Pain-facilitating medullary neurons contribute to opioid-induced respiratory depression

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1Department of Neurological Surgery, Oregon Health and Science University, Portland, Oregon; 2Center for Neuropharmacology and Neuroscience, Albany Medical College, Albany, New York; 3Vollum Institute, Oregon Health and Science University, Portland, Oregon; and 4Department of Behavioral Neuroscience, Oregon Health and Science University, Portland, Oregon

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Phillips RS, Cleary DR, Nalwalk JW, Arttamangkul S, Hough LB, Heinricher MM. Pain-facilitating medullary neurons contribute to opioid-induced respiratory depression. J Neurophysiol 108: 2393–2404, 2012. First published September 5, 2012; doi:10.1152/jn.00563.2012. — Respiratory depression is a therapy-limiting side effect of opioid analgesics, yet our understanding of the brain circuits mediating this potentially lethal outcome remains incomplete. Here we studied the contribution of the rostral ventromedial medulla (RVM), a region long implicated in pain modulation and homeostatic regulation, to opioid-induced respiratory depression. Microinjection of the μ-opioid agonist DAMGO in the RVM of lightly anesthetized rats produced both analgesia and respiratory depression, showing that neurons in this region can modulate breathing. Blocking opioid action in the RVM by microinjecting the opioid antagonist naltrexone reversed the analgesic and respiratory effects of systemically administered morphine, showing that this region plays a role in both the analgesic and respiratory-depressant properties of systemically administered morphine. The distribution of neurons directly inhibited by RVM opioid microinjection was determined with a fluorescent opioid peptide, dermorphin-Alexa 594, and found to be concentrated in and around the RVM. The non-opioid analgesic improgan, like DAMGO, produced antinociception but, unlike DAMGO, stimulated breathing when microinjected into the RVM. Concurrent recording of RVM neurons during improgan microinjection showed that this agent activated RVM ON-cells, OFF-cells, and NEUTRAL-cells. Since opioids are known to activate OFF-cells but suppress ON-cell firing, the differential respiratory response to these two analgesic drugs is best explained by their opposing effects on the activity of RVM ON-cells. These findings show that pain relief can be separated pharmacologically from respiratory depression and identify RVM OFF-cells as important central targets for continued development of potent analgesics with fewer side effects.

rostral ventromedial medulla; analgesia; improgan; pain modulation; rat

While opioids remain the most powerful tool available for treating moderate to severe pain, their utility is limited by side effects, especially potentially lethal respiratory depression. Given this risk and the low therapeutic index for many opioids, clinicians often undertreat pain (Nickerson and Attaran 2012; Webster et al. 2011). Despite the clinical and social significance of opioid-induced respiratory depression, the underlying neural mechanisms and circuits are still not fully understood.

In contrast to respiratory depression, the analgesic actions of opioids have been studied intensely, and we now know that these agents produce pain relief by engaging an endogenous brain stem pain modulatory system. This system is the driving force behind the natural suppression or enhancement of pain in different behavioral states (Fields 2004). Its output influences pain behavior via projections from the rostral ventromedial medulla (RVM) to dorsal horn nociceptive circuits. Inactivation or lesion of the RVM can interfere with the analgesic effects of systemically administered opioids, and μ-opioid agonists applied directly in the RVM produce a potent analgesia (Fields et al. 2006; Proudhit 1980, 1981).

Two classes of RVM neurons, the “ON-cells” and “OFF-cells,” respond to opioids (Fields et al. 2006; Heinricher et al. 2009). ON-cells facilitate nociception, and these neurons are defined by activation during nociceptive withdrawal behaviors. Conversely, OFF-cells suppress nociception, and this cell class is defined by a withdrawal-related pause in activity. Drugs that prevent the OFF-cell pause produce behavioral antinociception, independent of whether ON-cell activity is changed (Heinricher and Ingram 2008; Heinricher et al. 2010b; Neubert et al. 2004). μ-Opioids, for instance, given systemically or locally in the RVM, produce continuous OFF-cell firing while inhibiting ON-cell activity. Whether these changes in OFF-cell and ON-cell activity collectively or separately relate to other effects of opioids, including respiratory depression, is not yet known.

The constituent regions of the RVM, including portions of raphe magnus, raphe pallidus, and raphe obscurus at the level of the facial nucleus, have also been tied to other regulatory functions, including thermogenesis and cardiovascular control (Cao et al. 2004; Lovick 1997; Nakamura and Morrison 2007). Although these areas have not been strongly implicated in opioid-mediated respiratory depression, they have been linked to respiratory modulation (Dias et al. 2007, 2012; Hellman et al. 2007, 2009; Madden and Morrison 2005; Menuet et al. 2011; Rice et al. 2009; Taylor et al. 2006; Verner et al. 2004). Nevertheless, the neuronal and physiological overlap of these homeostatic functions with pain modulation is not well understood, in part because of the lack of mechanistic studies that include both parameters.

Here we show that the RVM contributes to opioid-induced respiratory depression at doses that simultaneously produce behavioral analgesia. In this same brain region, the non-opioid analgesic improgan also relieves pain yet stimulates respiration. This functional separation reflects independent actions of...
the two distinct populations of opioid-sensitive RVM neurons, the ON-cells and the OFF-cells. Thus, while these results demonstrate an overlap of opioid-induced respiratory depression and analgesia within a common brain stem region, they also show promise for dissociating these two effects pharmacologically, at the level of functionally distinct neuronal populations.

**MATERIALS AND METHODS**

**Animals.** All experimental procedures were approved by the Institutional Animal Care and Use Committee at Oregon Health and Science University and followed the guidelines of the Committee for Research and Ethical Issues of the International Association for the Study of Pain.

**Surgical preparation and anesthesia.** Deep surgical anesthesia was induced in male Sprague-Dawley rats (250–350 g, Charles River) with 4% isoflurane in humidified O₂ at 1.25 l/min, and the animals were placed in a stereotaxic apparatus. For surgical preparation (see [MATERIALS and METHODS]), the isoflurane concentration was reduced to 3% and a small cranectomy performed to allow placement of recording electrode and/or glass microinjection pipette in the RVM. Animals were placed on a circulating warm-water pad to support body temperature.

After surgical preparation the isoflurane concentration was reduced from 3% to 1.5% over 30 min (~0.5% every 10 min) and then further adjusted in increments of 0.25% until a tail flick (TF) reflex was evoked (see *nociceptive testing*) without other signs of discomfort. This concentration was maintained for at least 30 min prior to the initiation of the experimental protocol. Isoflurane concentration and gas flow rate were fixed for the duration of the protocol.

**Nociceptive testing.** Nociceptive thresholds were measured by TF latency. With a feedback-controlled radiant heat source, the ventral side of the animal’s tail was maintained at 34°C between trials and then heated at a constant rate of 1.7°C/s until a tail movement was detected or the cutoff temperature of 53°C was reached. A motion transducer detected movement of the tail. Three locations, at 2, 4, and 6 cm from the tip of the tail, were tested in rotation to avoid sensitization and tissue damage. The holding temperature allowed us to rule out the possibility that any changes in latency could be attributed to changes in skin temperature. TF latency was defined as the difference in time between the point at which the tail surface temperature reached 36°C and the occurrence of the reflex. This protocol, with trials at 5-min intervals, produces a stable measure of nociceptive responsiveness over several hours (Martenson et al. 2005). The baseline threshold was the average withdrawal latency of three trials taken immediately prior to the drug injection. To aid in comparisons of drug effect among groups, TF latency is sometimes expressed as percentage of maximum possible effect: \( \% \text{MPE} = (\text{postdrug latency} - \text{baseline latency})/\text{cutoff latency} - \text{baseline latency} \).

**Respiration, heart rate, and rectal temperature.** Breathing was monitored by using two different noninvasive methods, both of which provide accurate measurements of breathing rate and relative tidal volume compared with whole body plethysmography (Cleary et al. 2012). Initial experiments used accelerometry-based plethysmography (Devonshire et al. 2009), where an accelerometer was attached to the chest wall of the animal to detect movements associated with breathing. In later experiments, respiration was monitored by ventilation pressure transduction (Cleary et al. 2012), which measures small changes in pressure just outside the animal’s nose resulting from inhalation and exhalation. The respiratory signals were amplified, filtered, and recorded for off-line analysis (Spike2; CED, Cambridge, UK). Respiratory rate was determined by averaging the interbreath interval over the 60-s period before each TF. Relative respiratory amplitude was determined by expressing peak-to-peak amplitude, a correlate of tidal volume (Cleary et al. 2012), as a percentage of the predrug baseline. Heart rate was derived from the electrocardiogram. Body temperature was measured with a rectal thermometer (TH-5; Physitemp, Clifton, NJ).

**RVM recording.** For the impropargin microinjection experiments (see *Experimental protocols*), a gold- and platinum-plated stainless steel recording microelectrode (Microprobe, Gaithersburg, MD) was attached to the microinjection pipette so that the tips were separated by no more than several hundred micrometers (Heinricher et al. 1994, 2010a, 2010b; Neubert et al. 2004). The assembly was lowered to the RVM with the use of anatomical landmarks. Cell recordings made before, during, and after the impropargin microinjection were stored for later off-line analysis to ensure accurate discrimination throughout the recording. Prior to the start of the recording protocol, each neuron was unambiguously classified as an ON-, OFF, or NEUTRAL-cell with standard criteria ([Fields et al. 1983](#)). ON- and OFF-cells are defined by a sudden activation or cessation in firing rate, respectively, beginning just prior to a nociceptive reflex such as the TF response. NEUTRAL-cells show no change in firing rate correlated with the occurrence of a nociceptive reflex. Spontaneous firing was determined by measuring the firing rate in a 30-s period immediately prior to each TF trial (5-min intervals). Reflex-related changes in firing were determined in a 3-s period beginning 0.5 s prior to the TF response.

**Experimental protocols.** In the first set of experiments, the contribution of neurons in the RVM to the antinociceptive and respiratory-depressant actions of systemically administered morphine was determined by microinjection of the opioid antagonist naltrexone in the RVM. TF trials were initiated at 5-min intervals throughout the protocol. After a 15-min baseline period, morphine (0.66 mg/kg iv) was given. Ten minutes later, naltrexone (3 μg/200 nl) or a control cerebrospinal fluid (aCSF, 200 nl) was microinjected into the RVM over a period of ~5 min or into surrounding regions as off-site controls. Naloxone (0.27 mg/kg iv) was given systemically at the end of the experiment to show that morphine effects were receptor mediated and reversible.

In the second set of experiments, we examined the effects of direct RVM microinjection of [d-Ala², N-Me-Phe⁴,Gly-ol⁵]-enkephalin (DAMGO, 200 pmol/200 nl) or the non-opioid analgesic impropargin (15 or 30 nmol in 200 nl; [Hough et al. 2000](#)) on nociception, respiratory parameters, heart rate, and body temperature. In the impropargin experiments, activity of an RVM neuron was also recorded as described above. A 15-min baseline was established, followed by microinjection of drug or vehicle (injected over 5–10 min, beginning immediately after the last baseline TF). TF, respiratory measurements, heart rate, rectal temperature, and cell activity (in the impropargin experiments) were recorded for the next hour.

In the third set of experiments, we microinjected either the GABAa receptor antagonist bicuculline (22 pmol/200 nl) to disinhbit RVM neurons or the GABAa receptor agonist muscimol (18 pmol/200 nl) to suppress activity of RVM neurons ([Heinricher and Tortorici 1994](#); [Martenson et al. 2009](#)). The protocol in this third set of experiments was identical to that for DAMGO and impropargin, with TF, respiration, heart rate, and rectal temperature recorded before and after microinjection of bicuculline or muscimol. However, cell data were not recorded in this set of experiments.

**Verification of microinjection and recording sites.** Microinjection locations and recording sites were marked either by fluorescent beads (FluoSpheres, Invitrogen, Eugene, OR) injected with the drug or by an electrolytic lesion created after the experimental protocol. Animals were overdosed with isoflurane and then transcardially perfused with physiological saline followed by 10% formalin. Brains were removed and stored overnight in 10% formalin. The brain stem was sectioned at 60 μm on a cryostat and mounted for microscopic examination.

**Identification of opioid-sensitive brain stem neurons.** To identify neurons in the region of the RVM that contain postsynaptic μ-opioid receptors and that could thus drive RVM opioid-induced changes in nociception and respiration, we microinjected a peptide μ-opioid agonist, dermorphin, that was fluorescently labeled with Alexa Fluor
594 (Arttamangkul et al. 2000, 2006). Dermorphin-A594 was dissolved in either 3% DMSO in saline (6 pmol/200 nl injections) or 30% DMSO in saline (66 pmol/200 nl). For injection of dermorphin-A594 into the RVM, animals were initially anesthetized with 5% isoflurane for placement of a jugular catheter, and the anesthetic was then switched from inhaled isoflurane to intravenous methohexital (30–60 mg·kg·h). After a stable baseline was achieved for at least 25 min, dermorphin-A594 was injected into the RVM. In some experiments, 45 min prior to the injection of dermorphin-A594 an injection of the irreversible μ-opioid antagonist β-funaltrexamine (β-FNA, 300 nl, 6 nmol; Torcix Bioscience), was injected into the RVM. Heart rate, respiratory rate, and rectal temperature were measured as described above. Nociceptive threshold was measured by placing a Peltier device on the left hind paw, slowly increasing temperature from 35 to 53°C, and noting the temperature at which a withdrawal was initiated. EMG recordings from the left calf were used to determine the beginning of the withdrawal. Antinociception is expressed as %MPE. These experiments allowed a comparison of the analgesic efficacy and respiratory and autonomic depressive effects of dermorphin-A594 with those of DAMGO and impropagon.

Physiological and nociceptive parameters were monitored before and after injection of dermorphin-A594. Sixty minutes after injection, animals were overdosed with methohexital and perfused transcardially with solutions of physiological saline and of 10% formalin. The brains were removed, fixed overnight in 10% formalin, and sectioned at 60 μm with a cryostat. Sections were mounted on glass slides with Permount, visualized on an Olympus BX51 fluorescent microscope (Olympus, Center Valley, PA), and photographed with a Microfire source image processing package Fiji (http://fiji.sc). Fluorescence was measured in the RVM, a midline area roughly 2 mm in width and 1 mm in height directly dorsal to the pyramidal tracts at the level of the facial nucleus. Background intensity for each section was also measured and then subtracted from the overall fluorescence.

Statistical analysis. All data are represented as means ± SE. Drug effects on TF latency, hind paw withdrawal threshold, respiratory rate, heart rate, and rectal temperature were determined by one- or two-way ANOVA, with post hoc comparisons used where indicated. Differences in mean RVM fluorescence between treatment groups and the effects of dermorphin-A594 relative to baseline were analyzed by unpaired and paired t-tests, respectively. Respiratory amplitude was analyzed with a Friedman’s analysis of variance by rank. RVM neurons exhibit a wide range of basal firing rates. A within-cell analysis approach was therefore used in which cell firing data after treatment were compared to baseline with a Wilcoxon’s signed-rank test for matched samples. Analyses were performed with GraphPad Prism or StatView. P < 0.05 was considered statistically significant.

RESULTS

RVM contributes to antinociceptive and respiratory-depressant actions of systemically administered morphine. The RVM is defined functionally as the area where low-current electrical stimulation produces behavioral antinociception and includes the nucleus raphe magnus and adjacent reticular formation at the level of the facial nucleus (Fields and Heinricher 1985). We first determined whether this region is required for respiratory-depressant actions of systemically administered morphine, as well as for analgesia. Respiratory parameters (rate and amplitude) were measured in parallel with the TF response evoked by noxious radiant heat. The latter is an index of nociception widely employed in awake behaving animals that can also be used in lightly anesthetized subjects (Fields and Heinricher 1985).

As shown in Fig. 1, systemically administered morphine produced both potent antinociception and a significant decrease in respiratory rate (ANOVA, P < 0.05 compared with baseline for all groups). Both effects were reversed by focal application of the opioid antagonist naltrexone in the RVM but not by aCSF vehicle. Naltrexone microinjections in areas immediately surrounding the RVM (dorsal, rostral, and caudal) were ineffective (Fig. 1, naltrexone placement control group). Subsequent systemic administration of naltrexone, a highly lipophilic, short-acting opioid antagonist, reversed antinociception and respiratory depression in RVM-vehicle and placement control groups, showing that both effects were opioid receptor mediated and reversible. These data demonstrate that opioid receptors in the RVM contribute to respiratory depression as well as to antinociception produced by systemically administered morphine.

Distribution of neurons in RVM driving opioid-induced changes in respiration, heart rate, and pain threshold. We next determined the distribution of neurons in the RVM and surrounding areas that could be the direct target of μ-opioid agents. By microinjecting the μ-opioid agonist dermorphin...
labeled with an Alexa Fluor 594 fluorophore (dermorphin-A594), we could identify individual cells in the RVM and surrounding regions that bind the agonist and internalize the μ-opioid receptor. These labeled neurons are potential drivers for the physiological and behavioral effects produced by opioid microinjections into the RVM.

We first determined that dermorphin-A594, like DAMGO, could produce antinociception and alter breathing when microinjected in the RVM. The higher dose of dermorphin-A594 (66 pmol/200 nl) produced significant effects on heat-evoked withdrawal (%MPE: 64.6 ± 18.4, n = 5, P < 0.05), respiratory rate (−16.2 ± 3.6 breaths/min, P < 0.05), heart rate (−23.0 ± 7.9 beats/min, P < 0.05), and body temperature (−0.28 ± 0.10°C, P < 0.05), consistent with results from microinjections of DAMGO into the RVM (see next section).

To identify the minimal distribution of neurons that could produce behavioral effects, we used the lowest dose of dermorphin-A594 (6 pmol/200 nl) that consistently produced measurable, albeit small, antinociception (%MPE: 9.5 ± 3.5, n = 4, P < 0.05) and then mapped the distribution of fluorescently labeled neurons. With this lower dose, respiratory rate was significantly decreased (−10.8 ± 3.0 breaths/min, P < 0.05), although there were no changes in heart rate (−25.0 ± 11.0 beats/min, P > 0.05) or body temperature (−0.21 ± 0.09°C, P > 0.05). Many neurons with strong A594 fluorescence were visible in the area immediately surrounding the injection site (Fig. 2), including numerous cells in the nucleus raphe magnus, nucleus raphe pallidus, raphe obscurus, and reticularis gigantocellularis pars alpha. Distinctively fluorescent single neurons were visible as far as 1 mm rostral and caudal to the injection site. Some larger neurons were also visible in the area dorsal to the injection site (nucleus reticularis gigantocellularis), predominantly in the sections containing the injection site or the track of the injector.

In control experiments with this lower dose of dermorphin, injecting the irreversible μ-opioid antagonist β-FNA 45 min prior to dermorphin-A594 injection significantly attenuated mean fluorescent labeling in the RVM (dermorphin-A594: 6.4 ± 1.1 arbitrary units averaged across all rostro-caudal levels, n = 4; β-FNA pretreatment: 1.8 ± 0.63, n = 4; P < 0.05 by unpaired t-test, Fig. 2F).

RVM supports opioid-induced respiratory depression. To compare the analgesic and respiratory effects of direct local RVM administration of the μ-opioid agonist DAMGO with those of the non-opioid analgesic improgan (Hough et al. 2000), we recorded nociception, respiration, heart rate, and body temperature simultaneously before and after microinjection of the two agents. We also recorded RVM neuronal activity in the improgan experiments, but not in the DAMGO experiments, since the effect of local DAMGO injection on activity of RVM neurons has been defined previously (Heinricher et al. 1994).

Microinjections of DAMGO or improgan in the RVM at sites shown in Fig. 3 produced potent antinociception. TF latency was increased significantly by both agents, but not by vehicle (Fig. 4). The peak antinociceptive effects of improgan and DAMGO were seen at 10–20 and 35–45 min after injection, respectively, consistent with the known time courses of these agents. Injections of improgan in areas surrounding the RVM, mostly dorsal and rostral (see Fig. 3), resulted in a small, but statistically significant, increase in TF latency (1.8 ± 0.5 s, n = 23, P < 0.01).

Although both DAMGO and improgan produced antinociception when microinjected into the RVM, only DAMGO produced a significant respiratory depression, decreasing both respiratory rate and amplitude (Fig. 4). In marked contrast, improgan in the RVM stimulated both respiratory rate and amplitude. The peak effects of improgan and DAMGO were seen at 10–20 and 35–45 min after injection, respectively, for both rate and amplitude. Vehicle injection had no effect on respiration, and injections of improgan in areas surrounding the RVM produced only a modest increase in respiration (4.8 ± 0.18 breaths/min, P < 0.05). These data demonstrate that the analgesic actions of drugs in the RVM are not inextricably linked to respiratory depression.

Effects of DAMGO and improgan on heart rate and body temperature are also distinct. DAMGO microinjection resulted in a decrease in heart rate, while improgan induced a substantial increase (Fig. 4). Peak effects on heart rate were evident at 10–20 min and 35–45 min after injection with improgan and DAMGO, respectively. A small but statistically significant decrease in heart rate (6.0 ± 2.0 beats/min) was seen in vehicle-treated controls over the course of the experiment. Injections of improgan in areas surrounding the RVM produced a statistically significant increase in heart rate (25 ± 6.6 beats/min, P < 0.01).

Like heart rate, body temperature was also differentially affected by DAMGO and improgan. DAMGO microinjection decreased, whereas improgan increased, body temperature (Fig. 4). The peak effects of improgan and DAMGO on temperature were seen at 35–45 min after injection. The delayed time course for improgan in this case presumably reflects the kinetics of whole body temperature change. Injections of improgan in areas surrounding the RVM produced a small but statistically significant increase in body temperature (0.1 ± 0.03°C, P < 0.01).

Thus, like respiratory depression, reduced autonomic output following manipulations of the RVM can also be dissociated from analgesia.

Changes in RVM neuronal activity from DAMGO and improgan administration. From a pain-modulating perspective, all neurons recorded in the RVM can be assigned to one of three mutually exclusive classes: OFF-cells (defined by nociceptive reflex-related inhibition of activity), ON-cells (characterized by nociceptive reflex-related activation), and NEUTRAL-cells (unresponsive to noxious stimuli; Fields et al. 2006). Both OFF-cells and ON-cells function as pain-modulating neurons, respectively suppressing and facilitating spinal nociceptive processing. The effects of μ-opioids on the firing of these RVM cell classes have been well documented. Local or systemically administered μ-opioid receptor agonists, including morphine and DAMGO, indirectly activate OFF-cells through presynaptic disinhibition, suppress ON-cell firing through direct inhibition, and do not alter NEUTRAL-cell firing (Fields et al. 2006; Heinricher and Ingram 2008). The effects of locally administered improgan on the different RVM cell classes have not been studied. We therefore recorded the activity of physiologically identified neurons within the RVM during the improgan injections described above (Fig. 4). As expected from previous work, these neurons exhibited a wide range of basal firing rates.

Improgan activated the pain-inhibiting OFF-cells in the RVM. Ongoing firing of these neurons was increased substan-
tially (Fig. 5). Furthermore, improgan prevented the characteristic inhibition of OFF-cell firing during noxious stimulation ($P = 0.03$, $n = 7$, Wilcoxon’s signed-rank test compared with baseline; data not shown). Improgan activation of OFF-cells thus mimics the net opioid effect of increasing the firing of these neurons (Heinricher et al. 1994). However, unlike opioids, improgan also strongly activated both ON-cells and NEUTRAL-cells (Fig. 5).

The differential effects of RVM DAMGO and improgan on respiration and autonomic parameters is therefore best explained by changes in the firing of the ON-cells, since only this cell class responds differentially to the two drugs.

**Functional effects of stimulating or blocking all RVM neurons.**

To corroborate the behavioral and physiological effects of RVM DAMGO and improgan, we examined the effects of nonselective excitation or inhibition of all RVM neurons on nociception, respiration, and autonomic parameters. The goal of these experiments was to contrast effects of selective manipulations of ON- and OFF-cells by using opioids with nonselective activation or inhibition to confirm the contributing role of these two cell classes in analgesia, heart rate, thermogenesis, and respiratory control.

To nonselectively excite RVM neurons, we microinjected the GABAA receptor antagonist bicuculline into the RVM. Like improgan, bicuculline activates both ON- and OFF-cell...
classes (Heinricher and Tortorici 1994). The physiological response to bicuculline generally mimicked the response to improgan rather than DAMGO, with antinociception accompanied by increases in respiratory rate, heart rate, and body temperature (Fig. 6). These data verify the above finding with improgan that concurrent activation of ON- and OFF-cells in RVM stimulates respiration at the same time that it produces analgesia.

To confirm that suppression of activity of a subset of RVM neurons was relevant to opioid-induced respiratory depression, we blocked activity of all RVM neurons by microinjecting the GABAA receptor agonist muscimol (Martenson et al. 2009). Breathing, heart rate, and body temperature were all significantly reduced after RVM blockade, although nociceptive threshold was not altered (Fig. 6). Inhibiting all RVM neurons thus reproduces the respiratory depressant actions of DAMGO and, furthermore, points to a role for this region in maintenance of basal respiratory function.

DISCUSSION

These experiments show that the RVM, a region long implicated in pain modulation and homeostatic regulation, contributes to both the analgesic and respiratory-depressant properties of μ-opioids. To determine whether RVM mechanisms of antinociception can be separated from those mediating respiratory depression, we compared the behavioral, physiological, and neuronal effects of DAMGO with those of improgan, a non-opioid analgesic (Table 1). While both drugs produced analgesia when microinjected into the RVM, DAMGO produced respiratory depression, whereas improgan stimulated breathing. Locally applied DAMGO, like systematically administered morphine, is known to activate OFF-cells and suppress ON-cell firing (Heinricher et al. 1994). Here, local improgan activated both ON- and OFF-cells. Thus, while OFF-cells show the same response to both DAMGO and improgan, the two drugs have opposing effects on ON-cells. The differential respiratory response to these two analgesic drugs in the RVM is therefore most readily explained by their opposing effects on the activity of ON-cells. By contrast, the common analgesic response to the agents is accounted for by their ability to activate OFF-cells.

Neural basis for analgesia and respiratory depression mediated by RVM. While histochemical and anatomical approaches to the study of RVM neurons are as yet incomplete, their physiological classification is comprehensive. That is, by definition, every RVM neuron recorded can be identified as an ON-, OFF-, or NEUTRAL-cell. These three cell classes have been identified in barbiturate-, ketamine-, and isoflurane-anaesthetized rats as well as in decerebrate-unanesthetized and awake animals (Clarke et al. 1994; Heinricher et al. 2010b; Leung and Mason 1995, 1999; McGaraughty et al. 1993a, 1993b). ON-cells facilitate nociception, and local or systematically administered μ-opioids suppress ON-cell activity. OFF-cells suppress nociception, and opioids increase OFF-cell firing through disinhibition. Sustained OFF-cell activity mediates the analgesic action of morphine and other μ-opioids. The NEU-TRAL-cells do not respond to μ-opioid agonists, whether given systemically or locally (Fields et al. 2006; Heinricher and Ingram 2008). Therefore, one or both of the two opioid-sensitive cell classes, the ON-cells and OFF-cells, must mediate the physiological and behavioral effects of μ-opioids in the RVM, including respiratory depression and analgesia.
To better understand how $\mu$-opioids act in the RVM to depress respiration, we compared the effects of opioids with those of improgan, a non-opioid analgesic. This compound does not cross the blood-brain barrier, but when administered intracerebroventricularly it acts at an unknown receptor site to stimulate descending antinociception through RVM OFF-cell activation (Heinricher et al. 2010b; Nalwalk et al. 2004), a finding consistent with the present results. The surprising observation in the present study was that improgan, applied directly in the RVM, produced a powerful respiratory stimulation in parallel with analgesia, allowing us to investigate the cellular basis for the differential influence on respiratory control and nociception. Locally administered improgan activated not only OFF-cells, mimicking the effect of $\mu$-opioids on these neurons, but also ON-cells, an effect opposite to that of $\mu$-opioids. Although NEUTRAL-cell firing was also increased by local improgan, these neurons do not respond to opioids (Barbaro et al. 1989), which argues against a role for this cell class in opioid-induced respiratory modulation via the RVM. These data therefore confirm the already substantial evidence that the OFF-cells are the analgesic output from the RVM (Fields et al. 2006; Heinricher and Ingram 2008) but, more important, suggest that RVM effects on respiration are mediated by ON-cells. A role for ON-cells in opioid-induced respiratory depression was unexpected but fits well with established interactions between pain and respiration. For instance, acute noxious stimuli, which activate ON-cells, have long been recognized to attenuate opioid-induced respiratory depression (Borgbjerg et al. 1996; Kamei et al. 2011; McQuay 1988). Should OFF-cells play any role in modulating respiration or autonomic parameters, that influence is masked by the overriding effect of the ON-cells.

**Dissociation of analgesia from respiratory depression at the level of RVM.** Since OFF-cells appear to mediate analgesia but not respiratory depression, our data imply that further separation of respiratory depression from analgesia is possible, based on both neural substrate and pharmacology. $\mu$-Opioid activation of OFF-cells is indirect, through a presynaptic mechanism, whereas inhibition of ON-cells is a direct postsynaptic effect (Heinricher and Ingram 2008; Heinricher et al. 1992; Pan et al. 1990). Because the pre- and postsynaptic actions of $\mu$-opioids invoke distinct second messengers and channels (Heinricher and Ingram 2008), presynaptic mechanisms could be critical targets for "pure" opioid-like analgesia. Focusing on OFF-cell-
selective pathways, including the presynaptic μ-opioid receptors and downstream molecules, therefore has the potential to provide potent pain relief without the risk of respiratory depression. Indeed, cannabinoids, like opioids, act in the RVM to produce analgesia but do not produce significant respiratory depression. This disparity between opioid and cannabinoid actions could be explained by the fact that cannabinoids do not have direct postsynaptic inhibitory actions on RVM ON-cells (Meng et al. 1998; Vaughan et al. 1999).

The RVM has the potential to modulate respiration through several pathways. Raphe magnus and raphe obscurus both send direct projections to the phrenic motor nucleus (Holtman et al. 1984, 1986; Hosogai et al. 1998), and stimulation of either raphe magnus or pallidus influences activity of phrenic mo-

Fig. 5. All RVM neuronal classes are activated after local application of the non-opioid analgesic improgan. A: ratemeter records showing firing rate (in spikes/s) of a typical OFF-cell, ON-cell, and NEUTRAL-cell before and after local microinjection of improgan during the period indicated below the trace. Triangles indicate TF trials, with filled triangles indicating that the animal responded to the heat and open triangles that there was no response prior to the cutoff time. B: group data confirm that all three RVM cell classes exhibit an increase in firing rate after improgan (IMP), but not vehicle (Veh), microinjection (6–8 cells/group). *P < 0.05 compared with preinjection baseline, Wilcoxon signed-rank test.

Fig. 6. Effects of RVM improgan and DAMGO compared with bicuculline and muscimol: TF latency (expressed as % maximum possible effect, %MPE), change in respiratory rate, change in heart rate, and change in body temperature. Each data set was analyzed with an ANOVA followed by a Dunnett’s test for comparison to aCSF vehicle control (9–36 animals/group). *P < 0.05 compared with preinjection baseline; **P < 0.01 and ***P < 0.001 compared with aCSF group.
toneurons (Lalley 1986; Millhorn 1986). Alternatively, the RVM has numerous afferent and efferent connections within the brain stem and could modulate relays at various stages of the chemosensory pathways or contribute to chemosensory-evoked activations (Guyenet et al. 2010; Huckstepp and Dale 2011; Nattie 2011; Pattinson et al. 2009). For example, medullary raphe regions are recognized to modulate chemosensory function of the retrotrapezoid nucleus (Depuy et al. 2011; Dias et al. 2008; Hilaire et al. 2010; Mulkey et al. 2007; Viemari and Tryba 2009).

Table 1. Responses of RVM neurons and associated changes in tail flick latency, respiratory rate, heart rate, and temperature to local application of vehicle, DAMGO, improgan, bicuculline, and muscimol in RVM

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Change in Firing</th>
<th>Behavioral or Physiological Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ON-cell</td>
<td>OFF-cell</td>
</tr>
<tr>
<td>Vehicle</td>
<td>No effect</td>
<td>No effect</td>
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<tr>
<td>DAMGO</td>
<td>No effect</td>
<td>No effect</td>
</tr>
<tr>
<td>Improgan</td>
<td>No effect</td>
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<tr>
<td>Bicuculline</td>
<td>No effect</td>
<td>No effect</td>
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<td>Muscimol</td>
<td>No effect</td>
<td>No effect</td>
</tr>
</tbody>
</table>

Summary of the responses of rostral ventromedial medulla (RVM) neurons and the associated changes in tail flick latency, respiratory rate, heart rate, and temperature to local application of vehicle, DAMGO, improgan, bicuculline, and muscimol in the RVM. Activation of OFF-cells is coupled to hypoalgesia, whereas changes in respiratory rate and autonomic parameters are linked to drug effects on the ON-cells.

Some labeled neurons were also found immediately rostral and caudal to the RVM, at the level of the superior olive and in the area of raphe obscurus dorsal to the inferior olive. Opioid-sensitive cell populations rostral and caudal to the RVM have also not been characterized, but neurons with respiration-related activity have been identified in the medial medulla immediately caudal to the RVM (Lindsey et al. 1994; Pilowsky et al. 1995) The observation that an opioid microinjected in the RVM can directly influence neurons beyond the conventional boundaries of this region raises the possibility that opioid-induced analgesia and respiratory depression are mediated not by RVM OFF- and ON-cells but by opioid-responsive neurons in surrounding regions (Depuy et al. 2011; Zhang et al. 2007). However, it seems unlikely that these areas were the primary target of the injected analgesic drugs, since local application of an opioid antagonist in areas surrounding the RVM did not prevent the analgesic or respiratory-depressant effects of systemically administered morphine. Furthermore, it has been shown that microinjections of DAMGO caudal and lateral to the RVM, at the level of raphe obscurus, do not activate OFF-cells or produce behavioral antinociception (Heinricher et al. 1994). Nevertheless, it is doubtful that a clear functional boundary can be drawn between the RVM and adjacent reticular areas, and there is likely to be significant anatomical overlap in the distributions of neurons important in pain modulation, respiration, and autonomic function (Kerman 2008; Lovick 1997; Rathner et al. 2001; Strack et al. 1989).

Integration of pain modulation and homeostatic regulation in RVM. Control of respiration occurs through the cooperative actions of a network of brain regions, with contributions from the cerebral cortex, hypothalamus, and multiple sites in the brain stem (Dean and Nattie 2010; Feldman et al. 2003; Guyenet 2008; Guyenet et al. 2010; Horn and Waldrop 1998; Nattie and Li 2009). While the outputs of these areas may converge before reaching respiratory motor neurons, no single brain site is responsible for all aspects of breathing. Thus, just as systemically administered opioids modulate nociception through synergistic spinal and supraspinal actions (Bodnar 2000; Budai and Fields 1998; Hirakawa et al. 1999; Yaksh and Rudy 1978), these agents likely depress respiration through concurrent actions in multiple brain areas, including rostral ventrolateral medulla, pre-Bötzinger complex, nucleus ambiguus, and cerebral cortex (Gray et al. 1999; Hassan et al. 1983; Lalley 2006; Miyawaki et al. 2002; Montandon et al.
REFERENCES


