Dexmedetomidine Pharmacodynamics: Part I

Crossover Comparison of the Respiratory Effects of Dexmedetomidine and Remifentanil in Healthy Volunteers

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Background: Dexmedetomidine, a highly selective α₂-adrenoceptor agonist used for short-term sedation of mechanically ventilated patients, has minimal effect on ventilation.

Methods: This study compared the respiratory effect of dexmedetomidine to that of remifentanil. The authors measured and compared respiratory responses of six healthy male volunteers during (1) a stepwise target-controlled infusion of remifentanil, (2) a stepwise target-controlled infusion of dexmedetomidine, and (3) a pseudonatural sleep session.

Results: Compared with baseline, remifentanil infusions resulted in respiratory depression as evidenced by a decrease in respiratory rate and minute ventilation, respiratory acidosis, and apnea episodes resulting in desaturations. Remifentanil disturbed the natural pattern of breathing and flattened the distribution of ventilatory timing (inspiratory time/ventilatory cycle time). The respiratory effects of dexmedetomidine markedly contrasted with those of remifentanil. When compared with baseline, during dexmedetomidine infusions, the respiratory rate significantly increased, and the overall apnea/hypopnea index significantly decreased. The distribution of inspiratory time/ventilatory cycle time showed an increased peak. In addition, dexmedetomidine seemed to mimic some aspect of natural sleep. While the subjects were breathing a 5% CO₂ mixture, hypercapnic arousal phenomena (documented by the Bispectral Index, the electroencephalogram, and sudden increase in the minute ventilation) were observed during dexmedetomidine infusions. Similar phenomena during natural sleep have been reported in the literature.

Conclusions: In comparison with remifentanil, dexmedetomidine infusions (1) did not result in clinically significant respiratory depression, (2) decreased rather than increased the apnea/hypopnea index, and (3) exhibited some similarity with natural sleep.

RESPRATORY depression is a concern when using potent analgesics or sedatives.1 Routine use of sedatives such as midazolam can lead to a fatal outcome when overdosed.2 Dexmedetomidine, a highly selective α₂-adrenoceptor agonist, is currently used for short-term sedation of initially intubated and mechanically ventilated patients. A high concentration of α₂ receptors is found in the locus ceruleus,3 which is involved in regulating sleep and may be involved in the modulation of the respiratory controls.4,5 Dexmedetomidine, through its actions on the α₂ adrenoceptors, imparts sedative and analgesic effects while having minimal ventilatory effects.6

The respiratory safety of dexmedetomidine has been suggested by three studies6–8 Although Ebert et al.6 investigated dexmedetomidine infusions over a wide range of concentrations, their respiratory data are limited to respiratory rate and blood gases. Belleville et al.7 presented a more elaborate respiratory analysis, but their study was limited to relatively small boluses of dexmedetomidine, and the plasma concentrations were not measured. Finally, Venn et al.8 performed a retrospective analysis of the respiratory rate and blood gas data from surgical patients in the surgical intensive care unit.

We designed this study to further characterize the respiratory and analgesic effects of dexmedetomidine over a wide range of plasma concentrations. The analgesic and respiratory depressant effects of opioids are well characterized.9 Therefore, to validate our methods and provide a clinical point of reference to the effects measured with dexmedetomidine, we compared the pharmacodynamic effects of dexmedetomidine to remifentanil, a very short-acting opioid. We measured and compared respiratory, analgesic, and sedative responses of healthy male volunteers during (1) a stepwise target-controlled infusion (TCI) of remifentanil, (2) a stepwise TCI of dexmedetomidine, and (3) a pseudonatural sleep session. This article focuses on the respiratory effects of dexmedetomidine, whereas a companion manuscript examines its analgesic properties.
Materials and Methods

Institutional Review Board and Inclusion/Exclusion Criteria

After this study was approved by the Institutional Review Board (Duke University Medical Center, Durham, North Carolina), signed informed consent was obtained from each study subject. Eight male subjects, aged 21–40 yr, with American Society of Anesthesiologists physical status I, were enrolled. Subjects with a history of drug, tobacco, or alcohol abuse; chronic use of medications; gastroesophageal reflux; anticipated difficult airway; body mass index of less than 18 or greater than 28 kg/m²; or the presence of a beard or physiognomies precluding a good fit of a facemask were excluded. The subjects underwent a screening session during which a physical examination, a medical history, electrocardiography, and laboratory tests were performed. During the screening session, the subjects were familiarized extensively with the study procedures, monitoring devices were applied, and subjects rested supine with a tight-fitting mask strapped to their faces for a minimum of 30 min. A carbon dioxide challenge was also performed during the screening.

Conduct of the Study

The protocol consisted of three parts, lasting more than 24 h (fig. 1). During parts 1 and 2, the subjects received remifentanil or dexmedetomidine, respectively, via TCI. During part 3, no drugs were infused, and the subjects were requested to sleep. Because there were measurable residual concentrations of dexmedetomidine during part 3, the sleep during that part is referred to as pseudonatural sleep. During parts 1 and 2, the stepwise infusions were designed to target and maintain remifentanil or dexmedetomidine plasma concentrations at four sequentially increasing steps. Each step lasted 40 min. Steps 1–4 targeted remifentanil (part 1) plasma concentrations of 1, 2, 3, and 4 ng/ml and dexmedetomidine (part 2) plasma concentrations of 0.6, 1.2, 1.8, and 2.4 ng/ml. Remifentanil plasma concentrations were chosen (from clinical experience) to be high enough to produce respiratory depression without inducing apnea, whereas dexmedetomidine plasma concentrations were chosen to range from a therapeutic level to supratherapeutic levels. The first step of dexmedetomidine (0.6 ng/ml) is a typical level used for sedating patients in the surgical intensive care unit. During part 1, at the end of step 4, the remifentanil infusion was stopped, and a 90-min recovery period was allowed before starting part 2 to ensure that the subject returned to baseline.10 Similarly, the dexmedetomidine infusion was stopped, during part 2 at the end of step 4, and, because the pharmacokinetics of dexmedetomidine is slower than that of remifentanil, a 240-min recovery period was allowed before starting part 3 (fig. 1).11,12

One of the eight subjects received a placebo instead of remifentanil, and another subject received a placebo instead of dexmedetomidine. This was randomly assigned, and the investigators were blinded to it. The two placebo subjects were excluded from the respiratory analysis to perform a crossover comparison. The stopping criteria for both drug infusions were the following: a 40% change in the baseline mean arterial pressure, a mean arterial pressure of 50 mmHg or less for 3 min, a heart rate of 40 beats/min or less for 3 min, or respiratory depression necessitating assisted ventilation to maintain an oxygen saturation measured by pulse oximetry of 90% or greater.

The subjects fasted for 8 h before the study and were asked to abstain from caffeine and alcohol consumption for the preceding 24 h. On arrival in the morning, an 18-gauge intravenous cannula was inserted, and lactated Ringer’s solution was infused at 100 ml/h. A 20-gauge catheter was inserted into the radial artery of the non-dominant hand. The subjects received 30 ml oral sodium citrate, 10 mg intravenous metoclopramide, and 50 mg intravenous ranitidine to minimize the risk of pulmonary aspiration. Nine gold cup electroencephalographic electrodes (C3, C4, F7, F8, Cz, Cz prime, A1, A2, and inion) were attached with collodion using standard sleep laboratory techniques. A three-lead electrocardiogram, a non-invasive blood pressure cuff, pulse oximeter probes, and

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Respitrace (Non-Invasive Monitoring Systems Inc., North Bay Village, FL) bands were also applied.

A three-way stopcock was used to allow subjects to breathe either 50% oxygen from a Venturi system or 5% CO₂ in 50% O₂ and 45% N₂ from the prefilled Douglas bag during the carbon dioxide challenge. The Douglas bag, connected to the carbon dioxide mixture cylinder, could be refilled as needed. The respiratory variables were measured continuously from a pneumotach, a capnograph, and the Respitrace (respiratory inductive plethysmograph that monitors changes in lung volume).13

After all of the monitors were placed and the facemask was carefully adjusted, the lights were dimmed, and the subject was requested to rest quietly in the bed in the decubitus position for 30–60 min. The protocol was then initiated with baseline measurements.

**Measurements**

At the beginning of each step, an infusion of the test drug (TCI) was initiated. A 5-min period was allowed for equilibrium between the plasma and effect sites. Subjects were then kept undisturbed for an additional 5 min to collect electroencephalographic data. A 6-min carbon dioxide challenge was then performed, followed by sedation and pain assessments before repeating the carbon dioxide challenge (fig. 2). The second carbon dioxide challenge was performed to detect a possible effect of the pain assessment’s stimulation on the hypercapnic ventilatory response (HCVR). During baseline, while no drug was infused, an identical procedure was performed.

At each step, the sedation was assessed using a visual analog scale,14 the Ramsay score,15 and the Observer’s Assessment of Alertness/Sedation sum.16 Blood samples were collected for pharmacokinetic analysis at 15 and 40 min of each step.

Before the beginning of each carbon dioxide challenge, the minute ventilation (MV) was averaged over 1 min, and an arterial blood gas (ABG) measurement was obtained. The three-way stopcock was then turned in position to allow the subject to breathe the 5% CO₂ mixture from the Douglas bag for 6 min.17,18 The MV was averaged during the last minute of the carbon dioxide challenge, and another ABG was obtained before the three-way stopcock was turned back in position to allow the subject to breathe the 50% O₂ mixture in nitrogen. For each carbon dioxide challenge, the breath-to-breath MV was plotted in function of time, and a monoexponential model was fitted to the data. The monoexponential fit was used to compute how far the MV responses were from steady state (percent of the maximum predicted response).

The respiratory data were also analyzed during the 5-min epoch of electroencephalographic data collection to ensure an undisturbed breathing pattern. The variables analyzed included the following: end-tidal carbon dioxide (ETCO₂), tidal volume (VT), MV, ventilatory cycle time (Ti), inspiratory time (Ti), expiratory time, respiratory rate (RR), rib cage contribution, and oxygen saturation (SaO₂).

The average MV was calculated from the sum of the tidal volumes of every breath in a 5-min epoch. The average Ti was computed by dividing the duration of the epoch by the number of breaths taken in that interval. The average Ti was computed by dividing the sum of the Ti by the number of breaths in that epoch. The capnograph data were analyzed using the average ETCO₂ in the minute preceding every ABG.

The drive V₉/Ti (mean inspiratory flow) and timing Ti/Tt components of ventilation19 were also recorded for each breath. The advantage of analyzing respiratory data in terms of V₉/Ti and Ti/Tt resides in the fact that these parameters have been shown to be physiologically independent19 one from another, while

\[ MV = V_9/Ti \times Ti/Tt. \]

The breath-by-breath Ti/Tt and V₉/Ti values of the six subjects were used to construct histograms of their distribution at each step.
Breathing patterns were monitored continuously using the Respitrace. The software RespiEvents (Non-Invasive Monitoring Systems Inc.) was used to classify all apnea events into one of two categories, either central or obstructive, and to compute the apnea/hypopnea index (AHI). An apnea event was defined as an absence of tidal volume for at least 10 s in duration. A hypopnea event was defined as tidal volumes smaller than 25% of the baseline tidal volume for at least 10 s in duration. The AHI is defined as the number of apnea and hypopnea events per hour. At each step, the subjects were classified as having significant apnea (AHI ≥ 15) or not having significant apnea (AHI < 15).

During the overnight portion of the study, while the subjects were sleeping without any drug being infused, the stages of sleep were assessed using continuous electroencephalographic monitoring. The respiratory pattern was analyzed throughout the night, whereas the carbon dioxide challenges were performed during slow-wave sleep stages (stages 3 and 4).20

**Monitoring and Equipment**

The following monitoring equipment was used: Spacelabs 90603a (SpaceLabs Medical Products, Redwood, WA) for the electrocardiogram and invasive arterial blood pressure; Dinamap (Critikon, Tampa, FL) for noninvasive blood pressure; Ohmeda 5200 capnograph (Datex-Ohmeda Inc., Louisville, CO); Bicore CP-100 pneumotach (Bear Medical Systems Inc., Riverside, CA); Biox 3700 pulse oximeter; respiratory inductive plethysmography Respitrace 204 (Non-Invasive Monitoring Systems Inc.)13; and A-1000 four-channel electroencephalograph and Bispectral Index® (BIS®) monitor (Aspect Medical Systems Inc., Framingham, MA). The respiratory equipment (Hans Rudolph, Inc., Kansas City, MO) included a 1-l calibrating syringe, a Douglas bag, nonre-breathing circuit and low-resistance valve, a three-way low-resistance stopcock, and a tight-fitting facemask. The data from the electronic monitoring equipment (including raw electroencephalograph, digitized at 128 Hz) were downloaded each second to a LabView data acquisition system (version 6.0; Labview, Austin, TX).

Arterial blood gases were analyzed with the VIA-ABG (VIA Medical Corporation, San Diego, CA). The TCI pump devices consisted of two laptop computers connected to infusion pumps (Harvard Pump 22; Harvard Apparatus, South Natick, MA). STANPUMP® was used to run the TCI pumps. The pharmacokinetic parameters used for the infusions of remifentanil and dexmedetomidine were those published by Minto et al.21 and Dyck et al.,11 respectively.

**Calibration**

Before each experiment, the VIA-ABG monitor was calibrated according to the manufacturer’s specification; the capnograph calibration was verified at room air using a 5% CO₂ mixture; and the Bicore pneumotach calibration was verified with the 1-l calibration syringe. The Respitrace was calibrated by qualitative diagnostic calibration (i.e., self-calibration)22 when subjects had been undisturbed and breathing at rest for 5 min. The drift of the Respitrace was minimized by turning on the monitor 3 h before the start of the study13 and by recalibrating the monitor before each of the three parts of the protocol.

**Statistical Analysis**

A paired Student t test with a Bonferroni correction was used for comparing continuous data involving three groups. For continuous data involving more than three groups, intergroup and intragroup comparisons were analyzed using analysis of variance, with the Dunnett method used for multiple comparisons.23 Contingency tables were analyzed using chi-square tests. Data are reported as mean ± SD or median (range), depending on the pattern of distribution. P values less than 0.05 were considered statistically significant. Histograms were constructed to visually assess the single-breath distributions of the timing and drive components of ventilation Ti/Tt and V̇e/Ti. The software programs S-plus 6.0 (Insightful Corp, Seattle, WA) and JumpIn (SAS Institute Inc., Cary, NC) were used for the statistical analyses.

**Results**

**Pharmacokinetics**

Plasma concentrations of remifentanil and dexmedetomidine are summarized in table 1. For both remifentanil and dexmedetomidine, there were no statistical differences between the first and second samples drawn within each step, showing that a stable level was achieved at each step.

**Sedation**

As shown in figure 3, the subjects were minimally sedated during remifentanil infusions. During dexmedetomidine infusion steps 1 and 2, the subjects were sedated and arousable. In contrast, during steps 3 and 4, deeper levels of hypnosis were attained, and most subjects were completely unarousable.

**Hemodynamics**

As shown in tables 2 and 3, remifentanil infusions had no effect on mean arterial pressure and heart rate, whereas higher concentrations of dexmedetomidine resulted in a statistically significant increase in mean arterial pressure and decrease in heart rate.
Hypercapnic Ventilatory Response

On average, 91% of the maximum predicted MV response was achieved within 6 min (SD = 10.9%), and 75% of the challenges reached 86% of the maximum predicted response or greater. Most of the challenges with no drugs reached stable MV. The response of a typical subject, at different steps of the study, is shown in figure 4. At baseline, the ETCO2 was rapidly stable, and the MV was relatively stable before the end of the carbon dioxide challenge. As the plasma concentration of remifentanil increases, the breath-to-breath MV response flattened, and the ETCO2 increased. By the last step of remifentanil infusion, breathing was irregular with periods of apnea, while the ETCO2 markedly increased. After cessation of the remifentanil infusion (recovery), the MV response and ETCO2 returned almost completely to baseline. During dexmedetomidine infusions, both the ETCO2 and MV responses were relatively preserved and similar to the baseline and recovery.

Although the MV responses during baseline and recovery mostly followed an exponential and smooth increase (fig. 4), they were often irregular with sudden dramatic changes in MV during dexmedetomidine infusions (figs. 5A and B), as if the subject was being aroused. The plots of the BIS values (fig. 5) confirm this impression. During the carbon dioxide challenges exhibiting sudden changes in MV, the BIS values correlate closely with MV (figs. 5A and B). Conversely, during the carbon dioxide challenges exhibiting a smooth exponential response, the BIS values showed no correlation with the MV (fig. 5C). Because two recent articles suggested that BIS values might track muscle activity,24,25 we plotted the raw electroencephalographic signals, which confirmed that BIS was indeed detecting a true arousal phenomenon rather than a muscle artifact (fig. 6).

The changes in arterial carbon dioxide tension (Paco2) and in MV during the HCVRs are summarized in table 4. A statistical analysis was performed by comparing to the baseline the change in Paco2 and the change in MV during the remifentanil, recovery, and dexmedetomidine phases. Each of the four steps of remifentanil infusions resulted in a statistically significant decrease in the change in MV when compared with baseline. No significant changes were observed during the recovery or dexmedetomidine steps.

Respiratory Pattern Analysis (Respirtrace)

During remifentanil infusions, decreases in MV and Ti/Tt, consistent with respiratory depression, were observed (table 2). In contrast, during dexmedetomidine infusions, an increased RR and a decreased Tt, consistent with an absence of respiratory depression, were observed (table 3). MV, Ti/Tt, RR, and Tt returned to their baselines after recovery from remifentanil and dexmedetomidine.

Central apnea was observed during remifentanil infusions, during the pseudonatural sleep part, but not during dexmedetomidine infusions. The frequency of these episodes (expressed in number of events per hour as median and range) were 3 (0–7) during remifentanil and 0 (0–3) during sleep. Episodes of obstructive apnea were observed during all three parts.

The AHI (tables 2 and 3) was analyzed using the chi-square test on the pooled data for remifentanil and dexmedetomidine. Remifentanil infusions increased the likelihood of observing AHIs greater than 15, compared with the likelihood of observing AHIs greater than 15 during baseline, remifentanil recovery, and sleep stages (P < 0.05). In addition, during remifentanil infusions, two subjects had episodes of prolonged (60–90 s) apnea

Table 1. Summary of the REMI and DEX Plasma Concentrations

<table>
<thead>
<tr>
<th></th>
<th>Remifentanil</th>
<th>Dexmedetomidine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Plasma</td>
<td>Measured Plasma</td>
<td>Target Plasma</td>
</tr>
<tr>
<td>Concentrations,</td>
<td>Concentrations,</td>
<td>Concentrations,</td>
</tr>
<tr>
<td>ng/ml</td>
<td>ng/ml</td>
<td>ng/ml</td>
</tr>
<tr>
<td>1.0</td>
<td>0.83 (0.21)</td>
<td>0.6</td>
</tr>
<tr>
<td>2.0</td>
<td>0.74 (0.21)</td>
<td>1.2</td>
</tr>
<tr>
<td>3.0</td>
<td>1.86 (0.48)</td>
<td>1.8</td>
</tr>
<tr>
<td>4.0</td>
<td>2.34 (0.45)</td>
<td>2.90 (0.28)</td>
</tr>
<tr>
<td></td>
<td>2.32 (0.52)</td>
<td>2.71 (0.09)</td>
</tr>
<tr>
<td>Recovery 30 min after termination of remifentanil infusion</td>
<td>0 (0)</td>
<td>3.74 (0.43)</td>
</tr>
</tbody>
</table>

Values are presented mean ± SD. For each step, the first and second values are for the first and second PK samples collected within each step, respectively.
associated with desaturation (SaO₂ ≤ 80%) and were prompted to breathe. In contrast, dexmedetomidine infusions resulted in a significant decrease in the likelihood of observing AHIs greater than 15, compared to the likelihood of observing AHIs greater than 15 during baseline, remifentanil recovery, and sleep stages (P < 0.003).

The distribution of breath-to-breath Ti/Tt pooled for each step is shown in figure 7. The Ti/Tt histograms flattened during remifentanil infusions and peaked during dexmedetomidine infusions when compared with baseline. The histograms returned to baseline after recovery from remifentanil and dexmedetomidine.

**ABG Analysis**

The average levels of arterial oxygen tension (Pao₂) and SaO₂ did not significantly change from baseline with either dexmedetomidine or remifentanil (tables 2 and 3). The ABG analyses performed during dexmedetomidine infusion were consistent with a well-compensated mild respiratory acidosis (table 3). The PaCO₂ levels increased

### Table 2. Breathing Pattern Variables during Part 1

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>REMI1</th>
<th>REMI2</th>
<th>REMI3</th>
<th>REMI4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti/Tt</td>
<td>0.39 ± 0.08</td>
<td>0.29 ± 0.10</td>
<td>0.30 ± 0.11</td>
<td>0.28 ± 0.09</td>
<td>0.25 ± 0.10*</td>
</tr>
<tr>
<td>V̇E/Ti, ml/s</td>
<td>310 ± 65</td>
<td>266 ± 48</td>
<td>334 ± 113</td>
<td>368 ± 87</td>
<td>425 ± 222</td>
</tr>
<tr>
<td>V̇E, ml</td>
<td>616 ± 224</td>
<td>450 ± 103</td>
<td>636 ± 247</td>
<td>578 ± 145</td>
<td>788 ± 433</td>
</tr>
<tr>
<td>RC, %</td>
<td>37.2 ± 4.9</td>
<td>44.3 ± 6.0</td>
<td>53.1 ± 11.6</td>
<td>50.3 ± 12.9</td>
<td>53.3 ± 14.2*</td>
</tr>
<tr>
<td>Ti, s</td>
<td>5.4 ± 2.3</td>
<td>6.6 ± 2.1</td>
<td>7.3 ± 3.0</td>
<td>6.1 ± 1.6</td>
<td>7.5 ± 2.2</td>
</tr>
<tr>
<td>MV, ml/min</td>
<td>6,994 ± 1,984</td>
<td>4,379 ± 1,982*</td>
<td>4,713 ± 1,270</td>
<td>5,419 ± 1,336</td>
<td>4,514 ± 1,325*</td>
</tr>
<tr>
<td>RR, breaths/min</td>
<td>12.1 ± 4.3</td>
<td>9.5 ± 4.8</td>
<td>8.2 ± 4.1</td>
<td>9.1 ± 3.1</td>
<td>6.8 ± 3.4</td>
</tr>
<tr>
<td>pH</td>
<td>7.42 ± 0.01</td>
<td>7.39 ± 0.02</td>
<td>7.37 ± 0.03</td>
<td>7.34 ± 0.04*</td>
<td>7.32 ± 0.04*</td>
</tr>
<tr>
<td>PaCO₂, mmHg</td>
<td>39.9 ± 2.7</td>
<td>44.6 ± 3.3</td>
<td>47.8 ± 5.9</td>
<td>52.3 ± 6.5*</td>
<td>55.3 ± 8.4*</td>
</tr>
<tr>
<td>PaO₂, mmHg</td>
<td>231.7 ± 33.4</td>
<td>194.6 ± 35.8</td>
<td>204.9 ± 55.2</td>
<td>166.2 ± 52.8</td>
<td>173.2 ± 57.8</td>
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<tr>
<td>SaO₂, %</td>
<td>99.1 ± 0.2</td>
<td>99.1 ± 0.2</td>
<td>98.5 ± 1.7</td>
<td>98.3 ± 1.0</td>
<td>97.3 ± 2.7</td>
</tr>
<tr>
<td>BE, mEq/l</td>
<td>0.0 ± 1.2</td>
<td>1.7 ± 1.3</td>
<td>2.3 ± 1.7</td>
<td>2.3 ± 1.1</td>
<td>2.1 ± 1.1</td>
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<tr>
<td>HCO₃⁻, mEq/l</td>
<td>24.4 ± 1.1</td>
<td>26.8 ± 1.3</td>
<td>27.5 ± 1.3*</td>
<td>28.1 ± 1.3*</td>
<td>28.2 ± 1.6*</td>
</tr>
<tr>
<td>ETCO₂, mmHg</td>
<td>35.5 ± 3.5</td>
<td>38.1 ± 6.9</td>
<td>43.4 ± 6.0</td>
<td>44.6 ± 11.3</td>
<td>46.3 ± 10.2</td>
</tr>
<tr>
<td>AH1 &gt; 15</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>64 ± 14</td>
<td>58 ± 14</td>
<td>60 ± 13</td>
<td>63 ± 12</td>
<td>63 ± 8</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>87 ± 5</td>
<td>85 ± 11</td>
<td>86 ± 11</td>
<td>87 ± 10</td>
<td>88 ± 12</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD.
*P < 0.05 from baseline (analysis of variance and Scheffé post hoc testing).

AHI = apnea/hypopnea index; V̇E = minute ventilation; SaO₂ = arterial oxygen saturation; Ti/Tt = respiratory cycle time; VT = tidal volume; V̇E/Ti = drive component of ventilation (mean inspiratory flow).

### Table 3. Breathing Pattern Variables during Part 2

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>DEX1</th>
<th>DEX2</th>
<th>DEX3</th>
<th>DEX4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti/Tt</td>
<td>0.39 ± 0.08</td>
<td>0.44 ± 0.05</td>
<td>0.48 ± 0.07</td>
<td>0.45 ± 0.05</td>
<td>0.45 ± 0.05</td>
</tr>
<tr>
<td>V̇E/Ti, ml/s</td>
<td>310 ± 65</td>
<td>292 ± 72</td>
<td>305 ± 135</td>
<td>342 ± 121</td>
<td>328 ± 95</td>
</tr>
<tr>
<td>V̇E, ml</td>
<td>616 ± 224</td>
<td>551 ± 136</td>
<td>491 ± 158</td>
<td>494 ± 177</td>
<td>461 ± 118</td>
</tr>
<tr>
<td>RC, %</td>
<td>37.2 ± 4.9</td>
<td>34.2 ± 18.0</td>
<td>41.2 ± 17.6</td>
<td>40.3 ± 32.1</td>
<td>37.2 ± 24.0</td>
</tr>
<tr>
<td>Ti, s</td>
<td>5.4 ± 2.3</td>
<td>4.3 ± 0.8</td>
<td>3.6 ± 0.5*</td>
<td>3.3 ± 0.3*</td>
<td>3.2 ± 0.3*</td>
</tr>
<tr>
<td>MV, ml/min</td>
<td>6,994 ± 1,984</td>
<td>7,054 ± 2,276</td>
<td>8,358 ± 2,863</td>
<td>9,432 ± 3,154</td>
<td>8,846 ± 1,998</td>
</tr>
<tr>
<td>RR, breaths/min</td>
<td>12.1 ± 4.3</td>
<td>13.1 ± 3.1</td>
<td>16.6 ± 3.5</td>
<td>19.0 ± 2.3*</td>
<td>19.2 ± 2.0*</td>
</tr>
<tr>
<td>pH</td>
<td>7.42 ± 0.01</td>
<td>7.40 ± 0.02</td>
<td>7.40 ± 0.01</td>
<td>7.38 ± 0.03*</td>
<td>7.40 ± 0.03</td>
</tr>
<tr>
<td>PaCO₂, mmHg</td>
<td>39.9 ± 2.7</td>
<td>45.1 ± 2.9</td>
<td>45.4 ± 3.5</td>
<td>47.5 ± 5.5</td>
<td>44.7 ± 5.1</td>
</tr>
<tr>
<td>PaO₂, mmHg</td>
<td>231.7 ± 33.4</td>
<td>238.9 ± 26.1</td>
<td>228.0 ± 43.6</td>
<td>205.3 ± 53.9</td>
<td>211.5 ± 44.5</td>
</tr>
<tr>
<td>SaO₂, %</td>
<td>99.1 ± 0.2</td>
<td>99.2 ± 0.3</td>
<td>99.0 ± 0.0</td>
<td>99.0 ± 0.3</td>
<td>99.2 ± 0.3</td>
</tr>
<tr>
<td>BE, mEq/l</td>
<td>0.0 ± 1.2</td>
<td>3.2 ± 1.9</td>
<td>3.1 ± 2.0</td>
<td>2.5 ± 2.5</td>
<td>2.4 ± 2.7</td>
</tr>
<tr>
<td>HCO₃⁻, mEq/l</td>
<td>24.4 ± 1.1</td>
<td>28.0 ± 1.9</td>
<td>27.9 ± 2.0</td>
<td>27.7 ± 2.5</td>
<td>27.3 ± 2.7</td>
</tr>
<tr>
<td>ETCO₂, mmHg</td>
<td>35.5 ± 3.5</td>
<td>39.2 ± 4.2</td>
<td>36.3 ± 2.8</td>
<td>38.2 ± 6.1</td>
<td>38.9 ± 4.2</td>
</tr>
<tr>
<td>AH1 &gt; 15</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>64 ± 14</td>
<td>62 ± 9</td>
<td>53 ± 9*</td>
<td>50 ± 13*</td>
<td>49 ± 10*</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>87 ± 5</td>
<td>82 ± 6</td>
<td>87 ± 9</td>
<td>98 ± 7*</td>
<td>103 ± 7*</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD.
*P < 0.05 from baseline (analysis of variance and Scheffé post hoc testing).

AHI = apnea/hypopnea index; BE = base excess; DEX = dexmedetomidine; ETCO₂ = end-tidal carbon dioxide; HR = heart rate; MV = minute ventilation; PaCO₂ = arterial carbon dioxide tension; PaO₂ = arterial oxygen tension; RC = contribution of the ribcage; RR = respiratory rate; SaO₂ = arterial oxygen saturation; Ti/Tt = timing component of ventilation; Ti = respiratory cycle time; V̇E = tidal volume; V̇E/Ti = drive component of ventilation (mean inspiratory flow).
during dexmedetomidine infusion but reached a plateau after step 1 (table 3). Conversely, with remifentanil, we observed a pattern of moderate to severe respiratory acidosis with partial metabolic compensation (table 2). The PaCO₂ levels during remifentanil infusion showed concentration-related increments (table 2).

**Placebo and Recovery**

Data from the two placebo subjects during placebo infusion were similar to their respective baselines. The data of the drug infusion part were consistent with the drug effects observed in the six nonplacebo subjects (data not shown). During recovery from remifentanil and dexmedetomidine infusions, all measured variables returned to their baseline values (data not shown).

**Discussion**

**Pharmacokinetics and Sedation**

All of the subjects were easily arousable throughout the remifentanil infusions. Dexmedetomidine infusions resulted in supratherapeutic plasma concentrations. Dosing guidelines of dexmedetomidine for intensive care unit sedation target a plasma concentration of 0.6 ng/ml, which is equivalent to our first infusion step. During step 4, the average plasma concentration of dexmedetomidine was 3.78 ng/ml, which is three times higher than the plasma concentration (1.2 ng/ml) associated with the maximum dosing recommended in the package insert (0.7 µg · kg⁻¹ · h⁻¹). While subjects were sedated but arousable during steps 1 and 2, deeper levels of hypnosis were attained during steps 3 and 4, and most subjects were completely unarousable.

**Hypercapnic Ventilatory Response**

As expected, the HCVR response was significantly decreased during remifentanil infusion. In contrast, the HCVR response did not change after dexmedetomidine infusions. However, as shown in figure 5, in some of the carbon dioxide challenges during dexmedetomidine infusions, the increase in MV coincided with arousal phenomenon. Such arousal phenomenon, secondary to the hypercapnia stimulation, has been described during natural sleep by Berthon-Jones and Sullivan, and their numbers are strikingly similar to ours. In addition, Nelson et al. recently demonstrated that dexmedetomidine converges on the natural sleep pathway to exert its sedative effects. Therefore, the similarity between the hypercapnic arousal phenomenon during dexmedetomidine infusions and natural sleep is not surprising. Previous studies during natural sleep, using special precautions to prevent the induction of arousal, have shown a consistent decrease in the HCVR response during different sleep stages (including slow-wave sleep). Some factors that have the potential to cause arousal include sudden inhalation of carbon dioxide and changes in circuit odor, pressure, temperature, humidity, and resistance. Therefore, rebreathing methods (with no carbon dioxide in the initial bag mixture) have been used. Belleville et al., using a pseudorebreathing technique...
(progressive computer-controlled increase in carbon dioxide), reported a modest decrease in the HCVR response after dexmedetomidine boluses, which is similar to what has been reported during natural sleep.\textsuperscript{26,28} The HCVR discrepancy between the results of Belleville \textit{et al.} and ours may lie in the fact that dexmedetomidine mimics natural sleep. By using the pseudorebreathing technique, Belleville \textit{et al.} may have minimized the arousal phenomenon and thus observed a decreased HCVR response, as seen during natural sleep. On the other hand, our results have been contaminated by arousals caused by the sudden inhalation of carbon dioxide, which is a phenomenon previously described during natural sleep.

\textit{Respiratory Patterns}

Dexmedetomidine and remifentanil were associated with two very different patterns of ventilation. The opposite tendencies observed with Ti/Tt correlate well with other studies.\textsuperscript{9,29,30}

![Fig. 5. Examples of different hypercapnic ventilatory responses during dexmedetomidine infusions. In A and B, arousal phenomena secondary to the hypercapnic stimulation are seen, and the Bispectral Index (BIS; dotted line) tightly correlates with the minute ventilation (MV; continuous line). C shows an absence of arousal where the BIS is not correlated with the MV.](image)

![Fig. 6. Raw electroencephalographic tracing showing arousal from slow-wave sleep pattern during dexmedetomidine infusion. This tracing is plotted from the data of the arousal phenomenon shown on the middle panel of figure 7. The arrow labeled Arousal is positioned at the same time point as the similar arrow of the middle panel of figure 7.](image)

Table 4. Summary of the Hypercapnic Ventilatory Response during Parts 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>$\Delta$MV</th>
<th>$\Delta$CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>7.7 (4.0)</td>
<td>5.9 (2.9)</td>
</tr>
<tr>
<td>REM1</td>
<td>2.8 (2.2)*</td>
<td>6.7 (4.7)</td>
</tr>
<tr>
<td>REM2</td>
<td>3.6 (1.7)*</td>
<td>7.2 (4.0)</td>
</tr>
<tr>
<td>REM3</td>
<td>4.3 (3.7)*</td>
<td>5.8 (3.0)</td>
</tr>
<tr>
<td>REM4</td>
<td>3.8 (2.4)*</td>
<td>7.7 (3.6)</td>
</tr>
<tr>
<td>Recovery</td>
<td>7.9 (2.0)</td>
<td>6.1 (2.6)</td>
</tr>
<tr>
<td>DEX1</td>
<td>8.2 (3.8)</td>
<td>4.9 (2.1)</td>
</tr>
<tr>
<td>DEX2</td>
<td>7.4 (4.0)</td>
<td>5.3 (2.7)</td>
</tr>
<tr>
<td>DEX3</td>
<td>6.4 (3.7)</td>
<td>4.4 (2.5)</td>
</tr>
<tr>
<td>DEX4</td>
<td>5.6 (3.6)</td>
<td>5.0 (4.0)</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD. * $P < 0.05$ from baseline. $\Delta$CO$_2$ = arterial carbon dioxide tension (Paco$_2$) at the end of the carbon dioxide challenge minus the Paco$_2$ preceding the start of the carbon dioxide challenge; $\Delta$MV = minute ventilation at the end of the carbon dioxide challenge minus the minute ventilation preceding the start of the carbon dioxide challenge; DEX = dexmedetomidine; REMI = remifentanil.
the study of Belleville could also result from the fact that boluses were used in we reported and discussed earlier. This discrepancy may result from the arousal phenomenon reported a statistically significant decrease in RR. This /H11549 from; REMI et al. during dexmedetomidine, although Belleville morphine and oxycodone. A change in the shape of a distribution may result in a subtle change of mean and SD. For remifentanil, while the mean value of Ti/Tt decreases, the SD has only a slight tendency to increase, which results in an increased coefficient of variation. Interestingly, Leino et al. looked at the drug effect of morphine and oxycodone on the coefficient of variation of VT, RC/VT (contribution of ribcage to VT), and RR. They found an increased coefficient of variation. Interestingly, Leino et al. observed an increased coefficient of variation of RR during drug infusions of both morphine and oxycodone.

Respiratory Rate and Apnea/Hypopnea Index
We observed a statistically significant increase in RR during dexmedetomidine, although Belleville et al. reported a statistically significant decrease in RR. This discrepancy may result from the arousing phenomenon we reported and discussed earlier. This discrepancy could also result from the fact that boluses were used in the study of Belleville et al., whereas we used infusions that resulted in sustained and higher dexmedetomidine concentrations. Interestingly, Ebert et al. used dexmedetomidine infusions similar to ours, and that study showed a significant increase in RR as well.

The AHI analysis adds a clinical perspective. In the current investigation, obstructive apnea was observed during baseline, remifentanil and dexmedetomidine infusions, and stages of deep sleep. However, the inci-
is another limitation of our method, because ventilation may be affected for several hours after a carbon dioxide challenge. Finally, the pharmacokinetic profile of dexmedetomidine prevented us from randomizing the sequence of drug administered, and although it is controversial, the possibility of acute opioid tolerance should be mentioned. In addition, the possibility that the increase in RR during dexmedetomidine infusions may be secondary to muscle exhaustion, and a consequence of the absence of randomization should be mentioned. However, this is unlikely because the RR is returning to baseline during recovery from dexmedetomidine.

Conclusion

As expected, when compared with baseline, remifentanil infusions resulted in respiratory depression as evidenced by a decreased HCVR response, decreased RR and MV, respiratory acidosis, and increased AHI and apnea episodes resulting in desaturations. In addition, remifentanil substantially disturbed the natural pattern of breathing and flattened the distribution of Ti/Tt.

Dexmedetomidine did have some respiratory effects, as would be expected because (1) one of its sites of action is the locus ceruleus, which is known to play a role in both respiratory control and sleep modulation, and (2) dexmedetomidine converges on the natural sleep pathway to exert its sedative effects, whereas natural sleep does result in ventilation modulation. However, the respiratory effects of dexmedetomidine were markedly different from those of remifentanil. Compared with baseline, during dexmedetomidine infusions, the HCVR response was unchanged, the RR was significantly increased, and the overall AHI was significantly decreased. The effect of dexmedetomidine on the breathing pattern also contrasts with the effect of remifentanil. The distribution of Ti/Tt showed an increased peak. More importantly, dexmedetomidine exhibited a hypercapnic arousal phenomenon similar to what has been described during natural sleep.

Clinically speaking, dexmedetomidine stands apart from other sedatives. Dexmedetomidine seemed clinically safe from a respiratory point of view, even during doses high enough to cause unresponsiveness to vigorous stimulation. Even supramaximal plasma concentrations of dexmedetomidine did not cause respiratory acidosis and did not cause prolonged apnea leading to desaturation, as was seen with relatively low plasma concentrations of remifentanil. Dexmedetomidine also exhibited a hypercapnic arousal phenomenon in a similar fashion to what has been described during natural sleep. The fact that dexmedetomidine mimics natural sleep could be seen to have significant positive clinical implications. Therefore, important clinical questions to be addressed in future clinical studies on dexmedetomidine should include the following: (1) Could sedation with dexmedetomidine decrease the incidence of delirium in the intensive care unit? (2) Could sedation with dexmedetomidine be restorative as natural sleep? (3) Could dexmedetomidine have an effect on the immune system as natural sleep has?

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