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Catecholaminergic A1/C1 neurons contribute to the maintenance of upper airway muscle tone but may not participate in NREM sleep-related depression of these muscles

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ABSTRACT

Neural mechanisms of obstructive sleep apnea, a common sleep-related breathing disorder, are incompletely understood. Hypoglossal motoneurons, which provide tonic and inspiratory activation of genioglossus (GG) muscle (a major upper airway dilator), receive catecholaminergic input from medullary A1/C1 neurons. We aimed to determine the contribution of A1/C1 neurons in control of GG muscle during sleep and wakefulness. To do so, we placed injections of a viral vector into DBH-cre mice to selectively express the hMD4i inhibitory chemoreceptors in A1/C1 neurons. Administration of the hM4Di ligand, clozapine-N-oxide (CNO), in these mice decreased GG muscle activity during NREM sleep (F1,1,3 = 17.1, p < 0.05); a similar non-significant decrease was observed during wakefulness. CNO administration had no effect on neck muscle activity, respiratory parameters or state durations. In addition, CNO-induced inhibition of A1/C1 neurons did not alter the magnitude of the naturally occurring depression of GG activity during transitions from wakefulness to NREM sleep. These findings suggest that A1/C1 neurons have a net excitatory effect on GG activity that is most likely mediated by hypoglossal motoneurons. However, the activity of A1/C1 neurons does not appear to contribute to NREM sleep-related inhibition of GG muscle activity, suggesting that A1/C1 neurons regulate upper airway patency in a state-independent manner.

1. Introduction

Obstructive sleep apnea (OSA) is a sleep-related breathing disorder that has a prevalence of 13% in men and 6% in women in the United States (Peppard et al., 2013). OSA is characterized by recurrent episodes of partial or complete upper airway obstruction during sleep due to, at least in part, a depressant effect of sleep on upper airway muscle tone (Jordan et al., 2014). Individuals with chronic OSA have an increased risk for neurocognitive, cardiovascular, and metabolic disorders (Kheirandish et al., 2005; Pack and Gislason, 2009; Dempsey et al., 2010; Djonlagic et al., 2012; Veasey, 2012; Macey et al., 2013; Jordan et al., 2014; De Luca Canto et al., 2015). Despite substantial advances in both clinical and basic research, our understanding of the neural mechanisms underlying OSA pathogenesis and the circuitry involved in atonia of upper airway muscles remains incomplete.

Among upper airway muscles that are innervated by hypoglossal motoneurons (XIIms) (Dobbins and Feldman, 1995; Althshuler et al., 1994; Saboisky et al., 2007; Fregosi and Ludlow, 2014), the genioglossus (GG) muscle is the most important dilator because its activation increases airway caliber (Remmers et al., 1978; Brennick et al., 2009). The activity of both XIIms and GG muscle is reduced during non-rapid eye movement (NREM) sleep and it is further suppressed during rapid eye movement (REM) sleep (Sauerland and Harper, 1976; Surat et al., 1988; Horner et al., 1989; Richard and Harper, 1991; Mezzanotte et al., 1992; Katz and White, 2004; Saboisky et al., 2007; Eckert et al., 2009).

Neural mechanisms of depression of XIIms and GG muscle activity

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during NREM and REM sleep have been extensively studied in different animal models, with the majority of these studies focused on mechanisms of XIImns depression during REM sleep. From these studies, two divergent mechanistic hypotheses have emerged: postsynaptic inhibition vs. disfacilitation, i.e. withdrawal of excitatory inputs. Glycinergic postsynaptic inhibition has been found to be responsible for the atonia of postural muscles during REM sleep and was suggested to play a role in REM-related depression of XIImns (Chase et al., 1989; Soja et al., 1991; Yamuy et al., 1999; Fung and Chase, 2015). In contrast, follow-on experiments indicated that GABA and glycine might not be involved in the depression of XIImns during REM sleep (Kubin et al., 1993; Morrison et al., 2003; Fenik et al., 2005a). The withdrawal of monoaminergic drive to XIImns during REM sleep remains, arguably, the most experimentally supported mechanism of REM sleep-related suppression of XIImns (Fenik et al., 2004, 2005a, 2005b; Chan et al., 2006).

In addition, recent work has suggested that acetylcholine-mediated postsynaptic inhibition may contribute to sleep-related depression of XIImns in behaving rats (Grace et al., 2013).

With respect to monoaminergic mechanisms, serotonergic (5HT) and noradrenergic (NA) drive to XIImns originates from brainstem SHT and NA neurons that have axonal projections to the XII nucleus (Alidis et al., 1992; Manaker and Tischler, 1993; Rukhadze and Kubin, 2007; Rukhadze and Fuller, 2015) and exhibit state-dependent patterns of activity (Aston-Jones and Bloom, 1981; Reiner, 1986; Jacobs and Azmitia, 1992; Rukhadze et al., 2008). As the contribution of NA to depression of XII nerve activity during REM sleep-like state was determined to be relatively stronger than 5HT in both, anesthetized (Fenik et al., 2005a; Fenik, 2015; Kubin, 2014, 2016) and behaving rats (Sood et al., 2005; Chan et al., 2006), our research activity has focused most intensively on NA mechanisms. The role of different pontine NA neurons was assessed in functional studies, which have concluded that among the NA groups tested (A5, A7, SubC and LC) A7 neurons provide the major NA excitatory drive to XIImns (Fenik et al., 2002, 2008, 2012). Importantly, however, the role of A1/C1 neurons was not tested in these previous studies. Therefore, we sought to determine the effect of acute inhibition of A1/C1 neurons on the activity of GG muscle in naturally sleeping mice using a chemogenetic approach.

In the present study, we tested the following two hypotheses: 1) A1/C1 CA neurons contribute to the maintenance of XIImns activity, and 2) the activity of A1/C1 neurons contributes to state-dependent modulation of XIImns. A preliminary report has been published (Rukhadze et al., 2014a,b, 2015).

2. Materials and methods

2.1. Animals

Adult male mice Tg(Dbh-cre)KH212Gsat/Mmucd or B6.FVB(Cg)-Tg (Dbh-cre)KH212Gsat/Mmucd (henceforth DBH-cre; C57BL/6 background) originally obtained from the Mouse Regional Resource Center at the University of California, Davis, CA (stock # 032081 or 036778-UCD) (DePuy et al., 2013)) (8–12 weeks, 25–32 g, n = 19) were used in this study. Using stringent exclusionary criteria, data from only four mice had acceptable GG/Neck EMGs and EEG signal recordings, i.e., with no evidence of malfunction of GG implanted electrodes and successful placement of AAV injections into the A1/C1 region at approximately same AP level, were used for data analysis. Three mice were used in acute anesthetized experiments to optimize GG electrode placement and two mice were used for anatomical analysis of Cre-dependent gene expression in CA neurons. The remaining ten mice were excluded on the basis of post-mortem histological analysis that revealed 1) recording sites within the tongue muscles that were not located near the base of the tongue, and/or 2) AAV injections that missed the target site.

In this line of DBH-cre mice, Cre recombination was introduced upstream of the ATG start codon of the Dbh gene using the BAC clone RP23-354N13. This modification results in the expression of Cre recombine that is under the control of the dopamine β-hydroxylase (DBH) promoter, hence Cre recombine is expressed in all brainstem catecholaminergic (CA) neurons. DBH-cre mice were bred at our animal facility and underwent genotyping using the tail DNA PCR analysis. All procedures have been approved by the Institutional Animal Care and Use Committee of the Veterans Administration of Greater Los Angeles Healthcare system (VAGLAHS).

2.2. Mouse validation

Our initial goal was to identify a transgenic line of mice with little to no ectopic expression of the Cre-dependent gene beyond CA neurons. We therefore performed validation experiments on DBH-cre and TH-cre mice and compared Cre-dependent gene expression in CA neurons between the two mouse lines. To confirm that Cre activity mapped to brainstem regions of DBH-cre mice where the CA neurons are located as well as to assess the extent of ectopic expression, we used brain sections from the F1 progeny of adult, male DBH-cre mouse crossed with a tdTomato (tandem dimer derivative of DsRed) Cre-reporter (JAX B6;129S6-Gt(Rosa)26Sortm(CAG-tdTomato)Hze/J stock #007905/ A9 or A9(RCL-tdT) (Madisen et al., 2010)). In these reporter mice, neurons that produce Cre-recombine induce the expression of tdTomato (a red fluorescent protein variant). TH-cre mice B6.Cg-Tg(Th-cre) I1Mtd/J were obtained from the Jackson laboratories (stock # 008601). The TH-cre mice have TH-cre transgene with a 9 kb rat tyrosine hydroxylase (TH) promoter, directing expression of Cre recombine to catecholaminergic cells. We used brain sections from the F1 progeny of adult, male TH-cre mouse crossed with a cre dependent GFP reporter mouse (R26loxSTOPlox-L10-GFP strain). In these F1 mice, neurons that produce Cre-recombine activate Rpl10 and yields eGFP fused L10-ribosomal subunit expression (Krashet et al., 2014). Both reporter strains permit excellent visualization of whole neurons. Following, validation of the DBH-cre and TH-cre lines, and finding that DBH-cre mice has significantly less ectopic expression, we crossed heterozygote DBH-cre mice with C57/6J mice to generate heterozygote DBH Cre-driver mice that were used in our experiments (see Results). Given ATG targeting of Cre recombine, we did not use homozygous DBH-cre mice in our experiments.

2.3. Surgery and stereotoxic injections of AAV vector into the A1/C1 of mice

Mice of at least 8 weeks of age were anesthetized with ketamine/xylazine intraperitoneally (IP, 100 and 10 mg/kg, respectively) and placed in a stereotoxic apparatus. Bilateral injections of an adeno-associated viral (AAV) vector expressing the hM4Di receptor in a Cre-dependent manner (hSyn-Dio-hM4Di-mCherry-AAV10; henceforth AAV-hM4Di; Fig. 1A) were placed into the medullary A1/C1 regions (Fig. 1B) (coordinates: 1.0 mm lateral from the midline, 1.1 mm caudal to the obex, and 1.0 mm deep from the medulla surface). Microinjections were made using a fine-tipped glass micropipette (tip diameter 15–20 μm) by an air pressure-driven delivery system. The injected volume (50 nL) was monitored during the injection by observing the fluid meniscus movement in the pipette through a calibrated microscope. The injection suspension contained AAV (3.4 × 1012 vector genome copies/ml) expressing a Cre-dependent hM4Di. Each injection was made slowly (3–5 min) and was followed by a delay of 3 min before the pipette was slowly retracted. Following the injections, muscles and skin overlying the 4th ventricle were separately sutured and animals were observed until full recovery. Mice were then returned to their original cages for at least 4–5 weeks that are necessary for the full expression of hM4Di receptors (Anaclet et al., 2014, 2015; Venner et al., 2016).
2.4. Positioning of GG and Dia EMGs electrodes for acute and chronic experiments

To establish landmarks to position GG EMG electrodes within the mouse tongue we recorded GG and diaphragmatic (Dia) EMGs in mice (n = 3) under ketamine/xylazine anesthesia (100/10 mg/kg, IP). For GG and Dia muscle recordings two Teflon-insulated stainless steel multi-stranded wires (A-M systems, 0.003/0.0055 " bare/coated diameter) were used. A midline incision was made inferior to the jaw and the skin overlaying the diaphragmatic muscle (a jaw opener) was retracted laterally to expose the pharyngeal region of the mouse. The recording ends of the wires had insulation removed over ∼0.3 mm and were inserted into a 26 gauge injection needle (Monoject, Hypodermic Needle 26GA ½; 0.45 mm x 12.7 mm) slightly bent to form the circle shape. The anterior belly of digastricus was separated into two parts at the midline and for each wire the needle was inserted into the ventral surface of the tongue on the opposite sides of the midline, toward the base of the tongue close to the mandibular symphysis. Implantation of GG electrode closer to this point at the mandible produces less instability of the muscle-electrode interface thereby reducing scattering, which improves signal quality (I. Rukhadze, unpublished observations in rats and mice). Each time when the needle was gently withdrawn leaving the wire in the tongue, the wire was tied to the tongue surface by two knots using non-absorbable silk sutures. To record activity of the diaphragm, the same wires with insulation removed over ∼10 mm at the recording end were passed through the sternal diaphragm on both sides of the midline and the bare ends of the wires were anchored to the inferior part of the sternum. GG and Dia recording electrodes were connected to the recording amplifiers and, if needed, the depth of the GG recording electrodes was optimized by gentle repositioning of the inserted wires until a strongly modulated inspiratory EMG could be recorded (Morrison et al., 2002; Polotsky et al., 2011) concomitant to the diaphragmatic activity (Fig. 1, panel C, as an example). In separate experiments, sectioning of XII nerves on both sides abolished the activity that was recorded with GG recording electrodes, which confirmed that the recorded inspiratory EMG was fully controlled by XII motorneurons (Fig. 1C, D). The respiratory modulation of the tongue EMG in addition to the location of recording electrodes inclined that the activity was originating from GG muscle. Subsequent histology verified the locations of EMG electrode tips within boundaries of the GG muscle (Fig. 1E).

2.5. Instrumentation for monitoring of sleep-wake behavior and genioglossus muscle activity

Two weeks after AAV injections, mice were anesthetized with ketamine/xylazine IP (100 and 10 mg/kg, respectively) and implanted with two EEG screw electrodes (Pinnacle Technology) and a pair of neck electromyogram (EMG) flexible electrodes with sockets (Plastics One) that were previously soldered to a 6-pin connector (Hellind Electronics Inc.). For the recording of GG muscle activity, EMG electrodes were implanted bilaterally into the tongue at its pharyngeal region as described above. The free wire ends were tunneled subcutaneously towards to the head and connected to the miniature 6-pin connector (together with the neck wires and those attached to the EEG screws). The assembly was secured to the skull with dental cement (A-M Systems). The scalp wound was closed with surgical sutures and the wound was given antibiotic (Metacam, 5 mg/kg, i.m.) and analgesic
(Buprenorphine, 0.5 mg/kg, i.m.). Following surgery, the mice were kept in a warm environment until normal body activity was resumed and they were returned to home cages.

2.6. HM4Di-AAV and CNO

hSyn-DIO-hM4Di-mCherry AAV, serotype 10 (Anaclet et al., 2014, 2015; Venner et al., 2016) was used in our experiments. This mutated channel does not respond to endogenous acetylcholine but is selectively activated by a synthetic and pharmacologically inert ligand, CNO, which produces cell hyperpolarization through the Gi pathway. This gene has been cloned in reverse orientation (so-called double inverted orientation), so that a nonsense transcript is produced until the transgene is exposed to cre-recombinase, which flips the gene into the sense orientation. The cassette confers great selectivity, without transcriptional ‘leakage’ in cells that lack Cre. The DREADD was also fused to mCherry so that receptor expression can be visualized and monitored. The channel construct was subsequently packaged into an AAV vector (hSyn-DIO-hM4Di-mCherry-AAV10). The particular version of inhibitory DREADD used in this study was previously developed and rigorously validated both in vitro and in vivo and is described in detail in the following references (Anaclet et al., 2014, 2015; Venner et al., 2016).

2.7. Habituation and recording procedures

Four weeks after AAV-hM4Di injections, each mouse was connected to a recording cable and habituated to recording conditions for 2-4 h in a plethysmograph (Buxco Electronics) that was located inside an insulated soundproof recording chamber illuminated with a 12 V DC LED lights. The plethysmograph was ventilated with continuous flow of air (0.2-0.4 L/min at 22-24 °C) and allowed measuring respiratory rate and tidal volume. During the habituation days, optimal gains for all signals were established to obtain maximal amplification without saturation of the amplifiers or converters at times of maximal activity and were kept constant during all subsequent recording sessions. EEG, neck EMG and GG EMG were recorded in a bipolar configuration and amplified with the following bandwidths: 0.3–100 Hz for EEG and 30–1000 Hz for both EMG signals (Model 78 B amplifiers, Grass, Warwick, RI, USA). All signals were continuously monitored and digitally stored using sampling rates of 300 s⁻¹ for EEG and 2000 s⁻¹ for EMGs (Power-1401 A/D converter and Spike-2 v.7 data acquisition system; Cambridge Electronic Design, Inc., Cambridge, England). During recording sessions, all signals (EEG, neck and GG muscle activity, and animal’s respiration parameters that were derived from the plethysmograph) were recorded for 7 h (from 10:00 to 17:00) as following. After 2 h of baseline period (10:00–12:00), saline (control) or CNO (0.3 mg/kg, Sigma-Aldrich; (Anaclet et al., 2014, 2015; Venner et al., 2016)) were injected IP at 12:00 PM The injection effects were monitored during 5 h following the injections (12:00–17:00). In order to minimize the possibility of GG electrode failure, often caused by scarring from surgical implantation or misplacement of the tip of recording electrodes, we conducted our experiments on subsequent days rather than in a randomized sequence. Therefore, all animals received control injections of saline on the first experimental day and CNO injections on the next day (in 24 h after saline injection).

2.8. Scoring of sleep-wake states and data analysis

Data analysis was performed on animals that have satisfactory recordings of EEG and neck/GG EMGs, i.e., the recorded signals correlated with the state transitions and followed the behavioral activity of the animal with no evidence of malfunction of the implanted electrodes and with verified location of recording electrodes in the GG muscle. The behavioral states were defined using 1) the Spike-2 scoring and spectral analysis script by 10-s epochs according to the state that occupied more than 50% of the epoch duration; 2) visual analysis of the cortical and neck signals, and 3) the Spike-2 power spectrum analysis of cortical EEG. Wakefulness was recognized based on the presence of a low-amplitude and high frequency “desynchronized” EEG accompanied with a high amplitude erratic neck EMG. NREM was characterized by a high-amplitude and low frequency “synchronized” EEG accompanied by a low level and relatively stable neck EMG and a regular respiratory rate. REM sleep followed relatively prolonged periods of NREM sleep and was defined based on the desynchronized EEG with a prominent peak in the power spectrum at 5–8 Hz (“theta rhythm”), further reduction of neck EMG (“muscle atonia”) followed by muscle twitches that increase toward the end of REM sleep, and an irregular respiratory rate. We calculated the duration of wakefulness, NREM and REM sleep; the tidal volume and respiratory rate; and the mean amplitude of rectified neck and GG EMG. The measurements were obtained during 1 h periods “before” saline/CNO injections (from 11:00 to 12:00) and “after” saline/CNO injections (from 15:00 to 16:00).

2.9. Statistical analysis

For statistical analyses of the CNO effect, we used two-tailed paired Student’s t-test and two way repeated measures analysis of variance (ANOVA) with two factors: saline vs. CNO and before vs. after injections. The variability of means is characterized by the standard error (SE) throughout the report. Differences were considered significant at p < 0.05.

2.10. Histological procedures

Mice were deeply anesthetized with ketamine (100 mg/kg) and transcardially perfused with 100 mL of phosphate-buffered saline (PBS) at room temperature followed by 50 mL of 10% Formalin in PBS. Brains were removed, post-fixed overnight in formalin-PBS at 4 °C and, after cryoprotection in 20% sucrose-PBS, were cut into 40 μm-thick coronal sections on a cryostat. Separate 1-in-3 series of brain tissue sections were collected.

2.11. Immunofluorescence

To verify the expression of hM4Di receptor in A1/C1 neurons, we double-labeled sections from experimental DBH-cre mice with a rabbit polyclonal antibody that binds dsRed-derived red-fluorescent proteins to enhance the native fluorescence of mCherry and visualize hM4Di expression, and anti-TH sheep polyclonal antibody, a marker for CA neurons. Sections were washed in PBS, and incubated in primary dsRed antiserum (1:10,000, cat. #632496, Clontech) and TH (1:2000, cat. #AB1542, Millipore) diluted in PBS containing 0.25% Triton X-100 (PBST), for 12–24 h at 20–24 °C. Sections were then washed in PBS and incubated in secondary antiserum Cy3-tagged anti-rabbit IgG (for dsRed; 1:500; Jackson ImmunoResearch Laboratories); and Alexafluor 488-tagged donkey anti-sheep antibody (for TH; 1:500; Invitrogen) diluted in PBST for 2 h. Sections were then washed in PBS, mounted on SuperFrost Plus slides, dried overnight, cover-slipped using Prolong Gold antifade mountant (Molecular probes #P36930), and stored in slide folders at 4 °C until imaging. In all animals, we verified AAV-hM4Di injection sites in the A1/C1 region using the fluorescent and confocal microscopes (Zeiss LSM 710).

2.12. Histological verification of GG muscle recording sites in the tongue

Prior to perfusion, in deeply anesthetized mice, a low intensity (18 μA) positive current was passed through the GG recording electrodes for 60 s to deposit iron ions (Fig. 1E). After the perfusion, tongues were removed, postfixed and cryoprotected and serially cut into 50 μm parasagittal sections and mounted. Using the Prussian blue iron staining kit (Polysciences, Inc #24199) that results in dark blue staining.
of iron deposit (Fig. 1E), we verified the location of GG recording electrodes with a brightfield microscope at 4x and 10x (Olympus CHBS).

3. Results

3.1. Cre-dependent gene expression in brainstem catecholaminergic neurons of DBH- and TH-cre mice

We compared specificity of Cre-dependent gene expression in brainstem SubC, A7, A5 and A1/C1 CA neurons between transgenic TH-cre mice and the more recently developed DBH-cre mice. In the TH-cre mice Cre recombinase is under the control of tyrosine hydroxylase (TH) promoter whereas in DBH-cre mice Cre-recombinase is expressed under the DBH promoter in all CA cells. Following dual fluorescent immunohistochemistry, we examined the distribution pattern of TH-positive (TH+) (Fig. 2A, green), tdTomato-positive (tdTomato+) (Fig. 2B, red) and double-labeled (Fig. 2C, yellow-orange color) A1/C1 neurons in both mouse lines. We found that the distributions of TH+ CA neurons in locus coeruleus (LC), sub-coeruleus (SubC), A7, A5 and A1/C1 in both mouse lines are similar to that described previously in rats (Rukhadze and Kubin, 2007; Rukhadze et al., 2008). We counted...
the total number of TH+ neurons, double labeled TH+/tdTomato+ and TH−/tdTomato+ (ectopic expression) in these CA regions. The ectopic expression (number of TH−/tdTomato+ neurons relative to the total tdTomato+ neurons) in DBH-cre mice mouse (n = 1) was lower for most CA regions (SubC 0.0%, A7 0.0%, A5 25.0%, A1/C1 30.0%) (Fig. 2C, H, I, J) as compared to TH-cre mouse (n = 1) (SubC 18.9%, A7 22.2%, A5 50.0%, A1/C1 35.7%) (Fig. 2G, K, L, M). Ectopic expression of a cre-dependent gene detected in these mouse lines might be related to transient promoter activity during development, as has been demonstrated in several other cre lines (Vong et al., 2011; Venner et al., 2016). In addition, eutopic expression (number of TH+/tdTomato+ neurons relative to the total TH+ neurons) in SubC, A7, A5 and A1/C1 regions tended to be higher in DBH-cre mice when compared to the TH-cre mice (84.2% ± 7.9 vs. 79.6% ± 9.0). We therefore opted to use DBH-cre mice rather than TH-cre mice for our study. As expected, injections of AAV-hM4Di into the A1/C1 of this line of DBH-cre mice show strong co-expression of the hM4Di receptor expression (red) in TH + A1/C1 neurons (green) (Fig. 2D).

### 3.2. Recording of genioglossus muscle activity in naturally sleeping mice

All experimental mice following habituation to the plethysmograph chamber and recording conditions (Fig. 3A) exhibited normal pattern of the sleep-wake behavior. During wakefulness, the GG and neck muscles displayed the highest amplitude of tonic or phasic activity (Fig. 3B). In recordings of A1/C1 neurons (green) (Fig. 2D).

When measured during NREM sleep, selective inhibition of A1/C1 neurons by CNO injections into the DBH-cre mice expressing hM4Di receptors in A1/C1 neurons resulted in suppression of tonic GG muscle activity as compared with saline (control) injections in the same mice (n = 4) (Fig. 4A). Mean GG muscle activity during NREM sleep tended to increase from the morning measurements (before saline injections) and the measurements made afternoon (after saline injections) in control experimental sessions: from 31.6 AU (arbitrary units) + 12–37.2 AU + 13. However, CNO injections reduced mean GG muscle activity from 34.9 AU + 7.8 to 28.1 AU + 5.4 (Fig. 4B). The depressant effect of CNO on GG EMG was statistically significant (F[1,1,3] = 17.1, p = 0.026, ANOVA, n = 4). In contrast with that observation, neither the amplitude of neck EMG, respiratory rate, tidal volume or the duration of states was changed during NREM sleep after the CNO when compared with saline injections in the same mice (Fig. 4C-F). These data suggest that chemogenetic inhibition of A1/C1 neurons has a specific effect on GG muscle activity.

The relative changes in GG and neck EMG after the saline/CNO injections were compared to their EMG levels before the injections during NREM sleep (Fig. 5). In control sessions, the relative increase of GG muscle activity after saline injection was to 122% ± 6.0. The CNO injection decreased GG EMG to 81.8% ± 4.6 relative to its pre-injection level (p < 0.01, paired t-test, n = 4). The relative changes for neck EMG were essentially the same in both control and CNO sessions: 97.7% ± 2.4 and 94.7% ± 5.7, respectively. The individual effects of CNO on GG muscle activity were consistent in the magnitude and direction in all animals (Fig. 5B).

During wakefulness, CNO injections tended to decrease the amplitude of GG EMG (180 AU + 39 before and 120 AU + 37 after, CNO) as compared to saline sessions (153 AU + 24 before and 142 AU + 37 after, saline). In relative units GG EMG decrease also tended to be larger in CNO sessions as compared to saline sessions: 72.7% ± 20 vs. 91.2% ± 18 (not significant, paired t-test, n = 4). During REM sleep, the CNO injections had no effect on GG EMG because the activity of GG muscle showed no activity during REM sleep and hence an effect of CNO could
not be determined.

3.4. Effect of CNO on the magnitude of sleep-related depression of GG muscle activity

Our next objective was to determine whether acute inhibition of A1/C1 neurons altered the magnitude of relative suppression of GG muscle activity that occurs following transitions from wakefulness to NREM sleep. After saline injections, the GG muscle activity decreased during NREM sleep by 62.1% ± 21 (n = 4) relative to its activity during wakefulness (Fig. 6). The mean GG muscle activity decreased during both wakefulness and NREM sleep after CNO injections (Fig. 6). However, and contrary to our expectations, NREM-induced depression of GG muscle activity following CNO injections was 66.6% ± 11, which was similar or higher to that obtained after saline injections.

4. Discussion

This is the first study to report on the activity of the GG muscle in behaving mice and to assess the functional role of CA A1/C1 neurons in...
the control of GG muscle activity during sleep and wakefulness. The major findings of this study are 1) the activity of A1/C1 neurons has a net excitatory effect on GG muscle activity; and 2) the activity of A1/C1 CA neurons does not contribute to NREM sleep-related suppression of GG muscle activity.

Important advances in understanding the neural mechanisms of sleep-related depression of upper airway motoneurons have been made over the past three decades with multiple neurotransmitter systems now implicated in REM sleep-related depression of XIImms. Yet the neuronal circuitry underlying the upper airway muscle depression during NREM sleep and REM sleep has not been fully identified and characterized. The research conducted to date has been largely focused on the mechanisms mediating REM sleep-related depression of XIImms, as XIImms innervate the muscles of the upper airway (Zauera and Harper, 1976; Remmers, 1978; Mezzanotte et al., 1992; Fenik et al., 2004, 2005b; Saboisky et al., 2007; Kubin, 2014, 2016). Two major competing theories have argued that REM sleep-related depression of activity in upper airway muscles results from either postsynaptic inhibition (increased glycine and/or GABA hyperpolarization) or disfacilitation (decreased serotonergic and noradrenergic excitation) of XIImms.

The first direct evidence that glycine is an essential neurotransmitter for mediating REM sleep-related atonia of postural muscles was provided in studies using behaving cats (Soja et al., 1991). General support for postsynaptic inhibition of XIImms during REM sleep derives from a microdialysis study showing that levels of GABA and glycine are increased in the hypoglossal nucleus during REM sleep (Kodama et al., 2003). However, other studies testing the direct role of GABA and/or glycine antagonists in REM sleep-related depression of XIImms in different animal models such as decerebrated cats (Kubin et al., 1993), anesthetized rats (Fenik et al., 2005b), and freely behaving rats (Morrison et al., 2003) have reported little or no effect of glycine/GABA receptors on the suppression of XIImms or GG muscle activity during either REM sleep or REM sleep-like state. Hence consensus on this important mechanistic issue remains lacking.

The hypothesis that withdrawal of monoaminergic drive to XIImms during REM sleep might underlie changes in GG activity has received support from direct pharmacological studies (Fenik et al., 2004, 2005a, 2005b; Chan et al., 2006). For example, depression of XII nerve activity during carbachol-elicited REM sleep-like state can be pharmacologically abolished by microinjections of GABA, glycine, NA and SHT antagonists into XIImms in urethane anesthetized rats (Fenik et al., 2004). It has also been shown that a combination of NA and SHT antagonists is both necessary and sufficient to abolish depression of XII nerve activity during REM sleep-like state (Fenik et al., 2005a), with the contribution of NA being larger than SHT (Fenik et al., 2005a; Kubin, 2014, 2016; Fenik, 2015). These findings were confirmed by reports that NA has a significant contribution to REM sleep-related depression of GG muscle activity in naturally sleeping behaving rats (Chan et al., 2006) whereas the contribution of SHT was minimal (Sood et al., 2005).

The role of glutamate and acetylcholine in REM sleep-related depression of XIImms has been suggested by an in-vitro study, in which glutamatergic excitation of XIImms was presynaptically inhibited by muscarinic mechanisms (Bellingham and Berger, 1996). However, the investigation of glutamatergic mechanisms in behaving rats did not provide sufficient evidence to either support or refute the role of glutamate in this phenomenon (Steenland et al., 2008). In addition, no changes in the level of glutamate were detected in XII motor nucleus during REM sleep (Kodama et al., 2003). Recently, muscarinic inhibition has been reported to play a significant role in REM sleep-related depression of GG muscle activity mediated by G-protein-coupled inwardly rectifying potassium channels in behaving rats (Grace et al., 2013).

The density of NA terminals that closely apposed to GG motoneurons in the ventral region of XII nucleus increased in rats that were exposed to chronic-intermittent hypoxia, i.e., conditions mimicking OSA (Rukhadze et al., 2010). This finding is consistent with increased GG muscle tone in OSA patients (Mezzanotte et al., 1992). In our previous anatomical studies using retrograde tracers, we showed that the A1/C1, A7, LC, SubC and A5 neurons provide innervation of the XII nucleus (Rukhadze and Kubin, 2007). The individual contribution of each of these NA cell populations to the innervation of the XII nucleus was highest for A5 neurons and lowest for LC neurons (ibid). Recently, using conditional anatomic tracers in TH-cre mice, we examined the projections from A1/C1 neurons to XIImms and found TH-positive anterogradely labeled axon terminals within the ventral sub-division of the XII nucleus that innervates the GG muscle (Rukhadze and Fuller, 2015).

Brainstem NA neurons of the LC (Aston-Jones and Bloom, 1981) and SubC (Reiner, 1986) reduce their activity during NREM sleep and are virtually silent during REM sleep. In addition, Fos expression in A2/C2, A5, SubC and A7 neurons strongly correlates with parameters of pharmacologically induced REM sleep-like states, which suggests a state-dependent nature of their activity, whereas A1/C1 neurons did not show a significant correlation (Rukhadze et al., 2008). The fact that A1/C1 neurons did not significantly decrease their activity during REM sleep-like states could be explained by activation of C1 neurons during REM sleep-like state (Stettner et al., 2013). Clearly, further studies are needed to dissociate the mixed population of A1/C1 neurons and establish the functional relationship between GG muscle activity and noradrenergic A1 and adrenergic C1 neurons during sleep-wake states in behaving mice.

NA mechanisms appear to make an important contribution to REM sleep-induced depression of XIImms and the role of NA neurons in maintenance of XIImms activity was assessed in previous functional studies. For example, it was found that clonidine-induced decrease in activity of A7 neurons, but not A5, LC or SubC neurons, reduced activity of XIImms in anesthetized rats (Fenik et al., 2002, 2008, 2012). As indicated, the role of A1/C1 neurons was not tested in these studies. We therefore decided to investigate the effect of inhibition of A1/C1 neurons on upper airway muscles in behaving animals using the DREADD technique because 1) precise targeting of neural structures by nanoliter microinjections of agonists and antagonists is not feasible in behaving animals, and 2) the microdialysis approach can potentially damage the A1/C1 nucleus in mice. In addition, by using the DREADD technique we were afforded the opportunity to work with behaving animals and thereby assess the contribution of A1/C1 neurons to state-dependent modulation of GG muscle activity. We found that AAV-hM4Di receptor-mediated inhibition of A1/C1 neurons specifically decreased the activity of GG muscle during NREM sleep and had a tendency to do so during wakefulness.

Since A1/C1 neurons do not demonstrate strong state-dependent activity (Rukhadze et al., 2008), the contribution of these neurons to state-dependent modulation of XIImms activity would not have necessarily been predicted. However, as stated, it is possible that presynaptic mechanisms (Bellingham and Berger, 1996) might control the release of NA from the A1/C1 terminals to XIImms and, if so, this would permit A1/C1 neurons to contribute to state-dependent depression of GG muscle. We tested this hypothesis by analyzing the relative decrease of GG muscle activity during the transition from wakefulness to NREM sleep. If our hypothesis were correct, one would expect that the relative NREM sleep-induced depression of GG muscle activity would decrease after CNO as compared to saline injections. However, NREM-induced GG muscle depression did not decrease further following CNO injections, suggesting that the activity of A1/C1 does not contribute to the naturally occurring inhibition of GG muscle during transitions from wakefulness to NREM sleep. We did not test the effect of CNO on GG muscle inhibition during REM sleep for reasons that are discussed below.

In this study, our assessment focused on A1/C1 inhibition of GG muscle activity under normal isocapnic condition. Under this condition, similarly to naturally sleeping rats (Rukhadze et al., 2011, 2014a,
As CA neurons in A1/C1 region are implicated in cardiovascular control (Abbott et al., 2009; Guyenet et al., 2013; Burke et al., 2014), CNO could affect blood pressure, but this was not assessed in our experiments. However, we believe that any possible influence of blood pressure changes, secondary to CNO administration, on GG activity was negligible for two reasons: 1) since A1 neurons provide inhibitory control over C1 neurons (Granata et al., 1985), the simultaneous inhibition of both neural groups by CNO in our experiments likely resulted in minor or no changes in blood pressure; 2) since an increase in blood pressure inhibits respiratory discharges but not tonic activity in hypoglossal nerve (Wasicke et al., 1993), changes in blood pressure were unlikely to affect the tonic GG activity that was recorded in our experiments. In addition, we cannot exclude the possibility that inactivation of A1/C1 neurons during wakefulness may have reduced the frequency of oral behaviors (i.e., eating, drinking, grooming etc.), which, in turn, could have contributed to the tendency of GG activity to decrease.

Recent data provide support for the concept that the mechanisms underlying OSA may vary across individuals, with some patients exhibiting anatomical predisposition, others showing dysfunction in upper airway dilator muscles, and yet others having unstable ventilatory control or some combination of abnormalities (Veasey, 2012; Eckert et al., 2013). OSA patients experience upper airway obstruction only during sleep, whereas during wakefulness they maintain upper airway patency and adequate ventilation (Remmers, 1978; Mezzanotte et al., 1992). Decreased activity of Xllms that innervate upper airway dilator muscles during sleep may thus play a key role in a subset of OSA patients (Jordan et al., 2014). In fact, for these patients electrical stimulation of hypoglossal nerve effectively decreases the apnea/hypopnea index (Strollo et al., 2014; Schwartz et al., 2014; Kezirian et al., 2014). Studies of single motor units in humans have also revealed considerable complexity of upper airway motor control (Saboisky et al., 2007; Nicholas et al., 2010; Trinder et al., 2014). More human studies in combination with more basic studies such as the present one will be required to define new therapeutic approaches for OSA.

In summary, our data demonstrate that medullary A1/C1 CA neurons, similar to previously established pontine A7 noradrenergic neurons, are involved in control of upper airway muscle activity (Fenik et al., 2008). We found that acute and selective inhibition of A1/C1 neurons 1) decreased the activity of the GG muscle during NREM sleep, but 2) does not alter the magnitude of naturally occurring depression of GG muscle during transitions from wakefulness to NREM sleep. These findings suggest that A1/C1 neurons represent an important state-independent mechanism to protect upper airway from collapse during sleep onset in OSA patients.

References


