Neither Xenon nor Fentanyl Induces Neuroapoptosis in the Newborn Pig Brain

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ABSTRACT

Background: Some inhalation anesthetics increase apoptotic cell death in the developing brain. Xenon, an inhalation anesthetic, increases neuroprotection when combined with therapeutic hypothermia after hypoxic-ischemic brain injury in newborn animals. The authors, therefore, examined whether there was any neuroapoptotic effect of breathing 50% xenon with continuous fentanyl sedation for 24 h at normothermia or hypothermia on newborn pigs.

Methods: Twenty-six healthy pigs (<24-h old) were randomized into four groups: (1) 24 h of 50% inhaled xenon with fentanyl at hypothermia (Trec = 33.5°C), (2) 24 h of 50% inhaled xenon with fentanyl at normothermia (Trec = 38.5°C), (3) 24 h of fentanyl at normothermia, or (4) nonventilated juvenile controls at normothermia. Five additional nonrandomized pigs inhaled 2% isoflurane at normothermia for 24 h to verify any proapoptotic effect of inhalation anesthetics in our model. Pathological cells were morphologically assessed in cortex, putamen, hippocampus, thalamus, and white matter. To quantify the findings, immunostained cells (caspase-3 and terminal deoxynucleotidyl transferase–mediated deoxyuridine-triphosphate nick-end labeling) were counted in the same brain regions.

Results: For groups (1) to (4), the total number of apoptotic cells was less than 5 per brain region, representing normal developmental neuroapoptosis. After immunostaining and cell counting, regression analysis showed that neither 50% xenon with fentanyl nor fentanyl alone increased neuroapoptosis. Isoflurane caused on average a 5- to 10-fold increase of immunostained cells.

Conclusion: At normothermia or hypothermia, neither 24 h of inhaled 50% xenon with fentanyl sedation nor fentanyl alone induces neuroapoptosis in the neonatal pig brain. Breathing 2% isoflurane increases neuroapoptosis in neonatal pigs.

What We Already Know about This Topic

• Moderate hypothermia has proven clinical efficacy in protecting the brain against anoxic and ischemic injury
• Some inhalational anesthetics increase apoptotic cell death in the developing brain, whereas xenon enhances hypothermic neuroprotection in newborn rats and pigs
• The effects of xenon combined with opioids on hypothermic neuroprotection remain unknown

What This Article Tells Us That Is New

• By using a model of mechanically ventilated piglets in the absence of brain injury, the authors could show that neither 24 h of 50% inhaled xenon nor fentanyl, alone or in combination, induced apoptosis in the neonatal pig brain in normothermic or hypothermic conditions
• Isoflurane 2% was found to induce apoptosis in this experimental paradigm

RECLINICAL findings, indicating that common general anesthetic agents may trigger or induce neuronal apoptosis in the developing brain,1-3 have been the subject of much debate and have even been considered in a public hearing of the Anesthesia and Life Support Drugs Advisory Committee of the United States Food and Drug Administration (March 2007). However, species, age, and injury differences are major influencing factors. Programmed cell death plays a major role in normal brain development and synaptogenesis.4 Neuronal apoptosis is the major type of programmed cell death that occurs after exposure to general anesthetics in the newborn.3,5,6 There is a concern that anesthetics and sedative drugs may harm the immature brain by
increased neuroapoptosis.7–11 One important proapoptotic protease is caspase-3.5 It is positioned at the center of the apoptotic cascade and is activated by both the intrinsic and extrinsic pathways, leading to DNA fragmentation.12 Caspase-3 cleavage and activation occur in the pig brain after hypoxia and anesthetic exposure.6,13

Therapeutic hypothermia has been recommended by the international resuscitation guidelines (International Liaison Committee on Resuscitation 2010) for term newborns suffering from perinatal asphyxia.14 Clinical trials have shown that 3 days of therapeutic hypothermia is safe and reduces mortality and long-term neurodevelopmental disability in newborns with neonatal encephalopathy.15–18 The occurrence of death and severe disability is reduced from 66% to 50% in cooled infants, but there is evidence that neonates with the most severe forms of injury may not benefit from therapeutic hypothermia.15,16,18 Therefore, an additional neuroprotective treatment is needed.19

We and others have shown that the noble gas such as xenon enhances hypothemic neuroprotection in immature rats and pigs.20–23 Xenon is an inhalation anesthetic with sedative and analgesic effects and no documented clinical adverse effects. It exerts its neuroprotective properties mainly by partial inhibition of N-methyl-D-aspartate and other glutamate receptors.24–26 Other general anesthetics, which act as N-methyl-D-aspartate antagonists, have been shown to induce neuronal injury and cell death in the healthy newborn brain.2,5,27,28 Even though xenon is a very potent neuroprotective drug after experimental newborn hypoxic-ischemic injury, reports in neonatal rodents have shown contradictory effects of xenon administration on neuronal cell death.22,29

Because newborns undergoing intensive care treatment, not only during hypothermia after perinatal asphyxia but also during surgery and transport to theatre, receive opioids as background sedation and analgesia, it is very important to assess whether the combination of opioids with or without an anesthetic gas induces neuroapoptosis. Our aim was to examine whether xenon in combination with fentanyl or fentanyl alone or in combination with hypothermia treatment induces cell death in healthy newborn pigs at normal body temperature (38.5°C for pigs). As a control for the sensitivity of the model, we also needed to examine whether the newborn pig developed neuroapoptosis after exposure to isoflurane as seen convincingly in the immature rodent.30

**Material and Methods**

**Animals and Experimental Groups**

All experiments were conducted according to the United Kingdom Home Office license guidelines and were approved by the University of Bristol Ethical Review Panel (Bristol, United Kingdom). Thirty-one crossbred Landrace/Large White term-born pigs of either sex with a median (interquartile range) age of 11 h (8.5–13) and a median (interquartile range) weight of 1.67 kg (1.36–1.87) were used. Twenty-six animals were randomly assigned to the following treatments: (1) 24 h of 50% inhaled xenon with iv fentanyl sedation at hypothermia (rectal temperature 33.5°C, HTXFe), (2) normothermia (rectal temperature 38.5°C, NTXeFe) conditions, (3) nonventilated instrumented pigs with 24 h of iv fentanyl sedation at normothermia (NTFe, control sedation), or (4) nonventilated juvenile control pigs without any sedation at normothermia (NTCTR, juvenile control).

To verify the proapoptotic effect of inhalation anesthetics in this animal model, a nonrandomized group comprised five pigs was added afterwards and ventilated with 2.0% inhaled isoflurane at normothermia (NTIso; fig. 1).

**Animal Preparation, Baseline Data and Management of All Pigs**

The juvenile control group (group (4), n = 7) was not intubated and had no central lines inserted. Blood samples were taken by venepuncture. The remaining 24 animals underwent unrestrained induction in a closed plexiglas box with 2% isoflurane, 65% nitrous oxide, and 33% oxygen, followed by oral intubation with a 3.0-mm cuffed endotracheal tube (Mallinckrodt Medical, Athlone, Ireland). After intubation, animals were mechanically ventilated (SLE 2000; SLE, Surrey, United Kingdom) with 2% isoflurane, 77% nitrous oxide, and 21% oxygen until the end of the baseline period (≤90 min). Fentanyl infusion was started in groups (1) to (3). Transcutaneous arterial oxygen saturation (Nonin Medical, Plymouth, MN) and end-tidal carbon dioxide were monitored (Tidal Wave SP; Respironics Novametrix, Wallingford, CT), and ventilator settings were adjusted to maintain transcutaneous arterial oxygen saturation between 95 and 98% and the end-tidal carbon dioxide between 4.0 and 6.0 kPa. If required, the oxygen fraction in the gas mixture or ventilator settings was adjusted to keep transcutaneous arterial oxygen saturation and end-tidal carbon dioxide in the target range. After attaining iv access by cannulation of an ear vein, umbilical arterial and venous catheters were inserted to allow continuous monitoring of mean arterial blood pressure, blood sampling, and infusion of maintenance fluids and drugs. Blood sampling was undertaken at preset time points, as well as when clinically indicated. Blood gases (RapidLab 248 pH/blood gas analyzer; Siemens Healthcare Diagnostics, Surrey, United Kingdom), blood glucose (Optium; Medisense, Abingdon, United Kingdom), and lactate (Lactate Pro; Arkray, Kyoto, Japan) were measured. Intensive care management of the animals was performed as previously described.20 Pigs in groups (1), (2), and (5) received iv 5% dextrose and 0.45% saline to maintain a fluid intake of 10 ml·kg⁻¹·h⁻¹. Pigs in group (3) received iv 5% dextrose and 0.45% saline of 5 ml·kg⁻¹·h⁻¹, in addition to being bottle fed with pig formula (Pig formula milk “Baby Lactal”; Peter Möller A/S, Oslo, Norway) to a rate of 10 ml·kg⁻¹·h⁻¹. Pigs in group (4) were bottle fed every 2–3 h with pig formula and maintained a fluid intake of 10 ml·kg⁻¹·h⁻¹. Hypotension (mean arterial blood pressure <40 mmHg for ≥10 min) was first treated.
with two separate boluses of crystalloids (10 ml/kg, 0.9%, saline), followed by continuous dopamine infusion (5–20 µg·kg⁻¹·min⁻¹), which applied to one pig in group (1) and four pigs in group (5). Tracheal suction was performed every 8 h or as clinically indicated. Hence, pH, blood glucose, and lactate values were kept between 7.35 and 7.47 (analyzed at actual body temperature), 3.0 and 8 mM, and less than 3.5 mM, respectively (table 1).

### Table 1. Baseline Parameters for All Treatment Groups

<table>
<thead>
<tr>
<th></th>
<th>HTXeFe (n = 7)</th>
<th>NTXeFe (n = 6)</th>
<th>NTFe (Self Ventilating, n = 6)</th>
<th>NTCTR (Self Ventilating, n = 7)</th>
<th>NTIso (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median weight, kg (IQR)</td>
<td>1.42 (1.35–1.59)</td>
<td>1.73 (1.45–1.76)</td>
<td>1.75 (1.63–1.86)</td>
<td>1.36 (1.29–1.42)</td>
<td>1.90 (1.78–1.96)</td>
</tr>
<tr>
<td>Male</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Female</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Median age, h (IQR)</td>
<td>9 (6.5–19.5)</td>
<td>10 (8–14.2)</td>
<td>10 (9–11.7)</td>
<td>10 (9.5–11)</td>
<td>13 (11–13)</td>
</tr>
<tr>
<td>Median heart rate, min⁻¹ (IQR)</td>
<td>123 (108–126)</td>
<td>139 (131–146)</td>
<td>159 (153–164)</td>
<td>n/a</td>
<td>180 (161–188)</td>
</tr>
<tr>
<td>Median arterial blood pressure, mmHg (IQR)</td>
<td>49 (46.4–49.7)</td>
<td>49 (47.4–51.3)</td>
<td>53 (46.8–55)</td>
<td>n/a</td>
<td>44 (43.5–45)</td>
</tr>
<tr>
<td>Median tcSO2, % (IQR)</td>
<td>99 (98–99.5)</td>
<td>100 (99.3–100)</td>
<td>98 (97–99)</td>
<td>n/a</td>
<td>100 (97–100)</td>
</tr>
<tr>
<td>Median pH (IQR)</td>
<td>7.35 (7.34–7.36)</td>
<td>7.40 (7.36–7.44)</td>
<td>7.41 (7.38–7.45)</td>
<td>7.46 (7.42–7.50)</td>
<td>7.42 (7.38–7.46)</td>
</tr>
<tr>
<td>Median glucose, mM (IQR)</td>
<td>6.9 (5.6–7.9)</td>
<td>5.2 (4.5–5.9)</td>
<td>5.9 (5.4–6.1)</td>
<td>3.9 (3.4–4.3)</td>
<td>6.5 (5.3–7.1)</td>
</tr>
<tr>
<td>Median lactate, mM (IQR)</td>
<td>2.1 (1.5–3.0)</td>
<td>1.5 (1.3–1.7)</td>
<td>2.1 (1.4–3.1)</td>
<td>3.3 (2.9–3.5)</td>
<td>2.9 (2.8–3.5)</td>
</tr>
<tr>
<td>Median fentanyl dosage, µg·kg⁻¹·h⁻¹ (IQR)</td>
<td>55.0 (50–60)</td>
<td>50.0 (42.5–75.3)</td>
<td>17.5 (15–20)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Median (IQR) baseline parameters (weight, sex, and age), heart rate, arterial blood pressure, tcSO2, pH, blood glucose, and lactate levels of all the 31 animals in the different treatment groups and median fentanyl dosage for 19 pigs in the treatment groups receiving iv fentanyl. NTIso group was subsequently added to verify an apoptotic effect of inhalation anesthetics in newborn pigs. It was therefore not randomized and is separated by double border from the other groups.

HTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at hypothermia; IQR = interquartile range; iv = intravenous; NTCTR = juvenile controls at normothermia; NTFe = 24-h iv fentanyl at normothermia; NTIso = 24-h ventilation with isoflurane at normothermia; NTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at normothermia; TUNEL = terminal deoxynucleotidyl transferase–mediated deoxyuridine-triphosphate nick-end labeling.
Fentanyl Sedation and Xenon Inhalation

Fentanyl infusion was started immediately after intubation and iv access for groups (1), (2), and (3) with a bolus of 10 µg/kg followed by maintenance infusion. This iv sedation was adjusted to achieve adequate responsiveness for sedation. The median (interquartile range) fentanyl dosage was 55.0 µg·kg⁻¹·h⁻¹ (50.0–60.0) in group (1), 50.0 µg·kg⁻¹·h⁻¹ (42.5–75.3) in group (2), and 17.5 µg·kg⁻¹·h⁻¹ (15.0–20.0) in group (3). Pigs in group (3) were extubated after instrumentation under anesthesia to be self ventilating in air. Therefore group (3) received less iv fentanyl sedation than pigs in the ventilated treatment groups (1) and (2), who needed deeper sedation. Pigs in group (4) were always self ventilating and not sedated.

After experimental preparation, baseline physiological parameters were recorded for 60 min before the gas intervention was started. In groups (1) and (2), a xenon–oxygen–nitrogen mixture (50% Xe–30% O₂–20% N₂) was delivered using an automated version of a previously described closed-circuit delivery system for a period of 24 h.³¹ Xenon was maintained at a concentration of 50% throughout the whole 24 h.

Isoflurane Inhalation

Pigs in group (5) were ventilated for 24 h with 2% isoflurane and 21% oxygen–nitrogen, following the same experimental and monitoring protocol as pigs in groups (1) and (2). The isoflurane concentration was maintained throughout the whole 24 h at normothermia, providing adequate sedation for ventilation at normothermia, and therefore no fentanyl was added.

Neuropathology Assessment

After 24 h of allocated treatment, pigs were deeply anesthetized with isoflurane (after intubation in groups (3) and (4)). Brains were slowly flushed with 0.9% saline through the common carotid arteries followed by perfusion fixation with 10% neutral buffered formalin and dissected out. In addition, an autopsy of full body was performed. The right hemisphere of the brain was coronally cut into 5-mm blocks and paraffin processed. Two adjacent blocks were chosen, containing the cerebral cortex, subcortical white matter, hippocampus, basal ganglia (including putamen), and thalamus (fig. 2). In addition, two representative blocks of the cerebellum were chosen. Hematoxylin and eosin–stained sections were assessed at ×20 magnification by a neuropathologist blinded to the randomization and clinical details. Cells in the cerebral cortex grey matter, subcortical white matter, hippocampus, basal ganglia (including putamen), thalamus, and Purkinje neurons of the cerebellum were scored as apoptotic when showing typical morphology of apoptosis.⁵

For cerebral cortex, putamen, hippocampus, thalamus, white matter, and Purkinje neurons, apoptosis was assessed by examining two adjacent sections for positive staining of Cleaved caspase-3 (Cell Signalling Technologies, New England Biolabs, Hertfordshire, United Kingdom). To assess DNA fragmentation, the adjacent sections were stained with terminal deoxynucleotidyl transferase–mediated deoxyuridine-triphosphate (dUTP) nick-end labeling (Roche, Meylan, France).³² For immunohistochemical analysis, deparaffinized 5-µm thick sections were microwaved in 10-mM citrate buffer pH 6 at power 9 for 15 min before incubation in 3% H₂O₂ and methanol for 15 min, followed by 30-min incubation in 2.5% normal horse serum to block nonspecific staining. Sections were incubated overnight in monoclonal rabbit anti-caspase-3 antibody (1/500) at room temperature. After primary antibody incubation, sections were incubated in horse anti-rabbit biotinylated antibody (1/200) for 30 min, then ABC Elite (1/200; Vector Laboratories, Peterborough, United Kingdom) for 30 min. Diaminobenzidine-based peroxide substrate was used as a chromogen, and sections were lightly counterstained with Mayer’s Hematoxylin (Thermo Fisher Scientific, Runcorn, United Kingdom), dehydrated through graded alcohols to xylene, and then mounted using p-xylene-bis-pyridinium bromide. For each animal and each brain region, the two stained adjacent sections were counted for Cleaved caspase-3 and terminal deoxynucleotidyl transferase–mediated dUTP

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nicking positive cells at ×20 magnification. The complete hemispheric section was counted. For the right hemisphere of the cerebellum, Purkinje neurons of three complete gyri were counted for Cleaved caspase-3 and terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling positive cells at ×20 magnification.

Total cell counting was performed by three independent observers blinded to the randomization and to clinical details.

**Statistical Analysis**

Statistical analyses were performed with SPSS version 18 (SPSS Inc., Chicago, IL). The Wilcoxon test was used (two-tailed) for the two-group comparisons. One-way ANOVA was used to compare the results of cell counting, blood gases, blood sugar, and lactate levels within the different randomized treatment groups followed by a nonparametric post hoc test (Tukey–Kramer) if the ANOVA showed significant differences between treatment groups. Regression analysis was used to assess the effect of the independent variables such as total fentanyl dosage during the experiment, inhalation of xenon (yes or no), sex, cooling (yes or no), and age since birth in hours on the percentage of Cleaved caspase-3 and terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling positive cells in groups (1)–(4) for each of the five brain regions. A dummy code was used to include the categorical data (cooling and xenon) into the linear regression model. Statistical significance was considered at a probability (P) value of 0.05 or more on two-sided testing. Continuous variables were presented as median (interquartile range) or mean (±SD).

**Results**

**Physiological Data**

There was no significant difference in age (P = 0.700), weight (P = 0.055), and sex distribution (P = 0.475) among the treatment groups (table 1). There was a significantly lower dosage use of fentanyl in group (3) as compared with groups (1) and (2) (P < 0.001) because all the pigs in group (3) were self ventilating with normal PCO2 and therefore received less sedation (table 1). Table 1 summarizes the physiological parameters in the treatment groups for the 24-h duration of the experiment. Heart rate was significantly lower in the hypothermia group (P < 0.001), as expected because hypothermia reduces heart rate by 10 beats/1°C decrease in core temperature.33 Mean arterial blood pressure was higher than 40 mmHg in all pigs of all the five groups throughout the 24-h treatment period, providing an adequate cerebral blood flow in newborn pigs.34-37

Blood gases, blood sugar, and lactate values were within the normal range in all animals, and there were no significant differences among the four groups with regard to blood gases over the whole 24-h study time (P > 0.05; table 1).

**Histological Results**

Hematoxylin and eosin–stained sections did not show significant signs of brain pathology in the regions examined in treatment groups (1) to (4). No necrotic cells were seen, and apoptotic cells were analyzed based on morphological assessment in the hematoxylin and eosin–stained sections. For each individual brain region, the maximum number of apoptotic cells within one hemisphere was not different between groups (1) and (4) and not more than five cells representing normal developmental programmed cell death in a newborn pig brain.38 In Purkinje cells of the cerebellum, no apoptotic cell was seen.

Pigs in group (5) showed a large increase in apoptotic cells compared with other treatment groups for all assessed hematoxylin and eosin–stained brain regions, indicating isoflurane-induced neurotoxicity. To quantify this finding, Cleaved caspase-3 and terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling positive cells were counted in all assessed brain regions (tables 2 and 3 and figs. 3 and 4). The number of Cleaved caspase-3–positive cells for each treatment group and each counted brain area are presented in figure 3 and table 2. No positive immuno-stained cells were found in the Purkinje cell layer for any treatment group. One-way ANOVA showed a significant difference in Cleaved caspase-3–positive cells (P < 0.05). Post hoc analysis (Tukey–Kramer) showed that the NTIso group had a significant increase in Cleaved caspase-3–positive cells.

**Table 2.** Cleaved Caspase-3 Cell-counting Results

<table>
<thead>
<tr>
<th></th>
<th>N Cortex</th>
<th>Putamen</th>
<th>Hippocampus</th>
<th>Thalamus</th>
<th>White Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTXeFe</td>
<td>7</td>
<td>4.00 (1.83–10.50)</td>
<td>0.00 (0.00–0.50)</td>
<td>0.33 (0.17–0.50)</td>
<td>2.50 (2.00–4.67)</td>
</tr>
<tr>
<td>NTXeFe</td>
<td>6</td>
<td>3.83 (0.96–7.54)</td>
<td>0.08 (0.00–0.49)</td>
<td>0.00 (0.00–0.21)</td>
<td>1.08 (0.62–1.83)</td>
</tr>
<tr>
<td>NTFe</td>
<td>6</td>
<td>1.42 (0.95–1.83)</td>
<td>0.00 (0.00–0.12)</td>
<td>0.08 (0.00–0.45)</td>
<td>1.08 (0.41–2.33)</td>
</tr>
<tr>
<td>NTCTR</td>
<td>7</td>
<td>1.33 (0.67–1.50)</td>
<td>0.17 (0.00–0.17)</td>
<td>0.00 (0.00–0.33)</td>
<td>1.50 (0.50–2.00)</td>
</tr>
<tr>
<td>NTIso</td>
<td>5</td>
<td>78.00 (37.50–226)</td>
<td>0.25 (0.00–0.87)</td>
<td>0.75 (0.37–1.12)</td>
<td>1.50 (0.62–6.25)</td>
</tr>
</tbody>
</table>

Total cell count for each brain region in one hemisphere for Cleaved caspase-3–positive cells. Results are presented as median (interquartile range) number of Cleaved caspase-3–positive cells. There was a significant increase in Cleaved caspase-3–positive cells in the NTIso group for cortex (P < 0.001), hippocampus (P = 0.005), and white matter (P = 0.010) in the two-group comparison with the other treatment groups. The NTIso group was subsequently added and is separated from the other groups.

HTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at hypothermia; iv = intravenous; NTCTR = juvenile controls at normothermia; NTFe = 24-h iv fentanyl at normothermia; NTIso = 24-h ventilation with isoflurane at normothermia; NTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at normothermia.
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Fig. 3. Mean number of Cleaved caspase-3-positive cells (+SD) per counted brain region. There was a significant increase in Cleaved caspase-3-positive cells in the NTIso group (positive control group) in cortex ($P < 0.001$), hippocampus ($P < 0.001$), and white matter ($P = 0.005$), and for all brain regions in the two-group comparison with the other treatment groups ($P < 0.001$). Asterisks indicate a significance level of $P < 0.05$. HTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at normothermia; NTCTR = juvenile controls at normothermia; NTFe = 24-h iv fentanyl at normothermia; NTIso = 24-h ventilation with isoflurane at normothermia; NTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at normothermia; TUNEL = terminal deoxynucleotidyl transferase-mediated deoxyuridine-triphosphate nick-end labelling.

Table 3. TUNEL Cell-counting Results

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Cortex</th>
<th>Putamen</th>
<th>Hippocampus</th>
<th>Thalamus</th>
<th>White Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTXeFe</td>
<td>7</td>
<td>27.50 (21.75–34.50)</td>
<td>0.75 (0.50–2.00)</td>
<td>1.00 (0.50–1.75)</td>
<td>6.00 (4.00–9.00)</td>
<td>14.25 (13.75–15.75)</td>
</tr>
<tr>
<td>NTXeFe</td>
<td>6</td>
<td>14.88 (7.95–30.06)</td>
<td>0.46 (0.00–1.12)</td>
<td>0.38 (0.00–0.81)</td>
<td>2.88 (1.45–6.87)</td>
<td>5.88 (4.39–6.75)</td>
</tr>
<tr>
<td>NTFe</td>
<td>6</td>
<td>13.38 (10.20–20.00)</td>
<td>0.25 (0.18–0.81)</td>
<td>1.08 (0.75–1.50)</td>
<td>6.75 (5.06–10.00)</td>
<td>9.50 (5.94–13.68)</td>
</tr>
<tr>
<td>NTCTR</td>
<td>7</td>
<td>9.00 (7.00–18.17)</td>
<td>0.00 (0.00–1.33)</td>
<td>1.00 (0.75–1.50)</td>
<td>6.67 (4.50–10.83)</td>
<td>7.50 (4.67–10.50)</td>
</tr>
<tr>
<td>NTIso</td>
<td>5</td>
<td>183.00 (124.12–223.00)</td>
<td>11.25 (4.87–28.37)</td>
<td>5.00 (4.00–8.50)</td>
<td>36.25 (24.75–59.37)</td>
<td>32.50 (19.75–68.25)</td>
</tr>
</tbody>
</table>

Total cell count for each brain region in one hemisphere for TUNEL-positive cells. Results are presented as median number (interquartile range) of TUNEL-positive cells. There was a significant increase in TUNEL-positive cells in the NTIso group for all brain regions in the two-group comparison with the other treatment groups (cortex [$P < 0.001$], putamen [$P = 0.003$], hippocampus [$P < 0.001$], thalamus [$P < 0.001$], and white matter [$P = 0.001$]). The NTIso group was subsequently added and is separated from the other groups. HTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at normothermia; iv = intravenous; NTCTR = juvenile controls at normothermia; NTFe = 24-h iv fentanyl at normothermia; NTIso = 24-h ventilation with isoflurane at normothermia; NTXeFe = 24-h ventilation with 50% xenon and iv fentanyl at normothermia; TUNEL = terminal deoxynucleotidyl transferase-mediated deoxyuridine-triphosphate nick-end labelling.
in the cortex \((P < 0.001)\), the hippocampus \((P = 0.005)\), and the white matter \((P = 0.010)\). In addition, there was a significant difference in the one-way ANOVA for terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling positive cells, and post hoc analysis (Tukey–Kramer) showed that animals breathing isoflurane for 24 h had a significant increase in terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling positive cells in all assessed brain regions (cortex \([P < 0.001]\), putamen \([P = 0.003]\), hippocampus \([P < 0.001]\), thalamus \([P < 0.001]\), and white matter \([P = 0.001]\); fig. 4 and table 3). For both immunostaining methods, the percentage of injured cells in all treatment groups except group (5) was less than 0.1%, representing the normal developmental level in a newborn pig brain.38

We compared the number of apoptotic cells in each of the five brain regions within the four different treatment groups, except the positive control group which was not randomized, in a multivariate regression model. The results from all the ten regressions showed that there were no indications of any effect neither of fentanyl, of 24-h ventilation with 50% xenon, nor of sex on apoptosis. There was a slight indication that being cooled as well as being very young increased the number of caspase-3–positive cells, but if corrected for multiple testing only 3 of the 20 regression coefficients for cooling and age were statistically significant at the 5% level.

Figure 5 shows representative pictures of apoptotic cells (hematoxylin and eosin, Cleaved caspase-3, and terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling) from different brain regions and different treatment groups.

**Discussion**

This study showed that neither breathing 50% xenon combined with iv fentanyl nor fentanyl sedation alone for 24 h...
Fig. 5. Photomicrographs showing regional histopathological (A–D) and immunohistochemical (E–F) features. Hematoxylin and eosin–stained pictures from cerebral cortex (A1 to A2), CA4 area in the hippocampus (B1 to B2), putamen (C1 to C2), and pons (D1 to D2). Cleaved caspase-3–stained pictures (E1 to E2) and TUNEL-stained pictures (F1 to F2) from cerebral cortex. G1 shows a representative cortex from a juvenile control pig and G2 a representative cortex of our positive control group. Arrows in A–D and G point to apoptotic neurons with homogenous eosinophilic cytoplasm and pyknotic nuclei. Arrows in E to F point to Cleaved caspase-3 and TUNEL-positive cells. A scale bar for each picture is shown in the lower right. TUNEL = terminal deoxynucleotidyl transferase–mediated deoxyuridine-triphosphate nick-end labeling.
induces neuroapoptosis in newborn pig brains. In addition, we showed that the newborn pig is a feasible animal model to examine anesthesia-induced neurotoxicity, and also that 24-h ventilation with 2% isoflurane induced a large increase in apoptosis.

The effect of anesthetics on the newborn brain is of major clinical and research interest. The most commonly used anesthetic drugs have been shown to induce apoptosis particularly in the newborn brain.28 In perinatal hypoxic-ischemic brain injury, cell death by necrosis and apoptosis is predominantly caused by cellular energy failure.39,40 In contrast, anesthesia-induced neuronal cell death seems to be apoptotic and involves several caspase-dependent pathways.30 Caspase-3 activation, by the intrinsic mitochondria-dependent pathway or extrinsic by death-receptor activation or neurotrophic factor activation, results in DNA fragmentation and apoptosis.41 Anesthetic drugs mainly trigger apoptosis by acting as $N$-methyl-$d$-aspartate receptor antagonists and/or $\gamma$-aminobutyric acid receptor agonists. Ikonomidou et al.42 first reported that MK-801 and Ketamine, both are potent $N$-methyl-$d$-aspartate receptor antagonists, lead to widespread apoptotic neurodegeneration in the developing rat brain. This has also been shown by many other groups in the following years in newborn mammalian models.6,32 Xenon mainly acts by the inhibition of the $N$-methyl-$d$-aspartate receptor,43 and unlike other $N$-methyl-$d$-aspartate receptor antagonists, xenon does not induce neuroapoptosis, but instead is exceptionally neuroprotective.21,23 As reported by Ma et al.,22 xenon protects against isoflurane-induced neuroapoptosis.

Fig. 5. (Continued)
but does not induce neuroapoptosis itself in P7 rat pups. In contrast, Cattano et al. reported that xenon has paradoxical properties triggering apoptosis when administered alone, whereas being neuroprotective when administered in combination with isoflurane in P7 mice.

When assessing the neuroapoptotic effect of anesthetics, it is very important that the dosages tested in animal research are comparable with that used in humans. It is also important to use the same additional drugs such as opiates or type of inotropes in the design. In addition, one of the major complicating factors is the variation in brain maturation between animal species. In the past, it has been feasible to examine brain development and synaptogenesis in different animal species. Rodents, brain development occurs mostly postnatally, whereas in pigs and humans brain development occurs both before and after birth. Rizzi et al. assessed whether vulnerability to anesthesia neurotoxicity depends on when synaptogenesis occurs. They found that the most important determinant seems to be the timing of the exposure to anesthesia relative to the time point in synaptogenesis. They stated that the brain regions that are at the peak of synaptogenesis are most vulnerable, but that the precise timing of regional brain development and the exact peak of synaptogenesis for each brain region have not been well established.

In our study, we focused on the potential neuroapoptotic effect of xenon on a newborn pig brain, which has been shown to be comparable in maturation with a term newborn brain. Compared with rodents, there is not much evidence for anesthesia-induced neurotoxicity in the newborn pig brain. Rizzi et al. found a significant increase in caspase-3–positive cells in 5-day-old pigs, after 4 h of breathing 0.55% isoflurane with 75% nitrous oxide. Schubert et al. found a significant increase in terminal deoxynucleotidyl transferase–mediated 5′-bromodeoxyuridine labeling positive cells in growth-restricted newborn pigs breathing 2% isoflurane for 24 h. We chose 2% isoflurane, as we have previously shown that this is corresponding to 1 minimum alveolar concentration in newborn pigs. Median arterial blood pressure was higher than 40 mmHg in all pigs of all the five groups throughout the 24-h treatment period, providing an adequate cerebral blood flow in newborn pigs.

We also found that lactate values did not differ among the treatment groups, indicating an adequate organ perfusion.

Our findings validated the newborn pig as a feasible animal model to examine anesthesia-induced neurotoxicity. However, the duration of isoflurane exposure might also play an important role, as pigs in groups (1) to (3) were also exposed to 2% isoflurane during preparation and baseline data recording. The absolute number of Cleaved caspase-3 and terminal deoxynucleotidyl transferase–mediated 5′-bromodeoxyuridine nick-end–labeling positive cells among the treatment groups was very low in individual regions. By counting the whole hemisphere of every brain in all the treatment groups, we were able to quantify the number of Cleaved caspase-3 and terminal deoxynucleotidyl transferase–mediated 5′-bromodeoxyuridine nick-end–labeling positive cells in different brain regions. It is important to recognize that apoptotic cell death is a normal and necessary phenomenon in developing mammalian brains. The high maturational number of neurons seen during fetal and early neonatal life is reduced to normal values by apoptosis, leading to the elimination of surplus neurons. This phenomenon mostly occurs antenatally. This process establishes the normal structure of the central nervous system, and disruption of the physiological apoptotic cell death mechanism may lead to abnormal brain development. As stated by Istaphanous and Loepke, it remains unclear whether anesthetics accelerate apoptosis of cells destined to die by this physiological apoptosis, or whether it induces apoptosis of cells not otherwise destined to die.

We found that the number of apoptotic cells was somewhat increased if the pigs were cooled. This effect of cooling might represent cellular stress induced by hypothermia. As shown before, stress induced by awake hypothermia counteracts with its neuroprotective effect. As the pigs in our study did not have a hypoxic-ischemic insult and were only sedated, not fully anesthetized, it suggests that hypothermia by itself might be stressful, inducing apoptosis.

Xenon is a rare and expensive gas, not often used in clinical practice even though it was introduced in anesthesia more...
than 60 yr ago. We have previously published our closed-circuit recycling neonatal xenon delivery system that has been shown to decrease the cost of xenon usage and makes xenon applicable for clinical use even for long periods. We and others have previously shown that xenon is neuroprotective after hypoxic-ischemic injury, and we found that xenon adds equal neuroprotection to hypothermia.

These findings have led to the recent clinical investigation of xenon as an add-on treatment for newborns suffering from hypoxic-ischemic encephalopathy being treated with therapeutic hypothermia to reduce brain injury. We have carried out the first human clinical feasibility study and showed that breathing 50% xenon while being cooled is practical without significant side effects in newborns after perinatal asphyxia.††

In our current study, all the treatment groups received additional sedation with fentanyl. This was to reduce stress in the animals, to mimic the clinical scenario of therapeutic hypothermia, and to show any proapoptotic interaction between xenon and a background opioid sedation. Morphine is the first-line opioid used to achieve stress reduction in cooled newborns. However, in our previous studies, we did not achieve an adequate sedative effect with morphine in pigs. For this reason, fentanyl was used in the current and previous studies. The dosage used to achieve a sedative effect in healthy pigs is much higher than that used in newborns, and even with a dose ten times the human dose, we did not see increased apoptosis neither when given alone nor in combination with xenon.

There are some limitations to our study. First, the article reporting the potency of xenon to trigger apoptosis used a xenon concentration of 70% for 4 h in 7-day-old mice. We selected a xenon concentration of 50% administered for 24 h to healthy newborn pigs, as in all our previous neuroprotection work because 50% is the highest clinically practical fraction to administer because it allows the option of moderately increasing the oxygen fraction in those neonates who require this. One could argue that our xenon concentration was too low to increase apoptosis. However, it was applied for 24 h. The 7-day-old mouse is surely more immature than the newborn pig; however, neurogenesis is complete in both species. Second, even though median arterial blood pressure was kept above 40 mmHg during the 24-h treatment period, hypotension might be a confounding factor for increased neuroapoptosis. As our study was performed in healthy newborn pigs and not after hypoxia-ischemia, we found that lactate values did not differ among the treatment groups. However, we did not perform a dose-time-response for each pig at each time point, as this was not feasible. Low blood pressure indicates reduced cerebral blood flow which might result in increased neuroapoptosis.

In conclusion, our study shows that neither breathing 50% xenon combined with iv fentanyl nor high- or low-dose fentanyl alone induce neuroapoptosis when administered for 24 h in healthy newborn pigs. As the combination of xenon and therapeutic hypothermia is feasible in newborns suffering from hypoxic-ischemic encephalopathy and has shown additional neuroprotection in preclinical studies, this study supports the implementation of a clinical neonatal neuroprotection trial and may have implications for the choice of anesthesia in the developing brain.

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