO2 interpretable signal remained relatively stable. This is not surprising, given the dependency of the PETCO2 signal on consistent nasal airflow. Nevertheless, an interpretable signal was obtained from both techniques for more than half of the total recording time regardless of AHI.

**Table 1**—Polysomnographic findings in study population (n=609).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>AHI &lt;10 (n=443)</th>
<th>AHI ≥ 10 (n=166)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (SD)</td>
<td>Median (Range)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>TRT</td>
<td>457.7 ± 14.8</td>
<td>466.2</td>
</tr>
<tr>
<td>(minutes)</td>
<td>(50.9 - 156.5)</td>
<td>(82.3 - 124.5)</td>
</tr>
<tr>
<td>AHI</td>
<td>3.5 ± 1.0</td>
<td>3.1</td>
</tr>
<tr>
<td>(events per hour)</td>
<td>(12.7 - 0.0)</td>
<td>(23.2 - 10.0)</td>
</tr>
<tr>
<td>Sleep Efficiency</td>
<td>84.4 ± 8.1</td>
<td>83.1</td>
</tr>
<tr>
<td>(% of TRT)</td>
<td>(12.5 - 98.9)</td>
<td>(14.7 - 12.0)</td>
</tr>
<tr>
<td>Max PeCO2 (mmHg)</td>
<td>75.6 ± 14.8</td>
<td>54.9 ± 14.8</td>
</tr>
<tr>
<td>Max PtcCO2 (mmHg)</td>
<td>(42.2 - 75.6)</td>
<td>(50.0 - 35.3)</td>
</tr>
<tr>
<td>Mean PeCO2 (mmHg)</td>
<td>(5.9 - 88.9)</td>
<td>(6.9 - 35.3)</td>
</tr>
<tr>
<td>Mean PtcCO2 (mmHg)</td>
<td>(3.5 - 65.1)</td>
<td>(3.5 - 39.5)</td>
</tr>
<tr>
<td>Interpretable Signal</td>
<td>299.2 ± 152.5</td>
<td>350.8 ± 114.3</td>
</tr>
<tr>
<td>PETCO2 (TRT-BD/TRT) (min)</td>
<td>0.0 - 519.4</td>
<td>(167.5 - 0.0)</td>
</tr>
<tr>
<td>Interpretable Signal</td>
<td>328.6 ± 114.3</td>
<td>361.3 ± 114.8</td>
</tr>
<tr>
<td>PtcCO2 (TRT-BD/TRT) (%)</td>
<td>0.0 - 507.9</td>
<td>348.6 ± 197.9</td>
</tr>
<tr>
<td>Difference in CO2 max (mmHg)</td>
<td>-0.4 ± 0.2</td>
<td>0.1 ± 0.3</td>
</tr>
<tr>
<td>(PtcCO2 max - PETCO2 max)</td>
<td>-23.1 ± 22.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Difference in CO2 mean (mmHg)</td>
<td>-0.6 ± 0.7</td>
<td>-0.5 ± 0.9</td>
</tr>
<tr>
<td>(PtcCO2 mean - PETCO2 mean)</td>
<td>-10.4 ± 12.6</td>
<td>4.2</td>
</tr>
</tbody>
</table>

TRT-BD/TRT: total sleep time - bad data/total sleep time
The second major finding of this study was that PtcCO$_2$ and PETCO$_2$ monitoring techniques were in very near agreement for the majority of cases (Table 1). More severe OSA was associated with an increased discrepancy between the 2 measuring tools, but the agreement remained close.

As the true gold standard test for measuring arterial CO$_2$ was not performed in this study (blood gas analysis), we analyzed the level of agreement between surrogate CO$_2$ monitoring methods, presuming the transcutaneous technique to be the more accurate method. Previous studies have confirmed the accuracy of both PtcCO$_2$ and PETCO$_2$ in a variety of patient populations by directly comparing these values with simultaneously obtained arterial CO$_2$ values. The Bland-Altman analysis confirms that the mean and max CO$_2$ values obtained by PtcCO$_2$ and PETCO$_2$...
techniques are comparable across the spectrum of clinical severity. Whether or not the limits of agreement are acceptable for the purposes of diagnostic pediatric sleep studies cannot be statistically determined but is rather a question of clinical judgment.

Interpretation of PSG studies involves attention to numerous variables in order to assess the severity of abnormality and attempt to predict related potential patient morbidity. Oxygenation status as well as the frequency, type, and severity of apneas are reviewed. The interpretation of the reported CO$_2$ levels is made in the context of these other important signals. Importantly, approximately 12% of our subjects with a low AHI, had abnormally high CO$_2$ levels during sleep, confirming the clinical importance of including CO$_2$ monitoring in pediatric polysomnography. By measuring the CO$_2$ via 2 different surrogate methods, recorded values can be compared, increasing the presumed level of accuracy when they are in close agreement. Thus, in the clinical setting, it is acceptable to use both PtcCO$_2$ and PETCO$_2$ monitoring techniques as a method to estimate arterial CO$_2$.

Children undergoing PSG study may remove sensors and electrodes during the night, reducing the amount of available data for

Figure 2—Bland-Altman Analysis of Subjects with AHI less than 10 events per hour (n=442). Bland-Altman comparison of transcutaneous (PtcCO$_2$) and end-tidal (PETCO$_2$) carbon dioxide measurements for PSG studies from subjects with an AHI less than 10 (n=442). A. Comparison of maximum CO$_2$ measurements. B. Comparison of mean CO$_2$ measurements.
the interpreting physician. This can be particularly problematic in younger children, as our data showed. The approximate cost of transcutaneous monitoring in our laboratory is $12 US/subject. The additional cost associated with the inclusion of PETCO$_2$ monitoring (approximately $20 US/subject for cannulae) may be problematic for diagnostic sites with limited budgets. In this situation, perhaps dual recordings would best be limited to the younger patients, as they are at highest risk of having increased uninterpretable data time. Additionally, when using both methods for routine study, and close agreement between the two techniques is confirmed earlier in the night, the clinician may feel more confident about the reliability of the remaining signal if the other sensor is displaced.

Obstructive respiratory events were observed to play some role in determining the level of agreement between PtcCO$_2$ and PETCO$_2$. The AHI is a measure of the frequency of respiratory events and is generally considered to be statistically significant in children when greater than or equal to one. An AHI of 10 or more clearly identifies children with sleep abnormalities greater than 2 standard deviations from the normal population.}

Figure 3—Bland-Altman Analysis of subjects with AHI greater than 10 events per hour (n=167). Bland-Altman comparison of transcutaneous (PtcCO$_2$) and end-tidal (PETCO$_2$) carbon dioxide measurements for PSG studies from subjects with an AHI greater than or equal to 10 (n=167). A. Comparison of maximum CO$_2$ measurements. B. Comparison of mean CO$_2$ measurements.
tion, a larger difference between PtcCO₂ and PETCO₂ values was seen in those with more severe OSA. The increased difference may be due in part to the limitations of PETCO₂ monitoring techniques under conditions of airway obstruction.

The decrease in PETCO₂ interpretable signal in pediatric patients with higher AHI’s may have also been due to the increased restlessness of these children, compared to children with less severe OSA. It has been shown that children with OSA have significantly more movement arousals than age matched controls and indeed, a mean of 20.4 movement arousals per hour has been reported for pediatric OSA patients.¹⁸ Since the nasal sampling cannulae used in PETCO₂ monitoring are more easily displaced with movement than the transcutaneous probe, increased movements in response to airway obstruction increase the potential for movement artifact and the subsequent identification of “bad signal” with resultant elimination of PETCO₂ data. Additionally, children with more severe OSA may have increased nasal obstruction and resultant decreased nasal airflow which would negatively impact the PETCO₂ signal. Further reduction in nasal airflow secondary to insertion of the nasal cannulae may further increase the likelihood of patient intolerance and poor data.

In the context of pediatric PSG, PETCO₂ monitoring has important advantages and limitations. The accurate correlation with arterial CO₂ with normal ventilation, the qualitative reflection of airflow signal, and the lack of requirement for warm-up or site changes all favor the use of PETCO₂ in pediatric PSG.¹¹ However, inaccuracies of PETCO₂ monitoring tend to occur in patients with respiratory disease. Since PETCO₂ accuracy depends on sampling undiluted alveolar gas during expiration, tachypnea or increased physiologic dead space may cause underestimation of the arterial CO₂.²⁷ Also, in patients with severe airway obstruction, mouth breathing and limitation of expiratory flow may limit the accuracy of obtained PETCO₂ values.¹¹ The difficulty of measuring PETCO₂ in patients who cannot tolerate placement of the nasal cannulae is another important, albeit infrequent, limiting factor of this technique.

PETCO₂ monitoring has the advantage of being more readily obtained than PETCO₂ values because the transcutaneous electrode is not as easily displaced with movement and the electrode induces less sleep disturbance due to its site of application (i.e., the chest or forearm). Also, the accuracy of PtcCO₂ monitoring is not subject to the same limitations as PETCO₂ due to the fact that PtcCO₂ measures the CO₂ in arterialized blood, thus the accuracy is not affected by ventilation-perfusion mismatching.²⁴ Effective PtcCO₂ monitoring is dependent on both technical and patient factors. Excess adipose tissue, movement and/or perspiration are all limiting patient-related factors. We did not see any important increases in poor data time in our obese subgroup overall, confirming that in most cases, an appropriate transducer site can be identified such as the back of a hand or the parasternal anterior chest wall. Pertinent technical issues associated with PtcCO₂ monitoring include avoiding improper placement of the transcutaneous probe, appropriate calibration, membrane integrity, and avoidance of thermal injury.²⁴ Other considerations when measuring PtcCO₂ are the lengthened response time for the transcutaneous electrode compared to changes recorded by PETCO₂, the possibility of electrical drift of the signal, the requirements of regular maintenance and changing of the electrode membrane, and the absence of an additional measure of signal integrity.²⁰

In summary, during diagnostic pediatric PSG, both PtcCO₂ and PETCO₂ monitoring provide easily obtained, interpretable data that are within agreement of each other. The utility of using both techniques in pediatric PSG is evident when considering how the advantages associated with either method complement each other. Because neither method can be expected to be 100% interpretable for every patient encounter, the use of two noninvasive CO₂ monitoring techniques increases the likelihood of obtaining useful data in every pediatric PSG study, particularly in children under 5 years of age.

**REFERENCES**

7. Loughlin GM, Brouillette RT, Brooke LJ. American Thoracic Society standards and indications for cardiopulmonary sleep studies in

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**Table 3—Comparison of end-tidal and transcutaneous carbon dioxide measurements amongst all subjects and subgroups based on severity of sleep apnea.**

<table>
<thead>
<tr>
<th></th>
<th>All studies (n=609)</th>
<th>AHI&lt;10 (n=442)</th>
<th>AHI ≥10 (n=167)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean difference</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max CO₂ (mmHg)</td>
<td>-0.1</td>
<td>-0.7 to 0.4</td>
<td>10.2 to 12.0</td>
</tr>
<tr>
<td>Mean CO₂ (mmHg)</td>
<td>-0.6</td>
<td>-0.8 to 0.1</td>
<td>6.4 to 7.6</td>
</tr>
<tr>
<td><strong>95% CI</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max CO₂ (mmHg)</td>
<td>-0.5 to 0.4</td>
<td>-11.3 to -7.9</td>
<td>-12.3 to -10.4</td>
</tr>
<tr>
<td>Mean CO₂ (mmHg)</td>
<td>-0.9 to -0.3</td>
<td>-8.5 to -7.3</td>
<td>-8.5 to -7.4</td>
</tr>
<tr>
<td><strong>Student t-score</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Max CO₂ (mmHg)</td>
<td>-0.24</td>
<td>-0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Mean CO₂ (mmHg)</td>
<td>-3.85</td>
<td>-2.51</td>
<td>-0.40</td>
</tr>
<tr>
<td><strong>p value</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max CO₂ (mmHg)</td>
<td>P&lt;0.05</td>
<td>P&lt;0.05</td>
<td>P&lt;0.05</td>
</tr>
<tr>
<td>Mean CO₂ (mmHg)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The means, limits of agreement, confidence intervals, student t-scores and p-values of the differences between end-tidal and transcutaneous measurement of Max CO₂ and Mean CO₂. P<0.05 rejects the null hypothesis.