

This article was published in *European Journal of Neuroscience*, 2002, 15(4), pp. 684-692  
doi :10.1046/j.1460-9568.2002.01909.x ; Blackwell Publishing, Inc  
The publication is available online at  
<http://www.blackwell-synergy.com/doi/abs/10.1046/j.1460-9568.2002.01909.x>

**Different Respiratory Control Systems are affected in Homozygous And Heterozygous  
*kreisler* Mutant Mice.**

**Fabrice Chatonnet<sup>1,CA\*</sup>, Eduardo Domínguez del Toro<sup>1,3\*</sup>, Octavian Voiculescu<sup>2</sup>, Patrick Charnay<sup>2</sup> and Jean Champagnat<sup>1</sup>.**

<sup>1</sup>Neurobiologie Génétique et Intégrative, UPR2216, Centre National de la Recherche Scientifique, Institut de Neurobiologie Alfred Fessard UFR 2218, 91198 Gif-sur-Yvette Cedex, France.

<sup>2</sup>Biologie Moléculaire du Développement, Unité 368 de l'Institut National de la Santé et de la Recherche Médicale, Ecole Normale Supérieure, 75230 Paris Cedex 05, France.

<sup>3</sup>Present Address: Division de Neurociencias, Laboratorio Andaluz de Biología, Universidad Pablo de Olavide, Sevilla 41013, Spain.

\*These authors contributed equally to this work.

<sup>CA</sup>: Corresponding author, at <sup>1</sup> as above, e-mail: Fabrice.Chatonnet@iaf.cnrs-gif.fr.

Running title: Respiratory phenotypes of *kreisler* mutants mice.

Key words: apneic breathing, neonate mice, *kreisler*, *Krox20*, rhombomeres.

Number of word in summary: 196, introduction: 476, whole paper: 7726.

Number of tables: 1, number of pages: 33.

## Abstract

During embryonic development, restricted **expression** of regulatory genes *Krox20* and *kreisler* are involved in segmentation and antero-posterior patterning of the hindbrain neural tube. The analysis of transgenic mice in which specific rhombomeres (r) are eliminated points to an important role of segmentation in the generation of neuronal networks controlling vital rhythmic behaviours such as respiration. Thus, elimination of r3 and r5 in *Krox20*<sup>-/-</sup> mice suppresses a pontine anti-apneic system (Jacquin *et al.*, 1996). We now compare *Krox20*<sup>-/-</sup> to *kreisler* heterozygous (+/*kr*) and homozygous (*kr/kr*) **mutant** neonates. In +/*kr* mutant mice, we describe hyperactivity of the anti-apneic system: analysis of rhythm generation *in vitro* revealed a pontine modification in keeping with abnormal cell specifications previously reported in r3 (Manzanares *et al.*, 1999b). In *kr/kr* mice, elimination of r5 abolished all +/*kr* respiratory traits, suggesting that +/*kr* hyperactivity of the anti-apneic system is mediated through r5-derived territories. Furthermore, collateral chemosensory pathways that normally **mediate** delayed responses to hypoxia and hyperoxia were not functional in *kr/kr* mice. We conclude that the pontine anti-apneic system originates from **r3r4**. A different rhythm-promoting system originates in r5 and *kreisler* controls the development of anti-apneic and chemosensory signal transmission at this level.

## Introduction

Hindbrain segmentation into rhombomeres (r) is a transient feature of early development (Lumsden & Keynes, 1989; reviewed by Lumsden & Krumlauf, 1996) followed by a dramatic reconfiguration of neuronal networks during foetal and neonatal brainstem maturation. Primordial rhythmic activities start in the hindbrain near the end of the segmentation process (Fortin *et al.*, 1994a, 1995), and the activity of specific rhythm-promoting connections has been recently found to require a 2-segment repeated rhombomeric code (Fortin *et al.*, 1999). Whether and how segmentation influences neuronal network properties remains an open issue. Our physiological approach to this problem is the analysis of the respiratory rhythmic neuronal network located in the pons and the medulla (reviewed by Bianchi *et al.*, 1995).

Among the genes expressed in rhombomere-restricted patterns (reviewed by Schneider-Maunoury *et al.*, 1998), *Krox20*, *Hoxa1* and *kreisler* are implicated in the control of segmentation **at distinct antero-posterior levels**, since their inactivation leads to the elimination of rhombomeres r3 & r5, r4 & r5, and r5, respectively (Mark *et al.*, 1993; Schneider-Maunoury *et al.*, 1993; Cordes & Barsh, 1994; Manzanares *et al.*, 1999b). Previous studies in *Krox20*<sup>-/-</sup> (Jacquin *et al.*, 1996) and *Hoxa1*<sup>-/-</sup> (Domínguez del Toro *et al.*, 2001) mice demonstrated that a normal embryonic expression of these genes **in r3 and r5 or r4 and r5 respectively**, is necessary for normal postnatal neuronal network function. *Krox20*<sup>-/-</sup> mutants exhibit a respiratory phenotype including low frequency and increased time spent in apnoeas, correlated with the absence of anti-apneic structures normally originating from r3 or r5. The present study seeks for a similar role for *kreisler*, in an attempt to elucidate the respective implication of r3 and r5 in respiratory controls.

The *kreisler* gene encodes a *mafB*-related transcription factor. It is expressed in r5, in r6 and in the roof plate along the hindbrain. It upregulates the expression of *Hoxa3* in both r5 and r6, and of *Hoxb3* in r5 (Manzanares *et al.*, 1997, 1999a). The *kreisler* mutants were generated by X-ray mutagenesis, the homozygous mutant animals (*kr/kr*) being hyperactive, a behavioural pattern characterised by head-tossing, running in circles, and deafness due to absence of a functional inner ear (Hertwig, 1942, 1944; Deol, 1964). These defects result from the early role of *kreisler* in r5 formation, since r5 is the only rhombomere that fails to form in *kr/kr* embryos. Later patterning in r6, including the caudal expression of *Phox2b* in a lateral cell column, is altered in *kr/kr* mice, even though the formation of r6 is not affected. Moreover, in both heterozygous (+/*kr*) and homozygous *kreisler* mutant embryos, patterning defects have also been observed in r3. *Hoxa3*, **normally expressed posterior to r4**, is upregulated and *ephrinB2* downregulated in r3 (Manzanares *et al.*, 1999b). We now show that this abnormal specification in r3 correlates at birth with alterations in the anti-apneic system and we identify specific defects resulting from the elimination of r5.

## **Material and methods**

### ***Genotype analysis***

The *kreisler* mutation was maintained in a 129 background in association with the *agouti* mutation. DNA was extracted from the tail of the mouse as described elsewhere (Lufkin *et al.*, 1991). The genotype at the *kreisler* locus was subsequently determined by a PCR assay using a set of oligonucleotide primers allowing amplification of the restriction site polymorphism associated with the *kreisler* mutation (Cordes & Barsh, 1994).

### ***Plethysmograph recordings***

Respiratory activity was measured using a modified barometric method previously employed in neonates (Fortin *et al.* 1994b). The plethysmograph chamber (20 ml) equipped with a temperature sensor (LN 35 Z) was connected to a reference chamber of the same volume. The pressure difference between the two chambers was measured with a differential pressure transducer (Validyne DP 103-14) connected to a sine wave carrier demodulator (Validyne, CD15). The spirogram was stored on a computer using a Labmaster interface at a sampling frequency of 1 kHz. Calibrations were recorded at the end of each recording session by injecting 2.5 - 5  $\mu$ l of air in the chamber with a Hamilton syringe.

Neonates were removed individually from the litter and placed in the plethysmograph chamber kept hermetically closed and maintained at 31°C during the recording session (165 s). In each sample, we identified the periods of quiet breathing recorded in the absence of limb or body movements. **Duration of these limb, body and head movements were used to determine activity of the neonate mouse during recording.** During quiet breathing, a computer-assisted method was used to measure the durations of inspiration and expiration from which respiratory frequency (f) is derived and the tidal volume ( $V_T$ ,  $\mu$ l/g) from which minute volume ( $V(\dot{)}=f*V_T/1000$ , ml/g/min) is derived. Periods of apneic breathing are not included in frequency calculation. Comparisons between two sets of data were performed by paired Student's t-tests. Naloxone (3.33 mg/kg in 50  $\mu$ l saline was administered subcutaneously using an Hamilton syringe). During hyperoxic exposure (40 s) the chamber was flushed with a humidified 100% O<sub>2</sub> gas during recording, during hypoxic exposure (40 s) the chamber was flushed with a humidified gas mixture of 12% O<sub>2</sub> in N<sub>2</sub>.

### ***Anatomical observation and immunochemistry***

Thirty days old mice (6 homozygous mutants, 6 heterozygous mutants and 4 wild-type animals) **were anaesthetised** and intracardially perfused for 15 min with 0.01M phosphate buffer (pH 7.4), followed by a mixture of 4% paraformaldehyde in 0.01M phosphate buffer (pH 7.4). The brain was removed and placed overnight in the same fixative. The brains were then rinsed in phosphate buffer containing 20% sucrose and stored at 4°C until used. Serial parasagittal 40 µm sections were cut on a freezing microtome. Sets of four adjacent sections were processed using cresyl violet and polyclonal antibodies to tyrosine hydroxylase and choline acetyltransferase (ChAT). Sections processed for tyrosine hydroxylase immunochemistry were incubated in the presence of Triton X-100 overnight at room temperature with the antibody (Boeringer, 1:1000 in PBS, pH 7.4) and for 2 hours with biotinylated anti-mouse serum (Amersham, 1:200, pH 7.4). Peroxidase was subsequently revealed in a staining mixture containing 0.05% 3,3'-diaminobenzidine hydrochloride (DAB, Sigma) and 0.03% H<sub>2</sub>O<sub>2</sub> (1 hour at room temperature). Sections processed for ChAT immunochemistry were incubated overnight at room temperature with the antibody (Chemicon International Incorporated, 1:2000 in PBS), which was subsequently revealed using the Vectastain ABC kit (Vector).

### ***In vitro perfused brainstem***

The brainstem-spinal cord preparations were isolated from anaesthetised 1 to 3 days old mice as described previously (Suzue 1984, Reckling *et al.*, 1996). To isolate the hindbrain-spinal cord without the cerebellum, the more rostral section was performed at the rostral part of the pons (ponto-mesencephalic preparation, PM). The caudal section was performed between the cervical and thoracic rootlets to preserve the integrity of the C6 (phrenic) level of the spinal cord.

The preparations were pinned down for electrophysiological recordings **and transections** with the ventral surface upwards in a 2 ml chamber and bathed in a ringer solution of the following composition (mM): KCl, 5.4; NaCl, 130; MgCl<sub>2</sub>, 1; NaHCO<sub>3</sub>, 26; D-glucose, 30; CaCl<sub>2</sub>, 0.8 equilibrated with a 10% CO<sub>2</sub> in O<sub>2</sub> gas mixture at 26°C, pH 7.0 and perfused at a rate of 1 ml/min. **Transections of the ventral (Borday *et al.*, 1997) pontobulbar respiratory controls were performed using a razor blade driven in the recording chamber.** A pontobulbar (PB) section was performed at the level of the inferior cerebellar arteries to isolate the medullar generator from its pontine afferences. **After PB sections, rostral and caudal parts of brainstem were fixed in 4% paraformaldehyde in Phosphate Buffer. Coronal sections stained with cresyl violet and analysed under light microscope indicated the same level of PB sections, at the caudal end of the facial motor nucleus, in *+/kr* (n=5) and *kr/kr* (n=4) animals, as in control animals. In *+/kr* (n=2) and *+/+* (n=2) animals, a trigemino-facial (TF) section was performed immediately rostral to the exit point of the facial nerve to eliminate rostral pons deriving from r3 and r4.**

Various dissected cranial nerves such as the V, VII, XII and C1 to C6 were recorded. In *kr/kr* animals, VI rootlet is missing, and ventral hypoplasia can be appreciated. Simultaneous recordings by pairs of any of those rootlets ipsilaterally or bilaterally were performed before and after ponto-bulbar sections. Rootlets were recorded using suction electrodes connected to Grass amplifiers. Data were stored on a PC computer using a Labmaster interface at a sampling frequency of 1 kHz. Smooth integration was performed from a full wave rectified signal with a 40 ms time constant.

## Results

A total of 72 animals resulting from inter-crosses between *kreisler* mutants were analysed. 24 of these animals were *kreisler* homozygous mutants, 32 were heterozygous and 16 were wild-types, as determined by PCR genotyping. Analysis of the phenotype and genotype was performed independently in blind experiments and compared afterwards. Anatomical studies were performed on animals allowed to survive 30 days, while behaviour was analysed during the first week after birth. We have studied the link between the *kreisler* mutation and respiratory and motor deficits by measuring the respiratory frequency,  $V_T$  (Table 1) and motor responses including activity, reactions to stress and the righting reflex (a normal reflex reaction of neonate mice, which turn back to prone position when placed in supine position).

### ***Inactivation of a Single kreisler Allele Affects Respiratory Pattern at Birth While the Homozygous Mutation Eliminates Respiratory Traits of +/kr Phenotype***

The *+/kr* mice showed a modified pattern of quiet breathing (Figure 1) with a higher than normal respiratory frequency (polypnea) resulting from shorter expirations and a lower tidal volume. This respiratory phenotype was highly penetrant in the mutant mice population when compared to wild-type animals (Figure 1C) and particularly significant during the first three days after birth (Figure 1B). During the first days after birth, wild-type mice exhibited irregular breathing including a significant number of apnoeas (i.e. expirations lasting more than 2 s). The total time spent in apnoeas was almost 1 order of magnitude less in *+/kr* mutants than in wild-type littermates (Table 1). **Comparison of *kr/kr* and *+/kr* demonstrates a significant reversion of the *+/kr* phenotype by the homozygous mutation (Table 1). In *kr/kr* mice, the *in vivo***

**respiratory frequency was slightly less than normal (Figure 1B) and the duration of apnoeas was normal (Table 1).**

Increased respiratory frequency can be related to stress, hyperthermia, **hyperactivity** or exaggerated chemosensitive responses. However, in the *+/kr* mice, no stress reactions nor **hyperactivity** were visible when observing the patterns of limb, neck or body movements in the plethysmographic chamber (Table 1). The buccal temperature (Table 1) and responses to hypoxic or hyperoxic stimuli (data not shown) were not significantly different from those of *+/+* animals.

Therefore, inactivation of one of the two *kreisler* alleles resulted in rather selective modifications of the quiet and apneic breathing patterns, without interfering with survival. **The homozygous mutation suppressed this phenotype.**

#### ***Pontine Origin of the Respiratory Phenotype in Heterozygous *+/kr* Mutants***

As previously done in *Krox20<sup>-/-</sup>* mice, central respiratory deficits were investigated using neonatal (P1-P2) hindbrain preparations, isolated and superfused *in vitro*, and from which a spontaneous, synchronised respiratory-like activity is recorded from the hypoglossal (12n, Figure 2A) or cervical spinal nerve roots. A ponto-mesencephalic section (PM, Figure 2A) delimited preparations including the pons and the medulla (PM frequency in Figure 2C). A section at the ponto-bulbar junction (PB, Figure 2A & 2B), **caudal to the facial motor nucleus (see Methods)**, isolated the medulla which retains the rhythmic respiratory-like activity originating in the ventral bulbar respiratory group (PB activity in Figure 2C). To quantify the effect of the pons in *+/kr* and wild-type animals, we measured the changes in respiratory frequency before and after the ponto-bulbar transection for each type of animal ( $\Delta f = PB - PM$ , inset in Figure 2C). We found a pontine inhibition that was significantly less in *+/kr* mutants as compared to wild-type animals

( $\Delta f = 0.0788 \pm 0.0089$  Hz in  $+/+$ ,  $n=4$ ,  $0.0429 \pm 0.0089$  Hz in  $+/kr$ ,  $n=7$ ,  $p < 0.05$ ). In  $+/kr$  mice, the PB frequency was normal ( $0.168 \pm 0.014$  Hz,  $n=4$ ) and the PM frequency was higher ( $0.133 \pm 0.018$  Hz,  $n=7$ ,  $p < 0.01$ ) than in wild-type littermates ( $0.090 \pm 0.009$  Hz,  $n=4$ ). Similar measurements led to contrasting observations in *Krox20*<sup>-/-</sup> mice, in which pontine inhibition was greater than normal (Jacquin *et al.*, 1996).

In *kr/kr* mice, the pontine control ( $\Delta f = \text{PB} - \text{PM}$ , inset in Figure 2C) was normal, in keeping with the behavioural and *in vivo* analysis suggesting a reversal, rather than an exaggeration, of respiratory phenotypic traits observed in *+/kr* mice *in vitro*. Caudally to PB sections, the rhythmogenic function of the ventral respiratory group was preserved (Figure 2C), although the burst frequency was lower ( $0.106 \pm 0.018$  Hz,  $n=4$ ) than in wild-type or heterozygous mice ( $0.155 \pm 0.008$  Hz,  $n=11$ ,  $p < 0.02$ ). Thus, the *kr/kr* mutation seemed to alter the medullar rhythm generation and abolished all phenotypic traits modifying the control of resting, apneic and *in vitro* respiratory frequencies in *+/kr* animals.

To further locate pontine defects in *+/kr* mutants, we have sectioned between the exit point of the trigeminal and facial nerves (TF section, Figure 2A), thereby eliminating r3-derived and more rostral structures. A sequential PB section then eliminated r4- and r5-derived structures. In wild-type animals, the TF section was responsible for the increase in burst frequency (Figure 2D). Neither of the two sections were very effective in *+/kr* mice. We thereby exclude that in these animals, the inhibitory effect of the rostral pons (r3-derived) was compensated by an excitatory effect of more caudal (r5-derived) structures.

### ***Respiratory Phenotype in +/-kr Mutants Does Not Result From the Elimination of Catecholaminergic or Enkephalinergic Neurons***

To demonstrate that the lack of pontine inhibition does not result from the elimination of certain neuronal populations, we have specifically investigated the two major systems that could possibly depress respiration at birth, the enkephalinergic system and the catecholaminergic A5 group. The group of noradrenergic neurons named A5, is a major pontine rhythm depressant system active *in vitro* in newborn rodents (Errchidi *et al.* 1991) and interacts with the enkephalinergic system (Romagnano *et al.*, 1991, Arvidsson *et al.*, 1995). Enkephalinergic neuron function was investigated pharmacologically *in vivo* by subcutaneous administration of the selective antagonist naloxone during quiet breathing. As noted previously (Jacquin *et al.*, 1996), naloxone has little effect in wild-type animals. In contrast, naloxone significantly stimulated respiratory frequency in +/-kr mice, indicating that enkephalinergic inhibition might be hyperactive in these animals (Figure 3). **This hypersensitivity to subcutaneous naloxone administration was reversed by homozygous mutation (Figure 3B).**

Immunohistochemistry of tyrosine hydroxylase, an enzyme of the catecholamine synthesising pathway, was performed in 6 heterozygous mutants and 3 wild-type animals at P30 and showed that the neurons of the A5 group appeared normal (not shown). These observations demonstrate that major populations of respiratory-depressant pontine neurons are not eliminated in +/-kr mutant.

### ***Pontine Neuronal Populations generated in Hoxa1<sup>-/-</sup> mice are not seen in +/-kr Mutants***

As in *Hoxa1<sup>-/-</sup>* mutants (Domínguez del Toro *et al.*, 2001), an exaggerated pontine excitation might result from the formation of a novel population of r3-derived, *Krox20-*

dependent, rhythm-promoting neurons. We have therefore investigated the anatomical correlates of this phenomenon previously identified in *Hoxa1*<sup>-/-</sup> mutants, namely: (i) a characteristic morphological abnormality of the anterior fourth ventricle, (ii) an increase in the antero-posterior length of the dorsal Pons and (iii) a compound reticular and motor supernumerary structure comprising radial stripes of reticular formation and ectopic trigeminal motoneurons, formed at the level of the wild-type parvocellular reticular nucleus, a dorsal pontine structure originating in r3. None of these phenotypic traits were observed in *+/kr* and *kr/kr* mutants. The parvocellular reticular nucleus, extending between the trigeminal motor nucleus and the facial nerve (length: 438±58.8 µm in *+/+*, n=4; 474±68.2 µm in *kr/kr*, n=4; 466±59 µm in *+/kr* n=4 ) and the morphology of the fourth ventricle were normal in *kreisler* mutants (Figure 4A and 4B).

#### ***Delayed Responses to Hypoxia and Hyperoxia are Eliminated in kr/kr Mice***

Lethal deficits previously described in *Krox20*<sup>-/-</sup> mice were not seen in *kr/kr* mutants, indicating normal function of the anti-apneic system. The *kr/kr* mice were characterised by a lack of righting reflex and a respiratory depression resulting from a small V<sub>T</sub> (Table 1). Respiratory depression was not life threatening because the mutation was lethal for only 3 *kr/kr* (out of 24); no wild-type or heterozygous animals died. The small V<sub>T</sub> might be indicative of chemosensory abnormalities as suggested by previous observations on *BDNF*<sup>-/-</sup> mice lacking subpopulations of sensory neurons (Erickson *et al.* 1996). Chemosensory signals controlling respiration are conveyed by glossopharyngeal sensory neurons (Neubauer *et al.*, 1990) that might be affected by the *kr/kr* mutation (Mc Kay *et al.*, 1994). We have used hypoxic and hyperoxic tests **at the age of P10** to investigate possible defects of the respiratory responses in *kr/kr* (Figure 5A) or *+/kr* mice (Data not shown). The responses were normal in *+/kr* animals. Significant changes in respiratory

minute volume were induced in all animals 30 s after the onset of these stimuli (Figure 5B). Hyperoxia which eliminates on-going chemosensory control, led to reduction of  $\dot{V}$ (dot), whereas hypoxia increased  $\dot{V}$ (dot) as a short term effect. Thus, chemoreceptors that normally detect the oxygen level and transmit this information to central structures (Gonzalez *et al.*, 1994; Vizeck & Bonora, 1998) were operational. However, processing of this information within the central nervous system (90 s after the onset of stimuli, Figure 5B) was modified in *kr/kr*. Hyperoxia-induced reduction of  $\dot{V}$ (dot) was sustained in *+/+* mice, while it is no more effective after 90 s in *kr/kr* mutants. The secondary effect of hypoxia was a reduction of  $\dot{V}$ (dot), which was not observed in *kr/kr* mice, suggesting the elimination of a previously described pontine control of hypoxic respiratory stimulation (Dillon *et al.*, 1991). These results provide further evidence that the *kr/kr* mutation affects neuronal populations mediating the control of respiratory parameters in response of both hypoxia and hyperoxia, leaving intact more direct chemosensory controls of the rhythm generator.

***Anatomical Defects of the kr/kr Hindbrain, Consistent with the Elimination of r5, are not observed in +/kr animals***

In *kr/kr* mice, anatomical defects were all located caudal to the r4-derived descending facial nerve fasciculus (7n in Figure 6). All structures located rostral to the 7n were normal, in particular r3-derived structures affected by the *Krox20*<sup>-/-</sup> mutation (Jacquin *et al.*, 1996). Caudal to the 7n, r5-derived structures were affected by both the *kr/kr* and *Krox20*<sup>-/-</sup> mutations. In particular, the abducens motor nucleus (6 in Figure 6) and the suprageniculate pontine nucleus (not shown) were eliminated, and the preganglionic facial nucleus (7pgg) and the superior olive (SO: largest diameter: 1197.5±78.5 µm in *+/+*, n=4, 537.5±114.4 µm in *kr/kr*, n=4, p<0.001)

were reduced. In extreme cases, we observed an unilateral ventral hypoplasia at the level of the facial exit point.

More posterior defects, found in *kr/kr* but not in *Krox20<sup>-/-</sup>* mice, possibly involve r6-derived structures. These defects are located rostral to the dorsal vagal motor nucleus (9-10 in Figure 6), the ambiguus (Amb) subnuclei and the intermediate reticular nucleus (IRt), all identifiable by their intact population of choline acetyltransferase positive neurons. A dramatic reduction was found in the gigantocellular (Gi) and paragigantocellular reticular nuclei, whereas the more ventral facial nucleus (7Mo) was not significantly modified. As a result, the rostral (pars compacta, ca) Amb and IRt were shifted rostrally and dorsally (distance between caudalmost descending facial nerve fibers and rostralmost ambiguus neurons: 1215±31.3 μm in +/+, n=4 and 680±93.4 μm in *kr/kr*, n=4, p<0.001). The facial nucleus itself was also shifted rostrally very close to the 7n (see Garel *et al.*, 2000), indicating that hypoplasia affected the reticular domain extending between ascending and descending branches of the 7n (distance between anteriormost facial nerve fibers, and anteriormost limit of facial nucleus: d=432.5±35.9 μm in +/+, n=4, and d=215±47.3 μm in *kr/kr*, n=4, p<0.001).

None of the anatomical defects described in *kr/kr* mice were found in *+/kr* mice therefore confirming that r5 and r6 were normal in heterozygous mutants. We observed normal distances between the 7n and the 7Mo (432.5±35.9 μm in +/+, n=4, and 420±59.4 μm in *+/kr*, n=4, NS), a normal sized SO (largest diameter: 1197.5±78.5 μm in +/+, n=4, 1267.5±99.8 μm in *+/kr*, n=4, NS) and normal AP lengths of the Gi (1215±31.1 μm in +/+, n=4, 1262±82.6 μm in *+/kr*, n=4, NS).

## Discussion

We have analysed anatomical defects and the physiological phenotypes in newborn *kreisler* mutant mice. Our observations support the hypothesis that r5 derivatives are eliminated in *kr/kr* animals, and are consistent with previous reports showing that respiratory parameters are genetically controlled by early segmentation genes (Jacquin *et al.*, 1996, Domínguez del Toro *et al.*, 2001). In this context, observations in *+/kr* mice provide the first description of a segmentation-related respiratory phenotype that is not associated with rhombomere elimination. Our data suggest that genetic abnormalities in hindbrain development having no obvious consequences on survival and general hindbrain anatomy, might nevertheless result in abnormal respiratory parameters, a factor potentially contributing to sudden infant death, when combined with environmental factors.

### *The Krox20-dependent Anti-apneic Neuronal System Originates from r3 Whereas kr/kr Phenotypic Traits are Related to r5 and r6*

We conclude from the present study that the *Krox20*<sup>-/-</sup> and *Hoxa1*<sup>-/-</sup> respiratory phenotypes and lethality (Jacquin *et al.* 1996, Domínguez del Toro *et al.*, 2001) result primarily from defects in **r3/r4**, since they are not reproduced in *kr/kr* mice in which **r3 and r4 are** present. In structures probably derived from **r3/r4**, many neurons (i) project to respiratory neuronal groups (Haxhiu *et al.*, 1993; Dobbins & Feldman, 1994; Nunez-Abades *et al.*, 1993), (ii) control the duration of inspiration in adult rodents (Jodkowski, *et al.*, 1994), (iii) depress the respiratory rhythm frequency in rodent neonates *in vitro* (Errchidi *et al.*, 1991, present results) and (iv) induce a periodic respiratory pattern in the foetal lamb (Dawes *et al.*, 1983). As discussed previously (Jacquin *et al.* 1996), the *Krox20*<sup>-/-</sup> mutation spares rhythm-depressant

controls and eliminates the rhythm-promoting and the anti-apneic systems. We show that this **r3/r4**-derived system is not eliminated by the *kreisler* mutation.

Phenotypic particularities of *kr/kr* mice, not observed in *+/kr* animals, appear as a result of the abnormal development of different neuronal populations derived from r5 or r6. **Systems stimulating frequency are difficult to locate because pontine hypoplasia causes a rostral shift of bulbar structures relative to the facial nerve, so that PB transection removes more bulbar structures in *kr/kr* than in wild-type mice. Therefore, low frequency in *kr/kr* mice might result from the elimination of non vital rhythm-promoting reticular circuits or alternatively from the impairment of the medullar rhythmogenic circuits themselves.** The delayed chemosensory control of breathing seems also to require neurons originating in r5/r6. Among reticular structures that are reduced in *kr/kr* mice, the lateral paragigantocellular nucleus has been first suspected to control breathing by Von Euler (1986). This nucleus contains neurons that are connected to dorsal and ventral respiratory groups and respiratory premotoneurons (Andrezik *et al.*, 1981; Ellenberger & Feldman, 1990, Nunez-Abades *et al.*, 1993, Dobbins & Feldman, 1994). It also receives afferents from the primary relay nucleus of respiration-related sensory afferents, the nucleus tractus solitarius (Andrezik *et al.* 1981, Lovick, 1986). The *kr/kr* mutation may also affect the retro-trapezoid nucleus, a small group of neurons, located between the ventro-medial border of the facial nucleus and the ventral surface of the brain, controlling the delayed respiratory effects of CO<sub>2</sub> (Nattie *et al.*, 1990, 2000) and hypoxia (Bodineau *et al.* 2000). **Further experiments isolating *in vitro* the pontine CO<sub>2</sub> sensitive structures would be needed to identify alterations of CO<sub>2</sub> sensitivity in *kr/kr* mutant mice.**

*The Heterozygous kreisler Mutation Increases The Efficiency of Anti-apneic Neuronal Systems Originating from r3*

Comparing  $+/kr$  with  $Krox20^{-/-}$  mice shows that the same respiratory parameters are affected in both mutants. **Thus, the  $+/kr$  respiratory phenotype was a mirror image of that previously found lethal in  $Krox20^{-/-}$  mice, in which the respiratory frequency was low, the tidal volume was large and the time spent in apnoeas dramatically increased compared to wild-type animals. Similarly, present observations *in vitro*, showing that the pontine inhibition is significantly less than normal in  $+/kr$  mutants contrasts with observations in  $Krox20^{-/-}$  mice, in which pontine inhibition was greater than normal as compared to wild-type animals. Altogether, results are therefore consistent with the hypothesis that the **r3-derived part of the** anti-apneic system is hyperactive in the  $+/kr$  mutants and probably contributes to the increased respiratory frequency. Furthermore, comparisons between  $+/kr$  and  $kr/kr$  mice, show that the  $+/kr$  mutation does not functionally modify r5-derived structures. These results may be in keeping with observations in  $+/kr$  embryos indicating that the pattern of gene expression is altered in r3 (Manzanares *et al.*, 1999b). Alternatively, since the *kreisler* mutation affects rather large genomic domains (Cordes & Barsh, 1994), other yet undetermined genes operating in **r3/r4** might be involved.**

The expression of *Hoxa3* is normally caudal to the r4/r5 limit and upregulated by *kreisler* in r5 and r6 (Manzanares *et al.* 1997). In  $+/kr$  mutants, *Hoxa3* has been found to be induced in r3, raising the possibility that there may be a partial change in r3 identity (Manzanares *et al.* 1999b), **but no deficits were found in r4.** We have recently investigated the functional consequences of a similar mis-specification. In  $Hoxa1^{-/-}$  mutant mice, in which parts of r3 and r4 acquires an r2-like identity, the mutation induces formation of ectopic motor subnuclei and supernumerary neuronal

circuits increasing respiratory frequency after birth (Domínguez del Toro *et al.*, 2001). Generation of these new neuronal populations changes the antero-posterior length of the pons and the morphology of the anterior end of the fourth ventricle. Present results show that production of supplementary reticular neurons is unlikely to occur in *+/kr* mice. Lack of any obvious anatomical phenotype in the pons of *+/kr* mice suggests that the development of efferent connections of r3-derived neurons has been changed without significant modification in the size of neuronal populations.

#### ***Hyperactivity of The Anti-apneic Neuronal System in +/kr Mice Requires kreisler dependent Neurons***

Additional experiments, performed at embryonic stages, are required to investigate developing efferent connections of r3-derived neurons. Nevertheless, comparing *+/kr* with *kr/kr* mutants provides information on how these connections are modified. **The behavioral analysis of *kr/kr* mice revealed a reversal, rather than an exaggeration, of respiratory phenotypic traits observed in *+/kr* mice, despite the mis-specifications of r3 persist in *kr/kr* mutants (Manzanares *et al.* 1999b). *In vivo*, the respiratory frequency was slightly less than normal and the duration of apneas was normal. Hypersensitivity to subcutaneous naloxone administration was also reversed. *In vitro*, studies of rhythm generation indicated that the pontine control was normal. Thus, the *kr/kr* mutation abolished all phenotypic traits modifying the control of resting, apneic and *in vitro* respiratory frequencies in *+/kr* animals.** It seems therefore that hyperactivity of the anti-apneic neuronal system in *+/kr* mutants requires intact relay structures originating from r5/r6. Indeed, rhythm promoting ponto-bulbar pathways (Borday *et al.* 1997), deriving probably from a lateral embryonic axonal tract (Lumsden *et al.*

1994), cross r5 before reaching the rhythm generator. Hence, hyperactivity in *+/kr* mice may result from the development of additional axonal arborizations or increased synaptic efficacy in r5/r6-derived territories. After elimination of r5 in *kr/kr* mice direct functional connections are preserved with the major synaptic target, i.e. the rhythm generator. Therefore, the *+/kr* mutation may generate, in r5/r6-derived territories, a novel collateral relay of the anti-apneic neuronal system. Although abnormal, this relay persists and functions after birth.

The question whether this *+/kr* phenotype results exclusively from abnormalities in r3, remains open. Within r3, the mechanisms by which the mutation may influence cell specification remains poorly understood, because *kreisler* expression in this rhombomere, at the level of the dorsal roof, remains unaffected in the mutants (Cordes & Barsh, 1994). Furthermore, assuming an exclusive r3 origin of the phenotype, only *Krox20*-dependent neuronal systems would be affected. Our observations on the enkephalineric control of the respiratory frequency show that, in fact, some neuronal populations that are not eliminated by the *Krox20*<sup>-/-</sup> mutation (Jacquin *et al.* 1996), can also be hyperactive in *+/kr* mutants and **presumably modified in *kr/kr* mutants, suggesting widespread abnormalities associated with the *kreisler* gene regulatory role, despite its restricted expression in r5 and r6.** We hypothesise a contribution of r5/r6 *kreisler*-expressing cells in the establishment and/or maintenance of their presynaptic connectivity patterns. The same mechanism may also operate in wild-type animals, in which *kreisler*-dependent neurons receive collateral inputs from the chemosensory pathway. **We suggest** that the molecular signalling initiated by *kreisler* expression in r5/r6 **may** act presynaptically, to control the development of functional collateral relays, according to the identity of presynaptic neurons. In wild-type animals, this mechanism **would** prevent collateralization of pontine (anti-apneic) or

widely distributed (enkephalinergic) neuronal systems and promote collateralization of medullar (chemosensory) systems.

### ***Conclusion***

Our results provide additional evidence that hindbrain segmentation during early embryonic development controls the functional organisation of neuronal networks after birth. Developmental processes initiated in r3 generate neuronal systems that are crucial to prevent sudden death during the restricted period of time extending during the first postnatal days in mice. In contrast, despite massive hypoplasia of the paragigantocellular reticular nucleus in *kr/kr* mutants, no evidence was found for a vital role of neuronal networks originating from r5; some of these neurons exert a positive control over respiratory frequency that relays pontine or chemosensory information controlling respiratory frequency.

These observations have important clinical implications for neonatal physiopathology. Observations in mice models point out at least three distinct syndromes indicative of abnormal embryonic development of hindbrain circuits. They might be detectable in human by scoring simple reflex reactions such as (i) suction for *Krox20*<sup>-/-</sup>-like syndromes (Jacquin *et al.* 1996), (ii) righting for *kr/kr*-like syndromes and (iii) chemosensory responses that are affected in human Ondine Course syndrome (Erickson *et al.*, 1996). Importantly, abnormalities of the suction-deglutition-respiration have been ascribed to different syndromes involving precise domains of the segmented hindbrain (Abadie *et al.*, 1999). Because transcription factors orchestrating hindbrain segmentation are organized in a regulatory network, a single mutation may have many consequences in this network. Therefore, prediction of neuronal deficits in patients is not straightforward.

A punctual mutation may not necessarily eliminate function of neurons. Thus, previous and present work shows that genetic abnormalities of hindbrain segmentation are as able to suppress (*kr/kr*, *Krox20<sup>-/-</sup>*) or enhance (*+/kr*, *Hoxa1<sup>-/-</sup>*) the function of respiration controlling neuronal system.

### **Acknowledgements**

This work was supported by a H.F.S.P. research grant 101/97. We wish to thank G. Fortin and S. Jungbluth for valuable discussions and comments on the manuscript. We thank M. Sahakian F.-H., Mss Fourcaudeau, Morales, Daoud & Callens for very useful technical assistance. We thanks Dr Barsh for kind gift of *kreisler* oligonucleotides. Work in J.C.'s laboratory was supported by ACI BDPI#57, Centre National de la Recherche Scientifique, Fondation pour la Recherche Médicale (FRM). E.D.T. was supported by European Community (BIO4-CT975-096) and FRM (EP001227/1) training grants. Work in P.C.'s laboratory was supported by Institut National de la Santé Et de la Recherche Médicale.

## Abbreviations

+/+ : wild-type mouse

+/*kr* : Heterozygous *kreisler* mutant

*kr/kr* : Homozygous *kreisler* mutant

ChAT: Choline acetyltransferase

NLX: Naloxone

PB: Ponto-bulbar preparation

PM: Ponto-mesencephalic preparation

TF: trigemino-facial section

V(dot): minute volume

V<sub>T</sub>: tidal volume

## References

- Abadie, V., Champagnat, J. & Fortin, G. (2000) Branchiomotor activities in mouse embryo. *Neuroreport*, **11**, 141-145.
- Abadie, V., Champagnat, J., Fortin, G. & Couly, G. (1999) Sucking-deglutition-respiration and brain stem development genes. *Arch. Pediatr.*, **6** (10), 1043-1047.
- Andrezik, J.A., Chan-Palay, V. & Palay, S.L. (1981) The nucleus paragigantocellularis lateralis in the rat. Demonstration of afferents by the retrograde transport of horseradish peroxidase. *Anat. Embryol. (Berl)*, **161** (4), 373-390.
- Arvidsson, U., Dado, R.J., Riedl, M., Lee, J. H., Law, P. Y., Loh, H.H., Elde, R. & Wessendorf, M.W. (1995)  $\delta$ -opioid receptor immunoreactivity: distribution in brainstem and spinal cord, and relationship to biogenic amines and enkephalin. *J. Neurosci.*, **15**, 1215-1235.
- Bianchi, A.L., Denavit-Saubié, M. & Champagnat, J. (1995) Central control of breathing in mammals: neuronal circuitry, membrane properties, and neurotransmitters. *Physiol. Rev.*, **75**, 1-45.
- Bodineau, L., Cayetanot, F. & Frugiere, A. (2000a) Possible role of retrotrapezoid nucleus and parapyramidal area in the respiratory response to anoxia: an *in vitro* study in neonatal rat. *Neurosci. Lett.*, **295** (1-2), 67-69.
- Bodineau, L., Frugiere, A., Marlot, D. & Wallois, F. (2000b) Connections between retrotrapezoid nucleus and nucleus tractus solitarii in cat. *Neurosci. Lett.*, **280** (2), 111-114.
- Borday, V., Kato, F. & Champagnat, J. (1997). A ventral pontine pathway promotes rhythmic activity in the medulla of neonate mice. *Neuroreport*, **8**, 3679-3683.
- Champagnat, J. & Fortin, G. (1997) Primordial respiratory-like rhythm generation in the vertebrate embryo. *Trends Neurosci.*, **20** (3), 119-124.

- Cordes, S.P. & Barsh, G.S. (1994) The mouse segmentation gene *kr* encodes a novel basic domain-leucine zipper transcription factor. *Cell*, **79**, 1025-1034.
- Dawes, G.S., Gardner, W.N., Johnston, B.M. & Walker, D.W. (1983) Breathing in fetal lambs: the effect of brainstem section. *J. Physiol. (Lond)*, **335**, 535-553.
- Deol, MS. (1964) The abnormalities of the inner ear in *kreisler* mice. *J. Embryol. Exp. Morphol.*, **12**, 475-490.
- Dillon, G.H., Welsh, D.E. & Waldrop, T.G. (1991) Ventrolateral pons mediates short-term depression of respiratory frequency after brief hypoxia. *Respir. Physiol.*, **121**, 87-100.
- Dobbins, E.G. & Feldman, J.L. (1994) Brainstem network controlling descending drive to phrenic motoneurons in rat. *J. Comp. Neurol.*, **347**, 64-86.
- Domínguez del Toro, E., Borday, V., Davenne, M., Neun, R., Rijli, F. & Champagnat, J. (2001) Generation of a novel functional neuronal circuit in *Hoxa1* mutant mice. *J. Neurosci.*, **21** (15), 5637-5642.
- Ellenberger, H.H. & Feldman, J.L. (1990) Brainstem connections of the rostral ventral respiratory group of the rat. *Brain Res.*, **513** (1), 35-42.
- Erickson, J.T., Conover, J.C., Borday, V., Champagnat, J. & Katz, D.M. (1996) Mice lacking BDNF exhibit visceral sensory neuron losses distinct from mice lacking NT4 and display a severe developmental deficit in control of breathing. *J. Neurosci.*, **16**, 5361-5371.
- Errchidi, S., Monteau, R. & Hilaire G. (1991) Noradrenergic modulation of the medullary respiratory rhythm generator in the newborn rat: an *in vitro* study. *J. Physiol.*, **443**, 477-498.
- Fortin, G., Champagnat, J., & Lumsden, A. (1994a). Onset and maturation of branchiomotor activities in the chick hindbrain. *Neuroreport*, **5**, 1149-1152.

- Fortin, G., Foutz, A.S. & Champagnat, J. (1994b) Respiratory rhythm generation in chick hindbrain: effect of MK-801 and vagotomy. *Neuroreport*, **5**, 1137-1140.
- Fortin, G., Kato, F., Lumsden, A. & Champagnat, J. (1995) Rhythm generation in the segmented hindbrain of chick embryos. *J. Physiol.*, **486**, 735-744.
- Fortin, G., Jungbluth, S., Lumsden, A. & Champagnat, J. (1999) Segmental specification of GABAergic inhibition during development of hindbrain neural networks. *Nat. Neurosci.*, **2**, 873-877.
- Garel S., Garcia-Dominguez M. & Charnay P. (2000) Control of the migratory pathway of facial branchiomotor neurones. *Development* ,**127** (24), 5297-5307.
- Gonzalez C., Almaraz L., Obeso A. & Rigual R. (1994) Carotid body chemoreceptors: from natural stimuli to sensory discharges. *Physiol. Rev.*, **74** (4), 829-898.
- Haxhiu, M.A., Jansen, A.S.P., Cherniack, N.S. & Loewy, A.D. (1993) CNS innervation of airway-related parasympathetic preganglionic neurons: a transneuronal labeling study using pseudorabies virus. *Brain Res.*, **618**, 115-134.
- Hertwig, P. (1942) Sechs neue Mutationen bei der Hausmaus in ihrer Bedeutung für allgemeine Vererbungsfragen. *Z. menschl. Vererbslehre*, **26**, 1-21.
- Hertwig, P. (1944) Die Genese der Hirn- und Gehörorganmißbildungen bei röntgenmutierten Kreisler-Mäusen. *Zeit. KonstLehre*, **28**, 327-354.
- Jacquin, T.D., Borday, V., Schneider-Maunoury, S., Topilko, P., Ghilini, G., Kato, F., Charnay, P. & Champagnat, J. (1996) Reorganization of pontine rhythmogenic neuronal networks in *Krox20* knockout mice. *Neuron*, **17**, 747-758.
- Jodkowski, J.S., Coles, S.K. & Dick, T.E. (1994) A 'pneumotoxic centre' in rats. *Neurosci. Lett.*, **172**, 67-72.

Lovick, T.A. (1986). Projections from brainstem nuclei to the nucleus paragigantocellularis lateralis in the cat. *J. Auton. Nerv. Syst.*, **16** (1), 1-11.

Lufkin, T., Dierich, A., LeMeur, M., Mark, M. & Chambon, P. (1991) Disruption of the *Hox-1.6* homeobox gene results in defects in a region corresponding to its rostral domain of expression. *Cell*, **66**, 1105-1119.

Lumsden, A. & Keynes, R. (1989) Segmental patterns of neuronal development in the chick hindbrain. *Nature*, **337**, 424-428.

Lumsden, A. & Krumlauf, R. (1996) Patterning the vertebrate neuraxis. *Science*, **274**, 1109-1115.

Manzanares, M., Cordes, S., Kwan, C.T., Sham, M.H., Barsh, G.S. & Krumlauf, R. (1997) Segmental regulation of *Hoxb3* by *kreisler*. *Nature*, **387**, 191-195.

Manzanares, M., Cordes, S., Ariza-McNaughton, L., Sadl, V., Maruthainar, K., Barsh, G. & Krumlauf, R. (1999a) Conserved and distinct roles of *kreisler* in regulation of the paralogous *Hoxa3* and *Hoxb3* genes. *Development*, **726** (4), 759-769.

Manzanares, M., Trainor, P. A., Nonchev, S., Ariza-McNaughton, L., Brodie, J., Gould, A., Marshall, H., Morrison, A., Kwan, C.T., Sham, M.H., Wilkinson, D.G. & Krumlauf, R. (1999b) The role of *kreisler* in segmentation during hindbrain development. *Dev. Biol.*, **211** (2), 220-237.

Marin, F. & Charnay, P. (2000) Hindbrain patterning: FGFs regulate *Krox20* and *mafB/kr* expression in the otic/preotic region. *Development*, **127** (22), 4925-4935.

Marin, F. & Puelles, L. (1995) Morphological fate of rhombomeres in quail/chick chimeras: a segmental analysis of hindbrain nuclei. *Eur. J. Neurosci.*, **7**, 1714-1738.

Mark, M., Lufkin, T., Vonesh, J.-L., Ruberte, E., Olivo, J.-C., Dollé, P., Gorry, P., Lumsden, A. & Chambon, P. (1993) Two rhombomeres are altered in *Hoxa-1* mutant mice. *Development*, **119**, 319-338.

- Mc Kay, I.J., Muchamore, I., Krumlauf, R., Maden, M., Lumsden, A. & Lewis, J. (1994) The *kreisler* mouse: a hindbrain segmentation mutant that lacks two rhombomeres. *Development*, **120**, 2199-2211.
- Nattie, E.E. (2000) Multiples suites for central chemoreception: their roles in response sensitivity and in sleep and wakefulness. *Respir. Physiol.*, **122** (2-3), 223-235.
- Nattie, E.E. & Li, A.H. (1990) Fluorescence location of RVLM kainate microinjections that alter the control of breathing. *J. Appl. Physiol.*, **68** (3), 1157-1166.
- Nattie, E.E. & Li, A.H. (1994) Retrotrapezoid nucleus lesions decrease phrenic activity and CO<sub>2</sub> sensitivity in rats. *Respir. Physiol.*, **97** (1), 63-77.
- Niederreither, K., Vermot, J., Schuhbaur, B., Chambon, P. & Dolle, P. (2000) Retinoic acid synthesis and hindbrain patterning in the mouse. *Development*, **127**, 75-85.
- Neubauer, J.A., Melton, J.E. & Edelman, N.H. (1990) Modulation of respiration during brain hypoxia. *J. Appl. Physiol.*, **68** (2), 441-451.
- Nunez-Abades, P.A., Morillo, A.M. & Pasaro, R. (1993) Brainstem connections of the rat ventral respiratory subgroups: afferent projections. *J. Auton. Nerv. Syst.*, **42**, 99-118.
- Onimaru, H. (1995) Studies of the respiratory center using isolated brainstem-spinal cord preparations. *Neuroscience Res.*, **21**, 183-190.
- Romagnano, M.A., Harshbarger, R.J. & Hamill, R.W. (1991) Brainstem enkephalinergic projections to spinal autonomic nuclei. *J. Neurosci.*, **11**, 3539-3555.
- Schneider-Maunoury S., Gilardi-Hebenstreit P. & Charnay P. (1998) How to build a vertebrate hindbrain. Lessons from genetics. *C. R. Acad. Sci. III*, **321**(10), 819-834.
- Schneider-Maunoury, S., Seitanidou, T., Charnay, P. & Lumsden, A. (1997) Segmental and neuronal architecture of the hindbrain of *Krox20* mouse mutants. *Development*, **124**, 1215-1226.

Schneider-Maunoury, S., Topilko, P., Seitanidou, T., Levi, G., Cohen-Tannoudji, M., Pournin, S., Babinet, C. & Charnay, P. (1993) Disruption of *Krox20* results in alteration of rhombomeres 3 and 5 in the developing hindbrain. *Cell*, **75**, 1199-1214.

Smith, J.C., Ellenberger, H.H., Ballanyi, K., Richter, D.W. & Feldman, J.L. (1991) Pre-Bötzinger complex: a brainstem region that may generate respiratory rhythm in mammals. *Science*, **254**, 726-729.

Suzue, T (1984) Respiratory rhythm generation in the *in vitro* brainstem spinal cord preparation of the neonatal rat. *J. Physiol.*, **354**, 173-183.

Vizek M, Bonora M. (1998) Diaphragmatic activity during biphasic ventilatory response to hypoxia in rats. *Respir. Physiol.*, **111** (2), 153-62.

Von Euler, C. (1986) Brainstem mechanisms for generation and control of breathing pattern. In Handbook of Physiology. *The respiratory system vol. II, control of breathing part I*, pp1-67.

**TABLE 1.** Comparison of *kreisler* homozygous and heterozygous mutant and wild-type animals (+/+) during the first day (P0).

Respiration (f: frequency;  $V_T$ : tidal volume; **V(dot)**: minute volume; apneas) was measured during quiet breathing. Durations of apnoeas and movements during plethysmographic recordings are expressed in % of the total time of recording (165s). Righting reflex measures time spent by the mouse for moving from supine to prone position. Data at P0 include 24 (-/-) and 32 (+/-) and 16 (+/+) animals from *kreisler* litters, 109 +/+ are added for respiratory parameters. Means  $\pm$  SEM; \*\*\*:  $p < .001$ ; \*\*:  $p < .01$ ; \*:  $p < .05$ ; NS: not significant.

<b>P0</b>					
<b>Measure</b>	<b>+/+</b>	<b>+/+ vs. +/-</b>	<b>+/-</b>	<b>+/- vs. -/-</b>	<b>-/-</b>
f (min <sup>-1</sup> )	118 $\pm$ 17	***	163 $\pm$ 4.5	***	102 $\pm$ 5.9
$V_T$ ( $\mu$ l/g)	13.9 $\pm$ 2.3	***	9.7 $\pm$ 0.5	***	7.1 $\pm$ 0.5
<b>V(dot)</b> (ml/g)	1.77 $\pm$ 0.47	NS	1.61 $\pm$ 0.09	***	0.75 $\pm$ 0.07
apnoeas (%t)	5.2 $\pm$ 2.0	*	0.6 $\pm$ 0.31	***	9 $\pm$ 2.1
buccal T° (°C)	31.4 $\pm$ 0.5	NS	32.9 $\pm$ 0.3	NS	32.1 $\pm$ 0.2
righting (s)	17.4 $\pm$ 5.2	NS	12.5 $\pm$ 1.6	***	26.9 $\pm$ 7.3
body mass (g)	1.44 $\pm$ 0.07	NS	1.50 $\pm$ 0.02	***	1.31 $\pm$ 0.03
Movement (%t)	4.87 $\pm$ 2.72	NS	5.41 $\pm$ 1.10	NS	5.23 $\pm$ 1.97
n	125/16		32		24

## Figure Legends

**FIG. 1. Respiratory frequency is elevated in  $+/kr$  mutant mice during the first days after birth.** (A) Representative samples of whole-body plethysmographic recording of  $+/+$ ,  $+/kr$  and  $kr/kr$  littermates during the first postnatal week (P0-P6); scale bars: abscissa: 2 s, ordinate: 50  $\mu$ l. Inspiration is upwards. (B) Evolution of the respiratory frequency in  $+/kr$  (open diamonds),  $kr/kr$  (open triangles) and wild-type (closed circles) littermates during the first postnatal week. The most significant differences between  $+/+$  and  $+/kr$  are found at P0 / P1 ( $+/+$ , n=16 from P0 to P4 and 7 at P5 and P6;  $+/kr$ , n=32 from P0 to P2 and 26 from P3 to P6;  **$kr/kr$ , n=24 from P0 to P2 and 18 from P3 to P6**): stars indicate significance: \*\*\*: p<0.001, \*\*: p<0.01, \*: p<0.5. (C) Individual values of tidal volume (ordinate) and respiratory frequency (abscissa) in  $+/kr$  (open diamonds, n=32),  $Krox20^{-/-}$  (open circles, n=12, data from Jacquin *et al.*, 1996) and wild-type mice (crosses:  $+/kr$  and  $kr/kr$  littermates, n=16; closed circles: animals added to provide an estimate of population variability, n=109) during the first postnatal day. The tidal volume is smaller in  $+/kr$  mutants and their respiratory frequency is abnormally high.

**FIG. 2. Pontine respiratory depression *in vitro* is weaker than normal in  $+/kr$  mice.** (A) Schematic drawing showing the levels at which transverse sections of the brainstem were performed (PM: ponto-mesencephalic, TF: trigemino-facial, PB: ponto-bulbar). The most caudal segment (PB) contains the rhythm generator and spontaneous rhythmic neural activity is recorded from the hypoglossal (12n) nerve root (arrow). TF and PB sections eliminates the rhythm-depressant effect of the caudal pontine reticular formation, rostral to the facial nerve (7n). Calibration bar : 500  $\mu$ m. (B) Cresyl violet staining of a coronal section made immediately

caudal to PB section in a *+/-kr* mutant mouse. Facial motor nucleus(7Mo) and vestibular nuclei (Ve) are visible. Calibration bar: 500  $\mu$ m. (C) Mean burst frequency before (PM) and after (PB) PB transection in wild-type (left, n=4), *+/-kr* (middle, n=7) **and *kr/kr* (right, n=6)** mice. Inset: Mean effectiveness of pontine depression in *+/+* (n=4), *+/-kr* (n=7) **and *kr/kr* (n=6) littermate mice**. Ordinates: difference in frequency before and after PB transection (f(PB)-f(PM) in Hz). (D) Evolution of the frequency (ordinate) during the time of an experiment (in abscissa, scale bar 15 min.) including subsequent transections at the TF and PB levels (arrowheads); the *+/+* (top) and *+/-kr* (bottom) preparations behave the same except in control (PM) situation: functional differences between the two genotypes are therefore located rostral to TF. Dashed lines indicate respiratory frequency recorded in PM preparation.

**FIG. 3. Enkephalinergic control of respiration in *+/-kr* and *kr/kr* mice *in vivo*.** (A) Whole-body plethysmographic recordings and (B) mean respiratory frequency (cycles/min) before (Control) and after (NLX) blockade of the depressant enkephalinergic control of respiration by subcutaneous administration of naloxone *in vivo* at P2. This treatment has no effect on respiratory frequency in wild-type animals (n=20) **nor in *kr/kr* animals (n=6)** and further increases frequency in *+/-kr* mice (n=9, p<0.001), stars indicate significance: \*\*\*: p<0.001, \*\*: p<0.01. Scale bars in A: abscissa: 2 s, ordinate: 25  $\mu$ l.

**FIG. 4. None of the *Hoxa1*<sup>-/-</sup> anatomical defects are found in *+/-kr* mutant mice.** (A) Sagittal section of brainstem at trigeminal level stained by ChAT immunohistochemistry. Rostral is left and dorsal is up. Left side is wild-type animal, right is *+/-kr* animal. Double arrow indicates the width of parvocellular reticular formation, measured between trigeminal motor nucleus (5Mo)

and facial nerve (7n). The parvocellular reticular formation does not increase in width, and does not contain ectopic trigeminal motoneurons in *+/kr* mice. (B) medial sagittal section showing the anterior part (V4a) of the fourth ventricle (V4). *+/kr* mice show normal, non invaginated V4a. A1, B1: wild-type, A2, B2: *+/kr* mice. Scale bars: 100  $\mu$ m.

**FIG. 5. Respiratory responses to hyperoxia and hypoxia in *kr/kr* and wild-type mice at the end of the first postnatal week.** (A) Direct plethysmographic recordings at P10 before (Control) and 30 s after the onset of hypoxic or hyperoxic challenges, traces are calibrated for  $V_T$ , scale bar: 2 s. (B) Trace plot of average minute volume ( $\mathbf{V(\dot{d})}$ , in % of control values) measured before and 30 s and 90 s after the onset of hyperoxia (B1) or hypoxia (B2), in *+/+* (n=20, black dots) and in *kr/kr* (n=11, open triangles), stars indicate significance: \*:p<0.5. In *kr/kr* mutants, the initial response is preserved (30 s) demonstrating function of chemoreceptive mechanisms, while later processing is abolished (90 s).

**FIG. 6. Anatomical defects in the hindbrain of *kr/kr* mice.** Sagittal sections of the brainstem of wild-type (+/+, left) and *kr/kr* (right) littermates showing ChAT immunoreactive neurons; top: location in the brainstem; bottom: structures (in gray) reduced in size by the mutation: the gigantocellular nucleus (Gi), the superior olive (SO), the preganglionic facial nucleus (7pgg); note the absence of the abducens nucleus (6) in *kr/kr* mice. The mutation does not affect the size of the trigeminal nucleus (5Mo), caudal pontine nucleus (PnC), facial nucleus (7Mo) and nerve (7n), intermediate reticular nucleus (IRt) and of the different subnuclei of the ambiguus nucleus, (Amb, ca: pars compacta, sca: pars semi-compacta, ra: pars retro-ambigualis). LC: locus coeruleus, Nts: nucleus tractus solitarius, Ve: vestibular nuclei, 9-10: dorsal glossopharyngeal and vagal nuclei; 12: hypoglossal nucleus. Scale bar: 200  $\mu$ m. Arrows indicate rostral (r) and dorsal (d).