Volatile Anesthetics Inhibit Calcitonin Gene-Related Peptide Receptor-Mediated Responses in Pithed Rats and Human Neuroblastoma Cells

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Received May 25, 2004; accepted August 5, 2004

ABSTRACT
Calcitonin gene-related peptide (CGRP) has a potent vasodilatory effect that is mediated by specific receptors predominantly coupled to the activation of adenylate cyclase. The effects of volatile anesthetics on CGRP-induced vasodilation are unclear. We studied the effects of sevoflurane and isoflurane on CGRP-induced vasodilation in pithed rats and CGRP receptor-mediated responses in SK-N-MC cells, which are used as a model system to study the CGRP receptor and its downstream pathways. Male Wistar rats were pithed by inserting a stainless steel rod into the spinal cord. Mean arterial pressure (MAP) and cardiac output were maintained at approximately 100 mm Hg and 50 ml·min⁻¹, respectively, with continuous infusion of noradrenaline. After 30 min of inhalation of anesthetics, CGRP (0.1, 0.3, 1.0, and 3.0 μg/kg) was administered intravenously. In SK-N-MC cells, CGRP-, forskolin-, or cholera toxin-induced cAMP production was measured with or without anesthetics using radioimmunoassays. CGRP receptor binding density and affinity for the agonist were determined with (2-[^125I]iodohistidiny1) CGRP with or without the anesthetics. Sevoflurane (4%) and isoflurane (2%) significantly inhibited cholera toxin-induced cAMP production. Both anesthetics did not affect ligand binding. These data suggest that sevoflurane and isoflurane inhibit CGRP-induced vasodilation at the site between the CGRP receptor and adenylate cyclase activation. The inhibitory site of volatile anesthetics on the CGRP receptor-mediated response involves Gα protein.

Peripheral vascular tone is maintained primarily by noradrenaline released from sympathetic adrenergic nerve terminals. Nonadrenergic nerves also directly innervate regional vascular beds, and nonadrenergic vasodilation occurs in many species (Bevan and Brayden, 1987). Perivascular nerve stimulation in mesenteric vascular beds induces neurogenic vasodilation; this effect is mediated by nonadrenergic, noncholinergic (NANC) nerves (Kawasaki et al., 1988). Primary afferent neurons, originating from the dorsal root ganglia, provide a perivascular network of fibers around the arterial system throughout the body. Stimulation of these fibers causes NANC vasodilation via the release of calcitonin gene-related peptide (CGRP) (Bell and McDermott, 1996).

CGRP is a 37-amino acid peptide that is generated by alternative RNA splicing processes during calcitonin gene expression in rat and human tissues (Bell and McDermott, 1996). CGRP binds to a specific cell surface receptor, a seven-transmembrane domain receptor protein that belongs to a subgroup of the G protein-coupled receptor family (McLatchie et al., 1998). The receptor is primarily coupled to the activation of adenylate cyclase, which produces cAMP, leading to smooth muscle relaxation (Bell and McDermott, 1996). CGRP is widely distributed in perivascular nerves throughout the cardiovascular system. It has a potent vasodilatory effect and positive inotropic and chronotropic effects in rat and human (Bell and McDermott, 1996). Intravenous administration of CGRP causes a significant decrease in the mean arterial blood pressure (MAP), total peripheral resistance, and sustained tachycardia in rats and humans (Bell and McDermott, 1996). CGRP is implicated in the regulation of circulatory homeostasis and pathophysiology of various diseases. For example, CGRP is known as a potent vasodilator in brain vessels and has been implicated in the pathogenesis of migraines (Moreno et al., 2002). Increased plasma

ABBREVIATIONS: NANC, nonadrenergic, noncholinergic; CGRP, calcitonin gene-related peptide; CO, cardiac output; GTPγS, guanosine 5’-O-(3-thio)triphosphate; GPCR, G protein-coupled receptor; IBMX, 3-isobutyl-1-methylxanthine; MAP, mean arterial pressure; MEM, minimal essential medium; SVR, systemic vascular resistance.
levels of CGRP have been demonstrated in endotoxemia, congestive heart failure (Bell and McDermott, 1996), hepatic cirrhosis (Henriksen et al., 2000), and during cardio-pulmonary bypass (Terazawa et al., 2003). The development of autonomic dysfunction in a mouse model of spinal cord injury is associated with sprouting of CGRP fibers (Jacob et al., 2001). These data suggest that CGRP is responsible for the hemodynamic alterations in these disorders. Because general anesthetics are often used for patients with such disorders, it is important to elucidate the effects of general anesthetics on the CGRP-induced hemodynamic response for better hemodynamic management of complicated patients.

The pithed rat model is used to investigate cardiovascular responses mediated by autonomic outflow from the spinal cord in vivo (Gillespie and Muir, 1967). In pithed animals, there is no intrinsic sympathetic nerve activity or centrally mediated compensatory reflex (Gray et al., 1990). The depressor response during spinal cord stimulation in the pithed rat is attributed to endogenous CGRP released from CGRP-containing nerves (Taguchi et al., 1992). Volatile anesthetics inhibit NANC depressor responses through inhibition of the CGRP depressor effect, not through inhibition of CGRP release after NANC nerve stimulation in the pithed rat model (Yoshikawa et al., 2003), suggesting that volatile anesthetics inhibit vascular responses to CGRP. Anesthetic actions on cardiac output (CO), systemic vascular resistance (SVR), and CGRP receptor-mediated cellular responses, however, have not yet been studied.

The purpose of the present study was to investigate the effects of volatile anesthetics on 1) CGRP-induced vasodilation by evaluating the changes in hemodynamic parameters, including MAP, CO, and SVR in vivo, and 2) the CGRP receptor-mediated signal transduction pathway in vitro. In the in vivo study, we used a pithed rat model to evaluate the direct vascular effect of drugs without interference of centrally mediated circulatory reflexes. In the in vitro study, we used SK-N-MC human neuroblastoma cells as a model system to study the CGRP receptor and its downstream pathways (Van Valen et al., 1990; Muff et al., 1992; Poyner et al., 1998; Choksi et al., 2002).

Materials and Methods

Animal Preparation

All surgical procedures and experimental protocols were approved by the Gunma University Institutional Animal Care and Use Committee. Surgical procedures were performed as described previously (Shiga and Yoshikawa, 1995; Yoshikawa et al., 1998; 2003). Male Wistar rats weighing 300 to 360 g were anesthetized with isoflurane in oxygen. The animals were ventilated artificially using a Harvard respirator (Harvard Apparatus Inc., Holliston, MA) via a tracheal cannula at a rate of 50 to 60 breaths·min⁻¹ with a stroke volume of 1 ml·100 g b.wt.⁻¹. Respiration rate was adjusted to maintain a PaCO₂ of 35 to 40 mm Hg. A polyethylene (PE-50) catheter was inserted into the right jugular vein for the administration of CGRP. Body temperature was maintained between 36° and 37°C using a heated blanket placed beneath the animal and controlled by a rectal thermistor probe (CMA/150; CMA/Microdialysis, Solna, Sweden).

Experimental Measurements

MAP was recorded with a Gould (Cleveland, OH) pressure transducer connected to the left carotid artery via a PE-50 catheter. Aortic blood flow was measured using a volume flowmeter (Transonic Systems Inc.). CO and SVR were normalized by the body weight using the following formula: CO = ml·min⁻¹·kg b.wt.⁻¹ and SVR (mm Hg·min⁻¹·mg b.wt.⁻¹) = MAP/CO. SVR was determined when MAP and CO reached their minimal values.

Cell Culture

The SK-N-MC cell line was obtained from the American Type Culture Collection (Manassas, VA). The cells were grown in minimal essential medium (MEM) supplemented with 10% fetal bovine serum, 2 mM l-glutamine, 0.1 mM nonessential amino acids, 1 mM sodium pyruvate, 100 U/ml penicillin, and 100 μg/ml streptomycin at 37°C, 95% humidity, and 5% CO2. For cAMP assays, the cells were seeded on 100-mm culture dishes and grown to confluence. For binding studies, the cells were seeded on 24-well plates at a density of approximately 5 × 10⁴ cells/well and grown to confluence.

Assay of cAMP Production

Equilibration with Volatile Anesthetics. Preincubation with volatile anesthetics was performed as described by Sill et al. (1993) with minor modifications. Serum-free MEM without cells at 37°C (4 ml) was aerated in semiclosed glass vials (5 ml) for 20 min with 95% O₂ and 5% CO₂ gas mixture at 50 ml/min to which volatile anesthetic was added using a calibrated anesthetic vaporizer. After a 20-min equilibration with anesthetics, the gas mixture containing an appropriate concentration of anesthetic was passed continuously over the medium to minimize the loss of anesthetic. The cells (5 × 10⁶ cells/ml) were gently added to the medium at 37°C and preincubated with anesthetic for 20 min before the addition of CGRP or forskolin, a direct adenylate cyclase activator, or cholera toxin, a G protein activator. Gas chromatographic analysis (GC-7A; Shimadzu, Kyoto, Japan) of the media at the end of the protocol indicated that exposure to 1% (v/v) sevoflurane, 3% sevoflurane, 4% sevoflurane, 0.5% isoflurane, 1% isoflurane, and 2% isoflurane corresponded to actual concentrations of 0.969 ± 0.116, 2.181 ± 0.211, 3.991 ± 0.119, 0.482 ± 0.015, 1.086 ± 0.154, and 1.978 ± 0.155% (v/v), respectively. Cell suspension for control experiments was prepared in the same manner but without anesthetics.

Measurement of cAMP. Suspensions of SK-N-MC cells were used for determining cAMP production. Incubation was terminated by adding 400 μl of 1 N HCl to a 4-ml cell suspension and strong vortexing at the end of each exposure protocol. The mixture was frozen quickly in liquid nitrogen and stored at −70°C until cAMP determination. After thawing, the cell debris in the mixture was pelleted by centrifugation (13,000g for 10 min at 4°C), and the supernatant was transferred to a test tube for the cAMP assay. A cAMP 125I-radioimmunoassay kit (YAMASA Corporation, Choshi, Japan) was used to determine the cAMP levels. All assay procedures were performed according to the manufacturer’s instructions. Data were normalized for protein content using Bradford’s method (Bradford, 1976).

Binding Studies

Equilibration with Volatile Anesthetics. Binding studies were performed at 37°C in an air-tight glass chamber (50 liters) under a continuous flow of a 95% O₂ and 5% CO₂ gas mixture at 3 liters/min, supplemented with 4% sevoflurane or 2% isoflurane using a cali-
brated anesthetic vaporizer. The anesthetic concentrations in the chamber were monitored continuously with a calibrated gas analyzer (Capnomac Ultima; Datex-Ohmeda, Helsinki, Finland). Eagle’s MEM was equilibrated by continuous bubbling with the corresponding concentration of anesthetic for 20 min at 37°C in semiclosed glass vials. Following the preparation, a gas mixture containing the anesthetic was passed over the medium to minimize the loss of anesthetic. Then 1% bovine serum albumin was added to the medium and incubated with anesthetic for 30 min at 37°C. The solution equilibrated with anesthetic was used as the binding buffer. The incubation volume was estimated without anesthetic. Then 1% bovine serum albumin was added to the buffer measured by gas chromatography (GC-7A). Control experiments were performed in the same manner without anesthetic.

Analysis of Binding Data. Saturation binding studies were performed using (2-125I)iodohystidyl(10) CGRP (2000 Ci/mmol; Amer-sham Biosciences, Ltd., Little Chalfont, Buckinghamshire, UK) at concentrations ranging from 5 to 200 pM per well in the absence (total binding) or presence (nonspecific binding) of excessive unla-beled human aCGRP (1 μM) (Peptide Institute, Inc., Osaka, Japan). Specific binding was determined as the difference of total binding and nonspecific binding. Scatchard analysis was used to determine receptor density (B_max) and the ligand dissociation constant (K_d) (Scatchard, 1949).

Experimental Protocols

Protocol 1: The Effects of Volatile Anesthetics on Hemody-namic Changes Induced by CGRP in Pithed Rat. Pithed rats were allowed to stabilize for 30 min before any experimental intervention. MAP and CO were measured at approximately 100 mm Hg and 50 ml · min⁻¹· kg⁻¹ by continuous infusion of norepinephrine (2 to 3 μg · kg⁻¹ · min⁻¹) throughout the protocol. Rats were randomly assigned to anesthetic groups (n = 7) and received isoflurane, sevoflurane, or sham treatment for 1 min after pithing. Concentrations of inspired anesthetics were administered after the observation period to avoid the effects of anesthetic. In the sham group, 1% bovine serum albumin was added to the buffer administered for 30 min after pithing. Cell suspensions were incubated with anesthetic for 30 min at 37°C. Then 1% bovine serum albumin was added to the buffer measured by gas chromatography (GC-7A). Control experiments were performed in the same manner without anesthetic.

Results

The Effects of Volatile Anesthetics on CGRP-Induced Hemodynamic Changes in Pithed Rats. Baseline values of hemodynamic parameters and the infusion rates of norepinephrine before the administration of CGRP at 0.1 μg/kg in control group were as follows: MAP = 109.0 ± 4.6 mm Hg, CO = 154.1 ± 6.3 ml · min⁻¹ · kg⁻¹, SVR = 0.709 ± 0.05 mm Hg · ml⁻¹ · min⁻¹ · kg⁻¹, and norepinephrine = 2.2 ± 0.9 μg · kg⁻¹ · min⁻¹, respectively. There was no significant difference in these data among groups (data not shown). Consistent with our previous reports, intravenously administered CGRP induced a transient increase in MAP followed by a persistent decrease. MAP and CO changed similarly. MAP and CO maximally increased immediately after injection of CGRP and reached the minimal value approximately 1 min after injection of CGRP. SVR also decreased 1 min after administration of CGRP. Injection of saline had no effect.

The effects of sevoflurane on CGRP-induced changes of the hemodynamic parameters are shown in Fig. 1. Sevoflurane significantly inhibited CGRP-induced decreases in MAP (p < 0.01, n = 7). On the other hand, CGRP induced a dose-dependent decrease in MAP, CO, and SVR. Sevoflurane concentration dependently inhibited the CGRP-induced decrease in MAP and SVR (p < 0.05, n = 7). The decrease in CO did not differ significantly among groups. Heart rate did not change significantly after administration of CGRP in either group. Isoflurane also inhibited CGRP-induced increases in MAP (p < 0.05, n = 7) and dose-dependently inhibited CGRP-induced decreases in MAP and SVR (p < 0.05, n = 7). Without effects on CO reduction and HR (data not shown)

The Effects of Volatile Anesthetics on CGRP-, Fors-kolin-, or Cholera Toxin-Induced cAMP Production in SK-N-MC Cells. Sevoflurane did not alter basal cAMP accumulation (Fig. 2A). The effect of sevoflurane on CGRP-induced cAMP production is shown in Fig. 2B. CGRP (10⁻⁷ M) increased cAMP production in SK-N-MC cells (fold increase over basal). Preincubation of cells with sevoflurane concentration dependently inhibited CGRP-induced cAMP production. Sevoflurane (4%) significantly inhibited CGRP-induced cAMP production to 35% of no anesthetic (p < 0.01, n = 6). Forskolin (10⁻⁶ M) increased cAMP production in SK-N-MC cells (20-fold increase over basal). Preincubation of cells with sevoflurane concentration dependently inhibited CGRP-induced cAMP production. Sevoflurane (4%) significantly inhibited CGRP-induced cAMP production to 35% of no anesthetic (p < 0.01, n = 6) or to 27% (p < 0.01,
n = 6), respectively, whereas preincubation with isoflurane did not alter forskolin-induced cAMP production (data not shown).

The effects of sevoflurane on time-dependent cholera toxin-induced cAMP production in SK-N-MC cells were shown in Fig. 3 (inset). After a lag of 15 min, cholera toxin (10^{-9} M) exhibited time-dependent increases in cAMP production in each group. Sevoflurane (4%) significantly inhibited cholera toxin-induced cAMP production at 90 and 120 min (Fig. 3 (inset); p < 0.05, n = 6). Dose dependence of sevoflurane on cholera toxin-induced cAMP production was shown in Fig. 3. Sevoflurane did not affect basal cAMP production (data not shown). Cholera toxin (10^{-9} M) increased cAMP production in SK-N-MC cells (30-fold increase over basal). Sevoflurane dose dependently inhibited cholera toxin-induced cAMP production. Sevoflurane (4%) significantly inhibited cholera toxin-induced cAMP production to 70% of no anesthetic (p < 0.05, n = 6). Isoflurane dose dependently inhibited cholera toxin-induced cAMP production. Although isoflurane (2%) did not significantly inhibit cholera toxin-induced cAMP production (83% of no anesthetic; p = 0.10), isoflurane (4%) significantly inhibited it to 58% of no anesthetic (p < 0.01, n = 6).

Radioligand Binding Studies. Specific binding of 125I-CGRP to SK-N-MC cells was saturable with increasing concentration of 125I-CGRP (5–200 pM). The receptor density (B_{max}) and the ligand dissociation constant (K_d) calculated from plots according to the method of Scatchard are shown in Table 1. There was no significant difference in B_{max} and K_d among groups. Preincubation with 4% sevoflurane did not affect CGRP receptor density and affinity. Isoflurane (2%) had no effect on B_{max} and K_d when compared with no anesthetic and sevoflurane.

Discussion

The major findings of the present study are summarized below. Sevoflurane and isoflurane, at clinically relevant concentrations, dose dependently inhibited the CGRP-induced increase in MAP and the decrease in MAP and SVR in pithed rats. Sevoflurane and isoflurane inhibited CGRP-induced cAMP production in a dose-related manner in SK-N-MC cells. Neither anesthetic had an effect on forskolin-induced cAMP production in the cells nor inhibited ligand binding to the CGRP receptor. Furthermore, both anesthetics dose dependently inhibited cholera toxin-induced cAMP production in the cells. These data suggest that both anesthetics inhibit CGRP-induced vasoconstriction by interfering with the signal transduction pathway between CGRP receptors and adenylate cyclase. The inhibitory site of volatile anesthetics on CGRP receptor-mediated response involves G_s protein.

The Effects of Volatile Anesthetics on CGRP-Induced Hemodynamic Changes in Pithed Rats. Yoshikawa et al. (2003) reported that isoflurane and halothane inhibited the NANC depressor response in pithed rats. Although isoflurane, halothane, and sevoflurane did not affect CGRP release after spinal cord stimulation, isoflurane and halothane inhibited the depressor response to exogenously administered CGRP. These results suggest that volatile anesthetics inhibit the NANC depressor response by inhibiting the CGRP depressor effect but not by inhibiting CGRP release.

In a pithed rat model, we investigated not only the effect of volatile anesthetics on CGRP-induced changes in blood pressure but also the CGRP-induced vasodilation by measuring SVR, which reflects the systemic vascular tone. Sevoflurane (4%) and isoflurane (2%) significantly inhibited the CGRP-induced decrease in SVR. Lower concentrations of volatile anesthetics (2% sevoflurane and 1% isoflurane) did not affect the decrease in SVR.

In general, there are four main mechanisms of the vasodepressor response elicited by intravenous drug administration: 1) central nervous system actions, 2) inhibition of vascular sympathetic transmission, 3) release of endothelium-derived relaxing factors, and 4) direct vasorelaxing effects (Saxena and Villalon, 1990). Both central and autonomic nervous system activity were excluded by using pithed va-
gotomized rats. Therefore, CGRP-induced vasodilatory effects in the present study were mediated by actions on the vascular endothelium (releasing relaxing factors) and/or the vascular smooth muscle cells (producing direct relaxation). CGRP, among the most potent vasodilating substances known, also exerts positive inotropic effects (van Rossum et al., 1997). These biologic responses are mediated by specific cell surface receptors predominantly coupled to the activation of adenylate cyclase (van Rossum et al., 1997). In the current study, 4% sevoflurane and 2% isoflurane inhibited the CGRP-induced vasodilatory effects. In addition, 4% sevoflurane and 2% isoflurane inhibited the increase in MAP after CGRP administration, suggesting that high concentrations of volatile anesthetics inhibit both vasodilatory and positive inotropic effects induced by CGRP. These data strongly suggest that volatile anesthetics inhibit the CGRP-induced response through an effect on CGRP receptor-mediated responses.

The Effects of Volatile Anesthetics on CGRP Receptor-Mediated Signal Transduction in SK-N-MC Cells.

CGRP relaxes vascular smooth muscle cells via both endothelium-dependent and endothelium-independent signal transduction pathways (Bell and McDermott, 1996). These responses are mediated by the specific cell surface family B G protein-coupled receptor (GPCR) and the calcitonin receptor-like receptor (McLatchie et al., 1998). The receptor is predominantly coupled to the activation of adenylate cyclase, which produces cAMP, leading to vascular relaxation in both pathways. In addition, there are other mechanisms by which CGRP elevates nitric oxide directly without the involvement of adenylate cyclase or activates ATP-sensitive potassium channels ($K_{ATP}$) (Bell and McDermott, 1996). On the other hand, CGRP-mediated inotropic action in the myocardium is mediated through CGRP receptors (van Rossum et al., 1997). In the present study, sevoflurane and isoflurane significantly inhibited CGRP-induced cAMP production but had no effect on for-
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