Breathing with Phox2b

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In the last few years, elucidation of the architecture of breathing control centres has reached the cellular level. This has been facilitated by increasing knowledge of the molecular signatures of various classes of hindbrain neurons. Here, we review the advances achieved by studying the homeodomain factor Phox2b, a transcriptional determinant of neuronal identity in the central and peripheral nervous systems. Evidence from human genetics, neurophysiology and mouse reverse genetics converges to implicate a small population of Phox2b-dependent neurons, located in the retrotrapezoid nucleus, in the detection of CO₂, which is a paramount source of the ‘drive to breathe’. Moreover, the same and other studies suggest that an overlapping or identical neuronal population, the parafacial respiratory group, might contribute to the respiratory rhythm at least in some circumstances, such as for the initiation of breathing following birth. Together with the previously established Phox2b dependency of other respiratory neurons (which we review briefly here), our new data highlight a key role of this transcription factor in setting up the circuits for breathing automaticity.

Keywords: Phox2b; breathing; retrotrapezoid nucleus; visceral nervous system

1. INTRODUCTION: Phox2b AND THE CORE REFLEX CIRCUITS OF THE VISCERAL NERVOUS SYSTEM

Phox2b is a homeobox gene specifically expressed in a limited set of neuronal types during development and for most of them, throughout adult life (Pattyn et al. 1997; Dauger et al. 2003; Tiveron et al. 2003; reviewed in Brunet & Goridis 2008). Unlike the vast majority of neural-type specific transcription factors, which are expressed either regionally or in discrete but unrelated sets of neurons, the expression of Phox2b matches a set of neurons related to each other based on their connectivity and function. These are the visceral neurons, afferent and efferent, that regulate the cardio-vascular, respiratory and digestive organs (Blessing 1997a) (figure 1). Indeed, the majority of Phox2b-expressing neurons make up the sensory and motor arms of the visceral reflex circuits. On sensory pathways, Phox2b is expressed in the three epibranchial sensory ganglia (geniculate, petrosal and nodose), which monitor blood pressure and the chemical composition of the vascular and digestive contents, and in their targets in the CNS, namely the sensory neurons of the nucleus of the solitary tract (nTS). Phox2b is also expressed in the two main chemosensitive organs: the carotid body (CB) (innervated by the petrosal ganglion and specialized in sensing blood oxygen and sugar levels) (Gonzalez et al. 1994; Pardal & Lopez-Barneo 2002) and the area postrema (AP) (appended to the nTS and which senses toxins in the bloodstream and cephalo-spinal fluid) (Miller & Leslie 1994). The visceral motor pathways also consist of Phox2b-positive neurons: this includes all autonomic ganglia (sympathetic, parasympathetic and enteric), the adrenal medulla and ‘general visceral’ motor (VM) or pre-ganglionic neurons to the enteric and parasympathetic ganglia (in the dorsal motor nucleus of the vagus nerve (dmnX), external formation of the nucleus ambiguus (nA) and salivatory nuclei). The only exceptions are the sympathetic pre-ganglionic neurons of the spinal cord that do not express Phox2b and appear more related by their transcriptional code to somatic motoneurons (Thaler et al. 2004). Phox2b is also expressed in the ‘special visceral’ or branchial motor (BM) neurons (in the trigeminal (nV) and facial (nVII) nuclei, the nA and the spinal accessory (nXI) nucleus) that share with VM neurons many developmental features: they are born at the same dorsoventral level in the hindbrain neuroepithelium, they have the same transcriptional code (Phox2a/b, Lhx3, HB9, Tbx20), they undergo a similar dorsal migration and like them send their axons to dorsal exit points. In terrestrial vertebrates, the visceral function of BM neurons is somewhat obscured and they are accordingly excluded from standard anatomical accounts of the visceral nervous system (VNS). However, in the aquatic relatives and ancestors of terrestrial vertebrates, the sole

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functions of BM neurons is digestive (for nV) and respiratory (for nV, nVII and nA) (see evolutionary discussion below). Beyond these core component of the VNS, Phox2b is expressed in only three other discrete sets of hindbrain neurons: (i) four atypical efferent nuclei of the hindbrain that share the transcriptional code of VM and BM neurons: vestibular and cochlear efferents in the medulla (Tiveron et al. 2003), and occulomotor and trochlear motoneurons in the isthmus (Pattyn et al. 1997); (ii) noradrenergic and adrenergic centres of the hindbrain (respectively A1–A7 and C1–C3) (Pattyn et al. 2000a)—some of which are bona fide parts of the VNS, such as the C1 pre-motor sympathetic neurons (Guyenet 2006); and (iii) a population of interneurons in the medulla and pons distributed in the ventrolateral medulla (VLM), intermediate reticulum formation and paratrigeminal region (Kang et al. 2007; J.-F. Brunet, unpublished data). The latter await attribution of a physiological function. In light of the overwhelming visceral theme of the Phox2b expression pattern, it seems a safe working hypothesis that at least some of them will turn out to participate in the control of visceral circuits and function. As this review will illustrate, this prediction has just started to be born out.

In all classes of Phox2b-positive neurons, expression of the gene starts either before or just after mitotic arrest (Pattyn et al. 1997). In Phox2b knock-outs, most Phox2b neurons fail either to appear or to differentiate (Pattyn et al. 1999, 2000a,b; Dauger et al. 2003; Huber et al. 2005), with the exception of the oculomotor and trochlear motoneurons, which depend on Phox2a—a paralogue of Phox2b (Pattyn et al. 1997), and possibly some hindbrain interneurons (Brunet & Goridis 2008; J.-F. Brunet, unpublished data). Thus, Phox2b can be viewed as a master regulator of core visceral circuits. The raison d’être for this unusual foreshadowing of connectivity among different neuronal types by a single transcriptional determinant is still elusive and speculations lie outside the scope of this review. Here, we will discuss recent insights into the first group of hindbrain Phox2b interneurons to be characterized. We show that they further illustrate the intriguing correlation of Phox2b with the VNS and have an essential role in both the neural control of breathing at birth and central chemoreception in the adult mammal.

2. MUTATIONS IN Phox2b AND THE DRIVE TO BREATHE

Until recently, the role of Phox2b+ neurons in the circuits that control breathing seemed patchier than in those that control digestion and blood circulation. On the afferent side of respiratory reflexes, Phox2b is required in the nodose ganglion, which contains the cell bodies of pulmonary stretch receptors responsible for the Herring–Breuer reflexes, in the CB, which contains oxygen and CO2 sensors, in the petrosal ganglion, which innervates the CB, and in the nTS, which integrates of chemosensory and barosensory information. On the other hand, the motoneurons for the diaphragm and parietal muscles that ensure breathing never express Phox2b (but see phylogenetic discussion below). The best characterized central component of the respiratory rhythm generator (RRG)—the pre-Bötzinger complex (preBöC) (Smith et al. 1991; Rekling & Feldman 1998)—contains few, if any, Phox2b-positive neurons (Blanchi et al. 2003). Finally, some pontine or medullary nuclei thought to provide positive or negative influences on the respiratory rhythm are Phox2b positive (e.g. noradrenergic nuclei A6 and A5; Hilaire et al. 2004) while others are not (e.g. the parabrachial and Kölliker–Fuse nuclei; Kang et al. 2007; J.-F. Brunet, unpublished data).

A direct assessment of the role of Phox2b in the neural control of breathing in mouse has been largely hindered because of the embryonic death of Phox2b null mutants from cardiovascular failure (Pattyn et al. 1999, 2000a). It was at first limited to the study of...
heterozygous knock-out pups who present a complex, mild and regressive ventilatory phenotype (reviewed in Gallego & Dauger 2008).

A new phase in our understanding of the respiratory role of Phox2b started when mutations in PHOX2B were discovered in humans with congenital central hypoventilation syndrome (CCHS; Amiel et al. 2003). PHOX2B mutations are now detected in 96 per cent of CCHS patients and considered causal for this condition (Weese-Mayer et al. 2005). The idea to look for PHOX2B mutations in CCHS sprung from the long list of symptoms associated with the disease (Chen & Keens 2004), each relating to a site of known Phox2b expression: for example, partial agenesis of the enteric nervous system (Hirschprung disease), tumours of the sympathetic ganglia or adrenal medulla (neuroblastomas), dysmotility of the intrinsic and extrinsic muscles of the eye (that receive innervation from the superior cervical and ciliary ganglia, and the oculomotor and trochlear nuclei, respectively), reduction of cardiac rhythm variability (which is under dual sympathetic and parasympathetic influence), dysphagia (which depends on both intrinsic innervation of the oesophagus and an extrinsic reflex loop passing through the nTS and the nucleus ambiguus). The diagnostic symptom of CCHS,

Figure 2. Expression of Atoh1 by RTN neurons and sensitivity to the Phox2b$^{27\text{Ala}+/+}$ and Phox2b$^{\text{beta-gal}/+}$ mutations. (a, b) In situ hybridization showing (in blue) expression of Atoh1 combined (b) with Phox2b immunohistochemistry (in brown) on parasagittal (a, anterior to the left) and transverse (b) sections through the hindbrain of a wild-type hindbrain at E15.5 Inset: close-up of Phox2b$^{+/+}$/Atoh1$^{+/+}$ in the RTN. (c) Parasagittal section through the hindbrain of a Phox2b$^{27\text{Ala}+/+}$ mutant at an equivalent position as in (a), showing the disappearance of Atoh1 expression in the RTN. (d) Transverse section through the hindbrain of a homozygous Phox2b null mutant at an equivalent position and treated as in (b) showing the disappearance of the Atoh1 signal in the RTN but not in pre-cerebellar neurons (asterisk). nVII, facial nucleus. Bars, 100 μm.

Figure 3. Expression of the leak potassium channel TASK2 in RTN cells. (a) Ventral view of the hindbrain of E17.5 Task2$^{\text{LacZ}+/}$ mouse embryo (Task2$^{\text{LacZ}+/}$ mouse line; adapted from W. C. Skarnes) stained by XGal for LacZ expression (rostral to the left). A bilateral population of positive cells is seen at the level of the facial nucleus. (b) Transverse section through the facial nucleus of an E15.5 embryo immunostained for Phox2b (in red) and beta-galactosidase (in green) showing coexpression of Phox2b and beta-gal in RTN cells at the ventral medullary surface. The square window delineated in white is enlarged in the three panels below. nVII, facial nucleus. Bars, 100 μm in (a) and 50 μm in (b).

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however, is respiratory: alveolar hypoventilation with no underlying muscular or cardiovascular deficit, and apneic episodes, typically during sleep. The severity of the disease ranges from respiratory arrests occurring late in life (in mild cases, which originally defined the syndrome (Mellins et al. 1970), and are now classified as ‘late-onset CCHS’ (Antic et al. 2006)), to the absence of spontaneous breathing at birth (Gozal 1998). In all cases, functional evaluation reveals the underlying defect: abrogation or a great reduction of the sensitivity to hypercapnia, which normally maintains pCO₂ within strict limits. Thus, the implication of Phox2b in CCHS not only paved the way for an understanding of a devastating disease but offered fresh insight into the long-standing quest for the anatomical site of CO₂ sensitivity. Two theories have dominated the field over the past decades (see Guyenet (2008) for a review). The ‘distributed chemoreception theory’ states that the exquisite CO₂ sensitivity of the respiratory network results from the summation of the lesser sensitivities of its parts (Feldman et al. 2003). Conversely, the ‘specialized chemoreceptor theory’ (Guyenet 2008) originated from the work of Loeschcke and Mitchell (Loeschcke 1982), who favoured dedicated sites for CO₂ sensing restricted to discrete regions of the ventral medullary surface. The two best-documented candidates for the latter role are raphe serotonergic nuclei (Richerson 2004) and the retrotrapezioid nucleus (RTN), a group of glutamatergic neurons located in the marginal layer of the VLM beneath the facial motor nucleus (Mulkey et al. 2004). The fact that mutations in Phox2b, a neuronal-type specific transcription factor, can abolish CO₂ sensitivity without affecting many other aspects of the respiratory behaviour pleads for the specialized chemoreceptor theory. Indeed, it implies (barring an unlikely widespread non-cell autonomous effect of the mutation) that the CO₂ response passes through at least one obligatory Phox2b⁺ neuronal relay. The simplest scenario is that the central CO₂ sensor consists in a Phox2b⁺ population of neurons sensitive to the CCHS mutations.

The mutations found in CCHS patients are mostly expansions of a stretch of 20 Alanines by 4 to 13 residues in the C-terminal part of PHOX2B, but frame shifts and missense mutations are also found (Weese-Mayer et al. 2005; Repetto et al. 2008). Three lines of evidence argue that they are not null. First, Phox2b⁺/− mouse mutants display a much more subtle phenotype than CCHS patients (Dauger et al. 2003; Cross et al. 2004; Durand et al. 2005). Second, patients with heterozygous deletions of the PHOX2B region do not have CCHS (reviewed in Weese-Mayer et al. 2005); and third, different PHOX2B mutations are associated with different combinations and frequencies of symptoms (Gaultier et al. 2005; Weese-Mayer et al. 2005). Rather, the mutant protein may cause CCHS by a dominant-negative mechanism or by a toxic gain of function (Bachetti et al. 2005; Trochet et al. 2005). In man, an argument for a dominant-negative activity or cellular toxicity of the mutated protein is that a fraction of CCHS patients have strabismus (Goldberg & Ludwig 1996), implying a dysfunction of the Phox2a-dependent third and fourth motor nuclei, where Phox2b is expressed but not required (see §1).

In an attempt to model CCHS, the most frequent mutation, a 7-residue expansion of the poly-Alanine stretch, was introduced in mice (Dubreuil et al. 2008). Transmitting chimeras produced heterozygous pups (Phox2b⁺/27Ala) that died soon after birth from respiratory failure (Dubreuil et al. 2008). Plethysmography performed prior to death revealed an absence of response to hypercapnia. Phox2b27Ala⁺ newborns are models of human CCHS in which to look for the cellular locus and developmental mechanism of the physiological defects of the disease.

3. Phox2b and the Retrotrapezioid Nucleus

Two independent lines of research have now established a link between Phox2b and the RTN, one of the two main contenders for the role of CO₂/pH sensor in the CNS (§2). First, neurons of the adult rat RTN, defined physiologically by their responsiveness to CO₂ in vivo (Mulkey et al. 2004; reviewed in Guyenet 2008), and phenotyped as Vglut2⁺ (but negative for glutamate decarboxylase and tyrosine hydroxylase) and located at the ventral medullary surface under the facial nucleus and extending approximately 500 μm caudal to it, were all found to express Phox2b (Stornetta et al. 2006). Second, inspection of the hind-brain of Phox2b27Ala/− newborn mice that have no response to hypercapnia (§2) showed that there was an 85 per cent depletion of the Phox2b⁺/Vglut2⁺ RTN neurons (Dubreuil et al. 2008). This observation held true for embryonic day (E)15.5 embryos, ruling out post-natal hypoxic injury as a cause. This defect contrasted with several other Phox2b⁺ neuronal populations involved in breathing (such as the CB, the petrosal and nodose ganglia, the noradrenergic centres and the nTS) that were present in normal numbers in the mutants, suggesting that among Phox2b⁺ neurons the mutation affects preferentially the RTN (Dubreuil et al. 2008) and that the RTN atrophy is causal to the lack of CO₂ sensitivity. Notably, the raphe nuclei were present and anatomically intact.

We recently found that a subset of Vglut2⁺/Phox2b⁺ neurons in the RTN region expressed the bHLH transcription factor Atoh1 (figure 2a,b, and data not shown). This, incidentally, points to the RTN as a potential culprit in the Atoh1 KO neonatal lethal respiratory phenotype (Ben-Arie et al. 1997). The very discrete expression of Atoh1 in the RTN, which disappears in Phox2b27Ala/− RTN mutants, allowed us to assess the fate of RTN neurons in a Phox2b null background where Phox2b is no longer available as a marker. Similar to Phox2b27Ala/− mutants, Atoh1 expression was abolished in Phox2b−/− E15.5 embryos (figure 2d), suggesting that the differentiation of the RTN (at least its Atoh1/Phox2b component) in addition to being sensitive to the Phox2b27Ala/− mutation, depends on Phox2b. However, we cannot, at this stage, exclude the possibility that this dependency may be non-cell autonomous and, for example, mediated by the disappearance of the nearby facial nucleus.

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Combined with the abundant physiological data concerning the RTN, the phenotype of the Phox2b<sup>27Ala<sup>i</sup>/i</sup> mutants suggests that RTN neurons are essential for the sensitivity to CO<sub>2</sub> of the respiratory circuitry. Moreover, these cells receive direct projections from a subpopulation of Phox2b<sup>+</sup> nTS neurons that themselves relay PaO<sub>2</sub> responsiveness via fiber input from the CB, via the petrosal ganglion (Stornetta et al. 2006), which are all dependent on Phox2b. Thus, the circuitry for monitoring blood gases, which provides a major drive to breathe, might consist of an uninterrupted Phox2b-dependent four-neuron circuit.

It remains that the Phox2b<sup>27Ala<sup>i</sup>/i</sup> mouse model, in which it is impossible to rule out subtle or purely functional deficits in Phox2b<sup>+</sup> neuronal populations other than the RTN, does not amount to a specific genetic deletion of that nucleus. Definitive proof that the RTN ensures CO<sub>2</sub> sensitivity will require triggering deleterious alterations of gene expression specifically in that nucleus. Co-expression of deleterious alterations of gene expression specifically in newborn rats (Kawai et al. 2006). Second, a collection of rhythm cells at the same location as the RTN/pFRG, but recorded in the mouse embryo, also express Phox2b and are responsive to CO<sub>2</sub> (Thoby-Brisson et al. in press). Thus, it is conceivable that the RTN and the pFRG represent overlapping, if not identical groups of cells that would change properties between the perinatal and adult stages of life. Together, these data point to the possibility that Phox2b cells control aspects of respiratory rhythm generation, at least at birth. This is compatible with the lack of spontaneous breathing at birth in severe cases of CCHS (Gozal 1998). It could also explain the abnormalities of the respiratory rhythm in Phox2b<sup>27Ala<sup>i</sup>/i</sup> newborns, which range from a slow rhythm to gasping (Dubreuil et al. 2008). Very recently, RTN/pFRG Phox2b cells, which are derived from neuronal precursors expressing the transcription factor Lbx1 (Pagliardini et al. 2008), were found to be missing in Lbx1<sup><sub>+/−</sub></sup> mice (Pagliardini et al. 2008) whose CO<sub>2</sub> sensitivity was not explored but that die at birth from extreme bradypnoea detectable from E15.5 on. These data are compatible with a role for the RTN in setting the neonatal respiratory pace, although massive abnormalities in other respiratory centres of the Lbx1 null mutants, such as the nTS and (nor)adrenergic centres (but not the preBötC) were also present and could play a role.

4. **Phox2b and the Homeostatic Side of Breathing**

Breathing in terrestrial animals is a complex behaviour that combines an obvious homeostatic function—maintaining pO<sub>2</sub> and pCO<sub>2</sub> in extracellular fluids—with voluntary or ‘somatic’ functions such as sniffing, vocalizing and sighing (Blessing 1997b). It is striking that Phox2b-dependent respiratory neurons, in line with the visceral roles of other Phox2b neurons, are preferentially associated with homeostatic or automatic control of breathing, which is evolutionary speaking, more ancient. Those parts of respiratory circuitry that have evolved more recently and that allow somatic functions involve Phox2b<sup>−</sup> neurons.

On the afferent pathways, as has been developed throughout this review, the homeostatic control of blood oxygen and carbon dioxide involves an uninterrupted chain of four Phox2b-dependent neuronal relays: the CB, the petrosal ganglion, the nTS and the RTN. As to the efferent pathways, a major change has occurred at the transition from aquatic to terrestrial life, which was accompanied by a shift from gills to lungs for gas exchange and a corresponding shift from gill, opercular and buccal muscles to axial muscles (e.g. intercostal, abdominal and the diaphragm) for respiratory pumping (Liem 1985; Brainerd 1999). Accordingly, the motor control of breathing shifted from Phox2b-positive neurons (BM neurons) to Phox2b-negative neurons (e.g. somatic motoneurons of the spinal cord such as phrenic motoneurons). In turn, the original visceral function of branchial muscles and motoneurons, while still apparent in a number of respiratory and feeding-related behaviours such as coughing, sucking or swallowing, has been obscured by the voluntary functions for which they have been recruited (e.g. facial expression or the motorization of the vocal cords). Work on the ascidian *Ciona intestinalis*, a representative of the tunicates—the closest relatives of vertebrates (Delsuc et al. 2006)—has shown that BM neurons in their original visceral avatar predate the advent of vertebrates. Indeed, the branchial basket of these sessile animals, which serves as both food collector and site of gas exchange, is motorized by CiPhox2<sup>+</sup> neurons. Moreover, these neurons express the T-box transcription factor Tbx20, a specific marker in the vertebrate CNS for both BM and VM neurons (Dufour et al. 2006). BM neurons with dual respiratory and digestive functions could represent one of the most primitive parts of the vertebrate visceral circuitry.

On a more speculative note, another shift from Phox2b<sup>+</sup> to Phox2b<sup>−</sup> neurons might have occurred at the advent of air breathing and is implicit in recent discussions on the evolution of the RRG (Vasilaros et al.
2005; Feldman & Del Negro 2006; Wilson et al. 2006). The ‘buccal oscillator’ of amphibians, which may derive from a fish-type respiratory oscillator, has been proposed as an evolutionary forerunner of the pFRG. Conversely, the preBoTc would be an invention of terrestrial vertebrates, possibly homologous to the ‘lung oscillator’ of amphibians. A cautionary note here is that the anatomical positions of the buccal and lung oscillators of frogs are not readily reconcilable with those of the pFRG and preBoTc, respectively (Vasilakos et al. 2005). When we have a cellular definition of the respiratory oscillator(s) of fish or amphibians, testing for Phox2b expression might provide an argument for or against homology. As things stand, it is only a seductive hypothesis that the pFRG would represent an ancestral RRG driving the purely homeostatic gill breathing, and that it would have been superseded by the preBoTc, which is better suited for the flexible integration of automatic breathing with many other behaviours observed in terrestrial vertebrates.

As mentioned at the beginning of this review, many Phox2b+ interneurons of yet unknown function are found in the VLM. The study of these neurons may shed further light on the architecture of visceral circuits, including those regulating respiration.

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