A Method to Calibrate the Carbon Dioxide (Chemical) Stimuli of Pneumatic Esthesiometer Externally

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Purpose: To determine the feasibility of using a portable carbon dioxide (CO₂) sensor to calibrate a pneumatic esthesiometer and then to calibrate the chemical stimuli.

Methods: The chemical stimuli in ocular surface experiments are combinations of medical air and added CO₂ (%CO₂). These stimuli were calibrated using a portable CO₂ sensor (COZIR CM-0041) and data logger, delivered for 100 seconds by using the Waterloo Belmonte esthesiometer. The distances between the sensor and esthesiometer tip were 0 (to measure feasibility), 3, 5, and 10 mm. In experiment I, 100% CO₂ was tested using four different flow rates (50, 100, 150, and 200 mL/min) at three working distances. In experiment II, flow rates of 20 to 100 mL/min and concentrations of 20% to 100% CO₂ were tested in 20 steps at 3 working distances.

Results: The CO₂ sensor correctly reported the esthesiometer extremes of 0% and 100% CO₂ when placed at the esthesiometer tip. There were progressive, systematic increases in concentrations reaching/reported by the sensor with increasing flow rates and nominal concentrations and progressive decreases in measurements with increases in working distance.

Conclusions: CO₂ concentrations in pneumatic esthesiometers can be calibrated and, as expected, vary with flow rate and distance, highlighting the importance of calibration and standardization of CO₂ stimuli in these instruments.

Translational Relevance: Calibrated CO₂, a chemical sensory stimulus in humans, may be used in testing the surface of the eye as well as other membranes within which the CO₂ can be dissolved (e.g., mucous) to produce an acidic stimulus.

Introduction

Esthesiometers have been used in estimating the sensitivity of various sensory systems, such as skin, particularly for measuring the touch sensitivity/pain sensitivity, each of which depends on the amount of pressure applied on the surface of interest.¹ Like other sensory systems, the sensitivity of the ocular surface has also been measured using esthesiometers.²⁻¹¹ Von Frey¹² developed the horsehair-based esthesiometer to measure the mechanical sensitivity of the ocular surface.¹³ The esthesiometer’s filaments are of a certain length and diameter to exert a precalibrated amount of pressure on the ocular surface.¹² The fundamental principle of stimulating mechanical sensitivity with a filament proposed by Von Frey was widely accepted, and many versions of the esthesiometers were developed to quantify corneal sensitivity; in ophthalmic research, perhaps the most significant of them is the Cochet-Bonnet (CB) esthesiometer that is used clinically as well as in research settings.²⁻⁴,⁶,¹⁴,¹⁵ However, the filament stimuli are unidimensional, as they measure the mechanical sensitivity of a localized area with a narrow dynamic range of stimulus intensity. Other limitations that have been documented include perceptible filament producing an anxious response when brought closer to the eyes and a variable/inconsistent pressure being applied to the ocular surface due to the bending of the filament.³,¹⁷,¹⁸ Even though a number of devices were developed with the limitations of the CB esthesiometer addressed,³,⁷,¹⁴,¹⁵,¹⁹ clinically, the CB esthesiometer is still the most frequently used esthesiometer. Other esthesiometers have been developed to measure
corneal sensitivity, including Lele and Weddell’s\textsuperscript{3} infrared heated air stimulus, Schirmer’s\textsuperscript{14} esthesiometer with a broader contact surface, Larson’s\textsuperscript{15} electromechanical esthesiometer, and Tanelian and Beuerman’s\textsuperscript{7} heated saline jet, and there has been a report of a CO\textsubscript{2} laser ocular surface esthesiometer.\textsuperscript{19}

Based on the reports of the cutaneous polymodal nociceptor’s responsiveness to chemical stimuli, such as acetic acid and capsaicin, Belmonte’s group\textsuperscript{8,20–24} recorded the single unit electrical activity of cat and rabbit corneas by using the same chemical stimuli and developed a pneumatic esthesiometer for human participants. CO\textsubscript{2} has been identified as an ideal stimulus for the human ocular surface chemical sensitivity experiments because of the sustained reduction in the pH of the ocular surface, unlike a buffered response obtained by an acetic acid stimulus.\textsuperscript{9} In a number of studies, corneal chemoreception using CO\textsubscript{2} was measured and illustrated, perhaps, the importance of measuring chemical sensitivity.\textsuperscript{9,24–29}

What emerged over a series of corneal physiological and psychophysical experiments was the demonstration of the utility of a pneumatic esthesiometer capable of measuring responses to mechanical, chemical, and thermal stimulation, and linking hypotheses were developed and empirically supported that in humans there are channels with similar attributes to the neural behavior reported in rabbit and cat corneas.\textsuperscript{9,24,25,30,31} Also, the experiments demonstrated that in animals (mainly cat and rabbit, initially), polymodal nociceptors were found to form a majority (about 70\% of corneal receptors, with mechanonociceptors (20\%) and cold receptors (10\%) forming the remaining corneal receptor population.\textsuperscript{32} It was hypothesized that these polymodal subgroups form the main peripheral sensory input from the cornea for the detection of nociceptive chemical, thermal, and mechanical stimuli.\textsuperscript{1,32,33}

There are different versions of pneumatic esthesiometers described in the literature,\textsuperscript{10,24,25,27,34–37} all of which were custom built or modified versions of Belmonte’s design that delivers air/CO\textsubscript{2} to the ocular surface. There are few reports on the calibration of the flow rate and temperature of the pneumatic stimulus.\textsuperscript{25,38–40} However, and perhaps because of technical issues, there are no reports on the calibration of CO\textsubscript{2} stimulus of the pneumatic esthesiometer.\textsuperscript{41,42} The CO\textsubscript{2} is controlled and calibrated internally either in the control box where the gas mixing occurs or at the nozzle with a closed-loop tube sampling CO\textsubscript{2} sensors.\textsuperscript{24,25} Even though the CO\textsubscript{2} is internally calibrated, the %CO\textsubscript{2} in the stimulus is unknown/not calibrated when it reaches the ocular surface (the place at which the pneumatic stimulus actually operates). The gases are not restricted to a closed column and so the stimulus has to interact with the air in the environment between the nozzle and the ocular surface. The physical chemistry at the level of ocular surface will be different from the tip of the esthesiometer, but it is unclear how much of the CO\textsubscript{2} is retained by the possible laminar flow (or otherwise) within the stimulus column.\textsuperscript{10}

Previously, the only way to measure %CO\textsubscript{2} in the stimulus externally was to use solid electrolyte sensors that were typically difficult to use and have long and short term drift effects, making the measurements less reliable over time.\textsuperscript{43} Recent advancements in the CO\textsubscript{2} sensors have made them more reliable to measure at ambient conditions and offer wider concentration detection range. These are solid-state nondispersive infrared (NDIR) sensors that are portable sensors that use a low-power infrared light-emitting diode and detector to estimate the CO\textsubscript{2} levels.\textsuperscript{43} Because these sensors have not been used previously for the calibration of esthesiometer stimulus, in this work, we initially determined the feasibility of using the sensor for calibration of the esthesiometer stimulus and then calibrated the CO\textsubscript{2} stimuli at different concentrations, flow rates, and working distances.

**Materials and Methods**

**Waterloo Modified Belmonte Esthesiometer**

The construction of the Belmonte esthesiometer has been discussed in detail by Belmonte et al.\textsuperscript{24} The essential components of an esthesiometer are the gas inputs, control box, and nozzle. The gas inputs to the control box are regulated at 5 psi from both the medical air and carbon dioxide (CO\textsubscript{2}) cylinders. The control box houses the electronic controls for manual input and flow meters/gas mixers to prepare the stimulus. Our esthesiometer (Waterloo version) has been extensively modified to include automation of flow control, mixing, and stimulus delivery (as well as the audio prompts and subject data collection) (Figs. 1 and 2).\textsuperscript{44} The stimulus is delivered through the nozzle mounted on an adjustable mount, controlling the x, y, and z position and yaw. The tip/nozzle of the esthesiometer was wrapped with a coil thermostat to control the temperature of the stimulus delivered (Figs. 1 and 2). A calibrated camera viewing system mounted on the side of the esthesiometer allows the examiner to position the tip at the desired working
distance and partly control/monitor the stimulus orthogonality relative to the ocular surface. To create a chemical stimulus, the flowmeters in the control box regulate the mix of medical air and CO₂ to a specified concentration and flow rate. The manual/automated inputs provided to create a stimulus include the flow rate (mL/min), nominal CO₂ concentration (0% in case of mechanical and cold stimulus) and duration of the stimulus (seconds). The temperature of the stimulus is maintained throughout the experiment at either 50°C (translating to approximately 33°C at the ocular surface for mechanical and chemical stimulation) or room temperature for the cold stimulus. The nominal concentration is the %CO₂ set by the observer/software for a given flow rate that would occur at the tip of the esthesiometer when the stimulus is presented.

Carbon Dioxide Sensor

A portable CO₂ sensor (COZIR CM-0041) from CO₂Meter.com was used (Fig. 3).45 (According to the manufacturer, the CM-0041 has been discontinued. The GC-001645 is the recommended replacement for the CM-0041, as both the models use the same COZIR 100% CO₂ sensor.) This compact, low power, diffusion sampling sensor uses NDIR technology with gold-plated optics to measure ambient CO₂ concentration. The measurement chamber is covered by a 100% CO₂-permeable membrane for the CO₂ molecules to enter the chamber. The information reviewed before choosing this particular type of sensor were its accuracy, sampling rate, optimal operating condition, and the ability to detect concentration from 0 to 100%. The COZIR CM-0041 sensor detects %CO₂ from 0 to 100% with an accuracy of ±70 ppm or ±5% of the reading at a sampling rate of 2 Hz. Also, the optimal operating condition for this sensor was between 0 to 50°C/room temperature and atmospheric pressures between 950 mBar and 10 Bar. It could be used for an instantaneous measure of %CO₂ or for fixed interval measure with the intermeasurement timing ranging from every second to every 30 minutes. The session data containing the time and concentration (ppm) could be exported to a spreadsheet by using the supplied data logger software. The sensor was precalibrated when purchased, and before each experimental session, the initial measurement of ambient room %CO₂ was 1300 ± 100 ppm (average of 3 trials). In addition, as is reported later, when the stimulus was set to deliver 100% CO₂ and the sensor was at the tip of the esthesiometer, it consistently reported 100% CO₂.

CO₂ Sensor Design

The sensor design is as explained in the manufacturer’s manual.45 The COZIR sensor uses an infrared LED light source and a detector (Fig. 3C)43 that is mounted on the bridgeboard facing the gold-plated parabolic reflector at the bottom (Fig. 3D). The active measurement area is the area between the bridgeboard and reflector. The LED is operated at 4.3 μm, as this wavelength is similar to the absorption spectra of CO₂. The infrared light from the LED passes through the gas in the active area and reflects back to the detector by the reflector. The amount of light reaching the detector depends on the concentration of

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Figure 1. (A) Setup of modified Belmonte esthesiometer and COZIR CM-0041 CO₂ sensor; and (B) the esthesiometer setup with the control box and calibrated viewing system.
the CO₂ inside the active area, and the rate of absorption or the proportion of light reaching the detector is used in the calculation of the %CO₂ at a given moment.

**Experimental Setup**

The sensor was removed from its original plastic enclosure (Fig. 3B) and mounted on the chin rest by using metal clamps for easier positioning of the sensor orthogonal to the tip of the esthesiometer (Fig. 1A). A calibrated measuring scale was used to adjust the working distance between the tip of the esthesiometer and front face of the sensor (Fig. 1B). The air vents in the room were partially blocked, and the room doors were closed to avoid air draft affecting the flow of the jet between the tip and sensor. The room setup was similar to the experiments with human participants performed in the lab. Due to the stimulus dimension and low flow rates used in the experiment, the stimulus duration for the trials was 99.9 seconds each.
allowing the active area to get saturated with the stimulus being presented. The working distance, flow rate, and nominal concentrations were changed systematically according to the experiment. The \%CO\textsubscript{2} inside the active area of the sensor was logged every second. Between each trial, a breathing time of 2 minutes was used to allow the concentrations inside the chamber to return to ambient conditions. Each trial was done three times to measure repeatability. The concentration was measured at room temperature.

**Experiment 1: Identifying an Optimal Location on the Surface of the Sensor to Deliver Corneal Pneumatic Stimuli**

The diameter of the front face of the sensor is larger than the esthesiometer tip (stimulus column) as well as the active measurement area inside the sensor. Because the sensor is designed to detect ambient conditions, it was unclear what effect it would have on the detection of the \%CO\textsubscript{2} in the stimulus column. As seen in Figure 3B, the front face of the sensor with a bridgeboard (black shadow in the middle) obscures the entry of the stimulus into the sensor. Therefore, the tip of the esthesiometer was placed at five different locations on the surface of the collector (no loss in the CO\textsubscript{2}), and a stimulus of 100\% CO\textsubscript{2} at 100 mL/min flow rate was delivered directly to the active area. The locations were center, left, right, top, and bottom half of the sensor surface (Fig. 4).

**Experiment 2: Effect of Flow Rate and Working Distance for a Maximum Nominal CO\textsubscript{2} Concentration**

This experiment was conducted to determine the concentration at the ocular surface plane with a constant stimulus concentration of 100\%, and the flow rate varied at 3-, 5-, and 10-mm working distances. The flow rates used were 50, 100, 150, and 200 mL/min, and the flow rates were increased methodically from lowest to highest at each working distance.

**Experiment 3: Estimation of %CO\textsubscript{2} Reaching the Ocular Surface at Smaller Intervals of Flow Rate and Concentrations**

In this experiment, all three components were changed to obtain their respective observed \%CO\textsubscript{2}. The flow rate and concentration were varied in smaller steps at three predetermined working distances similar to experiment 2. The flow rates used were between 20 mL/min and 100 mL/min in 20-mL/min steps, whereas the concentrations were from 0 to 100\% in 20\% steps.

**Data Analysis**

The maximum concentration achieved within each trial was extracted and used in the analysis. The data were analyzed using R statistics (version 3.4.3)\textsuperscript{46} in R studio (version 1.1.383)\textsuperscript{47}. Linear models were obtained using “lme4,”\textsuperscript{43} and the test-retest repeatability was obtained using “irr” package.\textsuperscript{48,49} The plots were produced using “ggplot2”\textsuperscript{50} and “cowplot”\textsuperscript{51} packages of R statistics.
Results

Determining the Feasibility and the Location of Stimulus Delivery

The feasibility was evaluated by delivering a 100% CO2 stimulus at a flow rate of 100 mL/min directly to the surface of the sensor. When delivered, the stimuli could still fill the active area with 100% CO2 when the tip was orthogonally positioned right against the surface in the top and bottom quadrants of the sensor. Even though the diameter of the esthesiometer tip/stimulus was smaller than the diameter of the collector, the stimulus could still saturate the chamber with 100% CO2, validating the use of the sensor in calibration. At locations other than the top and bottom quadrants, the observed %CO2 reached only 30% for a 100% CO2 stimulus, indicating a larger loss in the CO2 reaching the active area. As discussed in the construction of the sensor, the presence of bridgeboard may have (where the photo diode detector and LED are located) restricted/limited the CO2 molecules from entering the chamber, resulting in lower observed concentration. Because the CO2 molecules tend to rise when released, the stimuli for the experiments were delivered to the bottom half of the sensor for natural circulation of CO2 inside the active area of the sensor.

Figure 5. The observed concentration was plotted against the flow rate of the stimuli delivered with a concentration of 100% CO2. The colored lines indicate the working distance (distance between the sensor and esthesiometer tip) used in the trial.

Figure 6. The observed concentration was plotted against nominal concentration. The linear fits were plotted for each working distance and flow rate.

Determining the Observed CO2

The experiment with a fixed concentration (100% CO2) and a variable flow rate showed a progressive increase in the observed %CO2 with increasing flow rates, but the observed %CO2 values were relatively low at larger working distances compared to a 3-mm working distance (Fig. 5). The %CO2 values were strongest when the sensor was positioned 3 mm away from the tip, whereas the lowest was observed at 10 mm. A maximum concentration of 87.2% was obtained for a stimulus with the flow rate of 200 mL/min at 3 mm. Compared to low flow rates that had a linear increase in the %CO2, the amount of CO2 reaching the active measurement area lessened or plateaued at the strongest flow rates (150 and 200 mL/min) of the esthesiometer. In the subsequent experiment with the concentrations measured for flow rates within the usual test range and nominal %CO2 set at smaller steps, the rate of increase in the observed %CO2 corresponding to the nominal %CO2 was lower when the flow rates were lower and the sensor was positioned farther from the esthesiometer tip. There was a progressive increase in the variability of the observed %CO2 between flow rates with increasing nominal concentration resulting in a fan-like distribution of values at each working distance (Fig. 6). Both flow rate of the stimulus and working distance were found to be significantly important factors ($P < 0.001$) to determine the observed %CO2 reaching the ocular surface/sensor. Because the test-retest repeatability of each stimulus intensity was high with zero or small standard deviations for each mean (intraclass correlation coefficient [ICC] = 1), a nomogram was created using the average values so that the %CO2 at
the ocular surface plane could be obtained based on the nominal concentration, working distance, and flow rate (Table 1).

**Disc**ussion

Pneumatic esthesiometry is currently the only way to examine chemonociception on the human ocular surface. These experiments are more time-consuming than other pneumatic esthesiometry experiments because of the necessity to remove the gas from the previous trials. There is currently only one esthesiometer specifically designed with a vacuum component to do this without slowing down the experiments, and its CO₂ characteristics have also not been experimentally determined. In this study, we examined the feasibility of using a relatively inexpensive portable CO₂ sensor to calibrate the chemical (CO₂) stimuli of our pneumatic esthesiometer at the ocular surface plane. The research question arose because, perhaps, the CO₂ stimuli were internally calibrated, and the composition of the stimulus is unknown when it reaches the ocular surface. Because the stimulus released from the esthesiometer interacts with the environment before reaching the area of interest, calibrating the stimulus at the ocular surface would help in improving the experimental design to measure chemical sensitivity.

**Feasibility**

The feasibility was primarily tested because the column of gas produced by the esthesiometer was limited (diameter at the nozzle tip is 0.5 mm) and in our esthesiometer, the stimulus column (from the nozzle tip to the ocular surface) was 5 mm long, whereas the front face of the collector was 20 mm in diameter. It was unclear that the CO₂ measuring device would be able to reliably detect/measure the gas within the limits of the gas column and, in addition, if it were able to, what would be the characteristics of the column (or at least the characteristics of CO₂ within the column) determined by the sensor. Calibration of the esthesiometer using the sensor seemed generally viable based on the results obtained for both medical air (0% CO₂) and 100% CO₂ stimuli. The CO₂ measurements were accurate (based on readings with zero added and 100% CO₂ columns) and repeatable, even though there was a mismatch between the sensor output and nominal stimulus specifications.

**Relationship between Concentration, Flow Rate, and Working Distance**

A linear relationship was observed between nominal and observed concentrations for flow rates up to 100 mL/min depending on the working distance (Figs. 5 and 6). There was a reduction in the observed %CO₂

<table>
<thead>
<tr>
<th>Flow Rate (ml/min)</th>
<th>Distance (mm)</th>
<th>Nominal %CO₂</th>
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<tbody>
<tr>
<td></td>
<td>20</td>
<td>40</td>
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<td>20</td>
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<td>7.75</td>
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<tr>
<td></td>
<td>10</td>
<td>9.20</td>
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</table>

The ocular surface plane could be obtained based on the nominal concentration, working distance, and flow rate (Table 1).
at high flow rates (Fig. 5), which might be due to the turbulence in the stimulus or disruption in the laminar flow of the stimulus allowing the CO₂ to diffuse out of the stimulus column. The decrease in the %CO₂ was more pronounced when the sensor was placed away from the esthesiometer. Of course, the interaction between the stimulus air-column and surrounding air is to be expected and has been shown using Schlieren imaging of the mechanical stimulus, which showed turbulence fringes at higher flow rates. From our perspective when using pneumatic esthesiometry to measure psychophysical sensory performance, fortunately, the flow rate for chemoreception trials would never be more than 100 mL/min in our experiments. To minimize the mechanical sensory effect while measuring chemical thresholds, the flow rate of the stimulus would always be set at half of the mechanical (flow) thresholds and the maximum flow rate for the Waterloo modified esthesiometer is 200 mL/min. Although there were suggestions that the relationships can be more complicated with some non-linearities at higher flow rates, both of these attributes (the general “simple relationships” as well as the departure from what is expected) highlight the importance of understanding how the air column behaves to understand the sensory attributes of the tissue being examined when doing pneumatic esthesiometry, in our instance, of the ocular surface.

Repeatability

The study by Tesón et al. found that the chemical thresholds were the least repeatable thresholds among the corneal sensory measurements, with a variability of 18.06% and ICC of 0.49. This is the only study that measured repeatability of the chemical threshold. Many internal and external factors have been found to vary the ocular surface sensitivity. Calibration could be a factor that is closely related to the stimulus characteristics for the variability in the sensation perceived by the participants. In our study, we found that the chemical stimuli itself is repeatable (ICC = 1) considering the flow rate and working distance remain constant between the trials. When the flow rates were increased, there was an increase in the observed concentration at the ocular surface plane even though the concentration delivered remained same (Fig. 5). This phenomenon was easily noticeable at higher nominal concentrations, and a similar phenomenon was observed with the working distance that was discussed earlier. In a human ocular sensitivity experiment, the working distance will remain constant among all participants, but the flow rate is different between participants based on the mechanical thresholds. There might be a confounding factor in the form of flow rates that may reduce the repeatability of the chemical thresholds in human participants. The information on the difference in the flow rate of chemical stimuli were not available in the study by Tesón et al.

Complexity of Regression Models

One of the aims of this study was to create a regression model that predicts the observed concentration based on the nominal concentration, flow rate, and working distance. Mixed modeling and nonlinear multiple regression models were attempted to create the expected models. Partly due to very poorly behaved error distributions and fan-like distribution of observed values, the predictability of the models was poor especially at higher concentrations (Fig. 7). Because of the residual errors, simple linear regression lines were fitted to data for each flow rate at each working distance. The r-square values for all the linear regression lines were more than 0.95, indicating good fit (Table 2).

Limitations

Even though we were able to calibrate the chemical stimuli, there is still an inability to measure the %CO₂ in the stimulus column instantly, and the temperature of the stimulus was also not same as the one used in a regular experiment. The inability for an instantaneous measure of concentration in the stimulus column might be due to the size of the measurement chamber and the diffusion model of the sensor. In this study, we overcame the limitation by delivering the stimulus for an extended period to saturate the measurement chamber with the stimulus presented, and the maximum concentration attained within the trial was used as the observed concentration. The saturation of the gas inside the chamber can be monitored in the real-time graph of the data logger software provided. As soon as the chemical stimulus was on, the observed %CO₂ increased sharply from the baseline (ambient level) until it plateaued or slowed the increase in the concentration with time. The plateauing was apparent at high flow rates and closer working distance. The plateau indicated the saturation of the %CO₂ inside the chamber and there was no evidence of CO₂ pooling inside the chamber, as the %CO₂ started dropping instantaneously after the stimulus was off. The %CO₂ inside the chamber returned to ambient levels within half a minute after the stimulus was off.

In this study, the temperature of the stimulus was...
not the same as the one for human ocular surface chemoreception experiments because the NDIR sensor used in this experiment uses infrared LED to detect the concentration. A change in the temperature of the stimulus might affect the performance of the sensor as well as the temperature of the stimuli would, themselves, require additional calibrations. The 50°C temperature at the nozzle is designed explicitly for a stimulus delivered from a 5-mm working distance (as it translates to 33°C or normal ocular surface temperature when it reaches the ocular surface) and it may not translate to the ocular surface temperature at other working distances. As this calibration study explored the effects (among others) of other working distances to characterize the CO₂ in the stimulus, altering the thermal gradient would alter the sensor performance.

The sensor setup in this manuscript does not exactly reflect a human ocular surface experiment. The facial features such as nose and deep eye socket might provide a more closed environment affecting the air circulation and altering the dispersion of the CO₂ from and surrounding air into the stimulus air column. In addition, body temperature and the thermal gradient surrounding the body might be expected to influence these flows, in addition to the physical structure of facial features. We have previously shown that blocking the flow from and into the column by using a tube (obviously) does affect the distribution of measured CO₂; there was an increase in the CO₂ reaching the sensor. This might better control the concentration of the CO₂, but it cannot be implemented clinically because of the effect of the tube on the cornea and eyelids. Future calibrations more accurately simulating the ocular surface environment (including different brow and nose charac-

<table>
<thead>
<tr>
<th>Flow Rate (ml/min)</th>
<th>3 mm</th>
<th>5 mm</th>
<th>10 mm</th>
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</thead>
<tbody>
<tr>
<td>20</td>
<td>$6.07 \pm 0.073x$</td>
<td>$5.30 \pm 0.071x$</td>
<td>$4.20 \pm 0.055x$</td>
</tr>
<tr>
<td>40</td>
<td>$5.12 \pm 0.139x$</td>
<td>$4.93 \pm 0.125x$</td>
<td>$3.91 \pm 0.107x$</td>
</tr>
<tr>
<td>60</td>
<td>$4.07 \pm 0.224x$</td>
<td>$3.75 \pm 0.195x$</td>
<td>$3.51 \pm 0.153x$</td>
</tr>
<tr>
<td>80</td>
<td>$2.84 \pm 0.364x$</td>
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<td>$2.99 \pm 0.221x$</td>
</tr>
<tr>
<td>100</td>
<td>$2.87 \pm 0.532x$</td>
<td>$2.40 \pm 0.448x$</td>
<td>$2.16 \pm 0.317x$</td>
</tr>
</tbody>
</table>

Figure 7. (A) The observed concentrations were plotted against the nominal concentrations and a linear fit was added with flow rate and working distance as factors. (B) The predicted values were plotted against the observed concentrations in the scatter plot. The %CO₂ was predicted using the linear equation annotated in the figure and compared with the observed concentration from the sensor. Ideally, all points would be on the $y = x$ function (dotted line).
teristics and eye socket depths and ocular temperature) would provide information about the influences that these theoretical variables would have over the stimulus air column.

Recommendations

We would like to suggest a 5-mm working distance for ocular surface sensory processing experiments with the pneumatic esthesiometer. This particular working distance is recommended because the 3-mm working distance is too close to the eye and the esthesiometer tip will touch the eyelid/lashes, producing discomfort and false responses from the participants. On the other hand, longer working distances have the primary disadvantage of not being able to provide sufficient CO₂ concentrations at the eye to enable consistent measurements of thresholds, and other experimentation also requires higher amounts of CO₂ delivery, e.g., adaptation experiments.⁵⁵,⁵⁶

Summary

Calibration of the CO₂ in the air column of a pneumatic esthesiometer is critical. There is a systematic reduction in the %CO₂ reaching the ocular surface plane that depends on working distance and flow rate. The measures of CO₂ were repeatable for all stimulus combinations. It is evident that in pneumatic esthesiometers, it is necessary to standardize the chemical stimulus, as both working distance and flow rate could change the amount of CO₂ reaching the ocular surface.

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