Clinical Study
A Newly Developed Sublingual Tonometric Method for the Evaluation of Tissue Perfusion and Its Validation
In Vitro and in Healthy Persons In Vivo and the Results of the Measurements in COPD Patients

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Introduction. Since its first publication in 1959 [1], an extremely large number of references have demonstrated that the tonometric measurement of tissue perfusion is a reliable indicator of the actual condition of critically ill patients [2–4] and can even be used to predict their morbidity and mortality. The principle of the method is that the tissue PCO$_2$ (P$_t$CO$_2$) of the circulating blood measured inside the mucosa of the actual organ rises sharply with the failure of tissue perfusion. In general this was performed using a ballooned gastric catheter [5–8].

A new method was developed by the introduction of sublingual tonometry for the determination of tissue perfusion [9–11]. In comparison with gastric tonometry, the new method was simpler and could even be used in fully conscious patients [12–18]. Previous studies demonstrated high correlation between sublingual tissue PCO$_2$ (P$_s$CO$_2$) and gastric tissue PCO$_2$ (P$_g$CO$_2$) in various conditions, confirming sublingual tonometry as a rapid, minimally invasive method.

Unfortunately, in spite of these advantages, at present, owing to severe failures of manufacturing, the device is withdrawn from commerce. Materials and Methods. In this study, we present a new method using a newly developed tool for the P$_s$CO$_2$ measurement in sublingual tonometry as well as the data for its validation in vitro and in vivo and the results of 25 volunteers and 54 COPD patients belonging to different GOLD groups at their hospitalization due to the acute exacerbation of the disease but already in a stable condition at the time of the examination. Results and Conclusion. The results of the performed examinations showed that the method is suitable for monitoring the actual condition of the patients by mucosal perfusion tonometry in the sublingual region.

1. Introduction

Since its first publication in 1959 [1], an extremely large number of references have demonstrated that the tonometric measurement of tissue perfusion is a reliable indicator of the actual condition of critically ill patients [2–4] and can even be used to predict their morbidity and mortality. The principle of the method is that the tissue PCO$_2$ (P$_t$CO$_2$) of the circulating blood measured inside the mucosa of the actual organ rises sharply with the failure of tissue perfusion. In general this was performed using a ballooned gastric catheter [5–8].

A new method was developed by the introduction of sublingual tonometry for the determination of tissue perfusion [9–11]. In comparison with gastric tonometry, the new method was simpler and could even be used in fully conscious patients [12–18]. Previous studies demonstrated high correlation between sublingual tissue PCO$_2$ (P$_s$CO$_2$) and gastric tissue PCO$_2$ (P$_g$CO$_2$) in various conditions, confirming sublingual tonometry as a rapid, minimally invasive method.

Unfortunately, in spite of these advantages, at present, owing to severe failures of manufacturing, the device serving for the sublingual tonometry has been withdrawn from the commerce.

In this study, we present a new method using a newly developed device for the measurement of the P$_s$CO$_2$ in sublingual tonometry as well as the data for its validation and the first results in COPD patients in a stable condition following recovery after the exacerbation of the disease.

2. Materials and Methods

The study was registered on http://www.clinicaltrials.gov/ (ID: NCT01169506). The examinations were approved by
Figure 1: Scheme of the sublingual tonometer.

The New Sublingual Probe. The basic tool for $P_aCO_2$ measurement is a probe: a specially coiled silicone rubber tube produced by Medisintech Ltd., Budapest, Hungary. The gas content (room air) inside the tube of the sublingually inserted probe gets in equilibrium by diffusion with the gases of the blood circulating in the capillaries of the sublingual mucosa. Then it is transferred into a capnograph (Oridion Microcap, Oridion Capnography Inc., Needham, MA, USA) to measure its $CO_2$ content. During the production process the silicon rubber is moulded into a butterfly shape. In order to prevent the obstruction of the lumen by kinking, a 0.3 mm thick polyamide fibre is inserted along the tube; thereby after folding the tube, sufficient lumen volume remains to allow the filling test material to be transported into the measuring unit (Figure 1).

2.2. Methods

2.2.1. Technique of the Measurement of the $P_aCO_2$. The probe is kept under the patient's tongue between the tongue and the sublingual mucosa in such a way that it reaches the end of the frenulum linguae. During the measurement the patient is not allowed to breathe through the mouth until the full equilibration of the sublingual probe (15 minutes).

Then the probe is connected to a capnometer via a Luer lock connection, and its gas content is transferred into it.

2.2.2. In Vitro Validation Method. To measure the in vitro $CO_2$ uptake into the probe, a glass container was used for equilibration. The probe was inserted into this container up to the Luer connector part of the device and the container was closed in an airtight manner. Then it was perfused with air containing $CO_2$ at 35 mmHg, provided from gas cylinders at a flow rate of 5 L/min. The in vitro uptake of $CO_2$ of the probe was tested at room temperature and at 37°C as well, when the equilibration chamber was submerged in thermostated water of constant temperature. Room air was used as filling media. At each control time of the $CO_2$ uptake of the probe, four parallel measurements were made. The $PCO_2$ value of the container was checked every 10 minutes. These values were used as references for the in vitro measurement data. After the defined time intervals, the filling medium was aspirated and displayed by the capnograph. All in vitro measurement data obtained after the given equilibration times were expressed as percentages of the reference value.

2.2.3. Simultaneous Determination of $P_aCO_2$ ($P_cCO_2$). Realizing the difficulties in sampling of arterial blood we used arterialized capillary blood samples for the measurement in the study [19]. For this purpose blood was taken from the earlobe of each individual following local application of Finalgon (Boehringer Ingelheim GmbH, Ingelheim am Rhein, Germany) for 15 minutes. The blood samples were analysed by Radiometer ABL5, Radiometer Medical ApS, Brønshøj, Denmark.

2.2.4. In Vivo Validation Method. The in vivo $CO_2$ uptake by the probe was measured performing 25 sublingual tonometries in five healthy volunteers. Each volunteer underwent five measurements which lasted 1, 2, 6, 10, and 15 minutes, respectively. Each measurement was followed by a two-minute pause. In these experiments the highest measured value obtained at 15 minutes’ equilibration time served as reference value and to express the formerly measured data in percentages.

2.2.5. Controlling Rapid Changes during Hyperventilation of the Sublingual Tonometric Values. $P_aCO_2$, $P_cCO_2$ values were determined in healthy volunteers while ventilating normally for 5 minutes and during 5 minutes of hyperventilation.

2.2.6. Parallel Sublingual Tonometric Measurements. In order to test the consistency of the method, in 42 out of the 54 patients, parallel $P_aCO_2$ measurements were also carried out. That is, 15 minutes after the end of the first sublingual measurement (regeneration time) the patients placed the probe under their tongue for another 15 minutes’ time and the values were determined by the capnometer.

2.2.7. Study Population. 25 healthy volunteers were involved in the study. The COPD study population was composed of 54 patients hospitalized with symptoms of acute exacerbation.
Table 1: Clinical data of the study population.

<table>
<thead>
<tr>
<th>COPD GOLD groups</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>15</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>Sex (male/female) number</td>
<td>9/6</td>
<td>13/9</td>
<td>14/3</td>
</tr>
<tr>
<td>Age, years</td>
<td>60.7 ± 8.2</td>
<td>63 ± 16.2</td>
<td>57 ± 8.1</td>
</tr>
<tr>
<td>Body weight</td>
<td>77.6 ± 24.0</td>
<td>65.8 ± 16.2</td>
<td>77.2 ± 16.5</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>26.4 ± 7.2</td>
<td>23.4 ± 4.0</td>
<td>27.1 ± 5.8</td>
</tr>
<tr>
<td>O₂ therapy (+/-)</td>
<td>3/12</td>
<td>5/17</td>
<td>15/2</td>
</tr>
<tr>
<td>Smoking, pack-year</td>
<td>41.8 ± 24.1</td>
<td>36.7 ± 26.3</td>
<td>38.3 ± 23.5</td>
</tr>
</tbody>
</table>

Values given as mean ± SD.

They were involved in the study only after 7–14 days, following stabilisation of their condition with corticosteroid and/or antibiotic treatment. None of them needed either intubation or supplementary oxygen.

COPD diagnosis was based on medical history and spirometry (postbronchodilator FEV₁/FVC < 0.7) on the grounds of GOLD criteria [20]. The following parameters were registered in all patients: age, sex, postbronchodilator FEV₁, GOLD stages, smoking history, sublingual PCO₂ (PslCO₂), value of arterialized capillary blood gas analysis (PcO₂, P_cCO₂, pH), and body mass index [21].

2.2.8. Statistical Analysis. All numerical values are expressed as the mean ± SD. One-way analysis of variance (ANOVA) and post hoc analysis (LSD test with Sidak adjustment for multiple comparisons) were used for the comparison of the four groups, that is, the control group, COPD II, COPD III, and COPD IV. Paired t-test was used to evaluate differences in control PslCO₂ versus PcCO₂. The relationship between parallel measurements was examined by Pearson’s correlation. Normal ventilation to 5 min and hyperventilation to 5 min were also compared by paired t-test. A value of P < 0.05 was considered to be statistically significant. SPSS 15.0 was used for statistical calculations.

3. Results

3.1. Clinical Data of the Study Population at Hospitalization. Table 1 shows the clinical data of the COPD patients at the time of their admission.

3.2. Experimental In Vitro and In Vivo Measurements. The data of experimental in vitro CO₂ uptake by the probe at 37°C after given equilibration times are expressed as percentages of the reference data and are presented in Figure 2. Nearly the same results were obtained by performing the measurement at room temperature (data not shown). These data show that the time required for the in vitro CO₂ uptake from the closed equilibration chamber into the probe is very short. Equilibrium is virtually complete within 4 minutes in room air, as filling medium. However, the time required for equilibrium to be attained in in vivo measurements was significantly longer. Full equilibrium with room air within the probe was achieved in 15 minutes.

3.3. P₆CO₂, P_cCO₂ Measurements in Healthy Control and COPD Patients. The mean values of P₆CO₂ and P_cCO₂ did not differ significantly either in healthy individuals (39.7 ± 2.8 versus 37.7 ± 1.3 mmHg) or in patients with COPD (44.4 ± 9.3 versus 42.7 ± 7.7 mmHg), respectively. The difference between P₆CO₂ and P_cCO₂ did not change significantly in different severity stages (GOLD stages I–IV) of COPD. Moreover, the mean values increased as the stage of COPD was more severe (test for linearity, P < 0.0001). Normal pH indicated that the patients were in a stable phase of the disease (Table 2).

3.4. Effect of Hyperventilation in Healthy Volunteers. Similarly to previous studies [17], hyperventilation resulted in significant decrease in values also using our method. The mean difference between P₆CO₂ measured after 5 minutes’ equilibration at normal ventilation and after 5 minutes of voluntary hyperventilation was statistically significant (mean difference 6.4 ± 6.8 mmHg, 95% CI 4.49–8.31, P < 0.0001) (Table 3).

3.5. Results of the Parallel Sublingual Tonometric Measurements. The mean difference between the two tonometric parallel measurements of the PslCO₂ was 0.81 ± 2.61 mmHg, with a correlation of r = 0.958, P < 0.0001.
Table 2: Sublingual PCO$_2$, arterialized capillary blood PCO$_2$, and pH values in healthy controls and COPD patients.

<table>
<thead>
<tr>
<th></th>
<th>$P_{sl}$CO$_2$ mmHg$^*$</th>
<th>$P_{c}$CO$_2$ mmHg$^*$</th>
<th>$P_{sl}$CO$<em>2$ - $P</em>{c}$CO$_2$ mmHg$^*$</th>
<th>pH$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy controls</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Number</td>
<td>10</td>
<td>10</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>39.7 ± 2.8</td>
<td>37.7 ± 1.3$^c$</td>
<td>2.0 ± 3.1</td>
<td>7.43 ± 0.02</td>
</tr>
<tr>
<td>COPD stage II</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Number</td>
<td>15</td>
<td>15</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>37.4 ± 5.2</td>
<td>36.6 ± 3.0</td>
<td>0.8 ± 4.5</td>
<td>7.43 ± 0.02</td>
</tr>
<tr>
<td>COPD stage III</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Number</td>
<td>22</td>
<td>22</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>43.5 ± 8.1</td>
<td>41.2 ± 4.6</td>
<td>2.3 ± 6.7</td>
<td>7.43 ± 0.02</td>
</tr>
<tr>
<td>COPD stage IV</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Number</td>
<td>17</td>
<td>17</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>51.6 ± 8.8$^a$</td>
<td>49.9 ± 8.2$^a$</td>
<td>1.6 ± 4.2</td>
<td>7.41 ± 0.03</td>
</tr>
<tr>
<td>COPD in all cases</td>
<td>54</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>Number</td>
<td>54</td>
<td>54</td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>44.4 ± 9.3</td>
<td>42.7 ± 7.7</td>
<td>1.7 ± 5.4</td>
<td>7.42 ± 0.02</td>
</tr>
</tbody>
</table>

$P_{sl}$CO$_2$, carbon dioxide sublingual partial pressure; $P_{c}$CO$_2$, carbon dioxide arterialized capillary partial pressure; $P_{sl}$CO$_2$ - $P_{c}$CO$_2$, carbon dioxide sublingual arterialized capillary partial pressure; pH, arterialized capillary pH; $^a$ANOVA result for comparison of the four groups; $^c$ANOVA result for comparison of the four groups; $^b$ANOVA result for comparison of the four groups; $^d$ANOVA result for comparison of the four groups; $^e$ANOVA result for comparison of the four groups.

Table 3: Testing under hyperventilation in healthy volunteers.

<table>
<thead>
<tr>
<th></th>
<th>$P_{sl}$CO$_2$ mmHg</th>
<th>$P_{c}$CO$_2$ mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control, normal ventilation to 5 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>27.2 ± 3.1</td>
<td>37.7 ± 1.3</td>
</tr>
<tr>
<td>Control, hyperventilation to 5 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>20.8 ± 3.4</td>
<td>20.4 ± 2.8</td>
</tr>
</tbody>
</table>

$P_{sl}$CO$_2$, carbon dioxide sublingual partial pressure; $P_{c}$CO$_2$, carbon dioxide arterialized capillary partial pressure.

Table 4: Differences of blood gas parameters measured in the simultaneously sampled arterial blood and of the arterialized capillary blood in COPD patient with various conditions.

<table>
<thead>
<tr>
<th>Differences in</th>
<th>pH</th>
<th>PCO$_2$ mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.0013 ± 0.011</td>
<td>0.333 ± 1.345</td>
</tr>
<tr>
<td>Max–min</td>
<td>0.02–0</td>
<td>3–0</td>
</tr>
</tbody>
</table>

3.6. Results of the Parallel Measurements of the Arterial and ArterIALIZED Capillary Blood Gases. Data collected in Table 4 show that the difference between the two studies performed by different methods is not significant in terms of pH and PCO$_2$.

4. Discussion

The main object of the present study was to work out a method for the determination of sublingual mucosa PCO$_2$ ($P_{sl}$CO$_2$). According to the results described above we can declare that our technique is suitable for sublingual tissue perfusion measurement. Our data show that the generally accepted characteristic parameter of tissue perfusion, that is, the difference between sublingual mucosa PCO$_2$ and blood PCO$_2$ known as gap value measured using the new device, basically corresponds to the earlier results of conventional studies. $P_{sl}$CO$_2$ values were higher only in patients who were diagnosed with stage IV COPD at the admission to the department. However, at the time of the examination, a few weeks later, following recovery, they were also in a stable condition and the higher $P_{sl}$CO$_2$ value as compared to the other groups and the compensated respiratory data were the only indicators of the original stage IV COPD but the gaps of the measured values in this patient population group were not significantly more elevated than those measured in patients with II and III GOLD stages.

The observation that $P_{sl}$CO$_2$ values were considerably lower during spontaneous hyperventilation shows that the method is suitable for the follow-up of relatively short term changes in the $P_{sl}$CO$_2$ values. Concordance of the corresponding data of parallel measurements also supports the reliability of our method.

On the other hand, the fact that the test takes 15 minutes can be inconvenient for the patients and it can contraindicate the examination during acute exacerbation of the disease, which limits considerably the field of application of the present method.
The use of arterialized capillary blood samples instead of arterial blood can also be considered as a drawback of our method. The reliability of substitution of arterial blood samples with arterialized capillary blood is supported by a large body of scientific evidence in the literature [19] although in some studies negative opinions can also be met. There is no doubt that in this type of examination the use of arterial blood must be kept as the gold standard. We had to put this rule aside because of the need for a highly cautious method required for the determination of $P_aCO_2$. In order to counterbalance the disadvantages we applied the method of the highest standard for the examination of the arterialized capillary blood. Moreover, we compared the values of the different groups of our patients. The data in Table 4 show that the difference in terms of $pH$ and $PCO_2$ is not significant.

5. Conclusion

Based on the results of the study, we conclude that our method is a reliable new mean of sublingual tissue $PCO_2$ determination. The method cannot be recommended for everyday clinical practice as, for example, in shock or other acute life-threatening conditions, because of the time-consuming nature of the examination. Nevertheless, the technique can be a useful tool in the differential diagnosis of some diseases, such as panic disorder and pseudoasthma, or in the determination of $CO_2$ accumulation in patients on continuous oxygen therapy. We also think that our results may provide basis for further development and investigations in this field.

To give judgement on the validity of the modified technique further extended examinations are required.

Abbreviations

ANOVA: Analysis of variance
CI: Confidence interval
$CO_2$: Carbon dioxide
COPD: Chronic obstructive lung disease
FEV1: Forced expiratory volume/sec
FVC: Forced vital capacity
GOLD: Global Initiative for Chronic Obstructive Lung Disease
ID: Internal diameter
LSD: Least significant difference
OD: Outside diameter
$PCO_2$: Carbon dioxide partial pressure
$P_ACO_2$: Carbon dioxide arterial partial pressure
$P_CCO_2$: Carbon dioxide arterialized capillary partial pressure
$P_gCO_2$: Carbon dioxide partial pressure of gastric mucosa
$P_sCO_2$: Carbon dioxide partial pressure of sublingual mucosa
$P_tC02$: Carbon dioxide partial pressure of tissue mucosa
$P_O2$: Blood oxygen partial pressure
SPSS: Statistical Software for Social Sciences.

Conflict of Interests

The authors declare that they have no conflict of interests.

Authors’ Contribution

Zoltán Rózsavölgyi contributed to the study design and to the selection of patients, collected data during the investigation, and critically reviewed the paper. Domokos Boda developed the new examination tool, conceived, designed, and coordinated the study, performed the validation process in laboratory circumstances, analysed the data of the in vitro measurements, critically reviewed the study process, and took part in writing the paper. Andrea Hajnal took part in designing the study, made the patient selection, and collected data. Kristzina Boda made the statistical analysis and performed the statistical processing of the data and interpretation of the paper. Attila Somfay was the codeveloper of the study and critically reviewed and finally approved the paper. All authors read and approved the final paper.

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References


