There were two errors published in Development 140, 1583-1593.

On p. 1583, in the first paragraph of the Introduction, the alternative name given for CLIP-115 should be Clip2.

On the same page, the first sentence of the second paragraph of the Introduction should read: *Clip-115* KO mice are also viable…

We apologise to the authors and readers for these mistakes.
CLIPR-59: a protein essential for neuromuscular junction stability during mouse late embryonic development

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SUMMARY

CLIPR-59 is a new member of the cytoplasmic linker proteins (CLIP) family mainly localized to the trans-Golgi network. We show here that Clipr-59 expression in mice is restricted to specific pools of neurons, in particular motoneurons (MNs), and progressively increases from embryonic day 12.5 (E12.5) until the first postnatal days. We generated a Clipr-59 knockout mouse model that presents perinatal lethality due to respiratory defects. Physiological experiments revealed that this altered innervation prevents the normal nerve-elicited contraction of the mutant diaphragm that is reduced both in amplitude and fatigue-resistance at E18.5, despite unaffected functional muscular contractility. Innervation of the mutant diaphragm is not altered until E15.5, but is then partially lost in the most distal parts of the muscle. Ultrastructural observations of neuromuscular junctions (NMJs) in the distal region of the diaphragm reveal a normal organization, but a lower density of nerve terminals capped by terminal Schwann cells in E18.5 mutant when compared with control embryos. Similar defects in NMJ stability, with a hierarchy of severity along the caudo-rostral axis, are also observed in other muscles innervated by facial and spinal MNs in Clipr-59 mutant mice. Clipr-59 deficiency therefore affects axon maintenance but not axon guidance toward muscle targets. Thus, CLIPR-59 is involved in the stabilization of specific motor axons at the NMJ during mouse late embryogenesis and its role is crucial for mouse perinatal development.

KEY WORDS: Axon development, Cytoskeleton, Motoneurons, Mouse embryo, Neuromuscular junction, Clip3

INTRODUCTION

Cytoplasmic linker proteins, or CLIPs, define a family of molecules that all include microtubule (MT) binding domains, i.e. their cytoskeleton-associated protein Gly-rich (CAP-Gly) domains (Jaworski et al., 2008). The first member of the family, CLIP-170 (CLIP of 170 kDa; Clip1 – Mouse Genome Informatics), was described as a MT plus end-binding protein that mediates the interactions of endocytic organelles to MTs (Pierre et al., 1992). CLIP-170 is involved in the dynein-dynactin pathway and plays an important role in mitosis (Lansbergen et al., 2004; Wieland et al., 2004). CLIP-170 knockout (KO) mice are viable but males produce sperm with morphological defects (Akhmanova et al., 2005). In mutant mouse primary fibroblasts, MT ends contained less dynactin than those of control cells, but a similar level of CLIP-115 (Clip1 – Mouse Genome Informatics), a close relative of CLIP-170 involved in linking dendritic lamellar bodies to MTs (De Zeeuw et al., 1997). Although disruption of dynein/dynactin inhibits axonal transport in motoneurons (MNs) causing late-onset progressive degeneration (Teuling et al., 2008), no defect has been reported so far in the nervous system of Clip-170 KO mice.

Clip-170 KO mice are also viable but exhibit a mild growth deficiency and brain abnormalities, particularly hippocampal and motor coordination dysfunctions (Hoogenraad et al., 2002). This phenotype partially mimics Williams syndrome, a rare neurodevelopmental disorder caused by deletion of a region containing several genes, including CLIP-115. Moreover, in the absence of Clip-115, increased levels of both dynactin and CLIP-170 were observed on MT ends in fibroblasts.

Using a dominant-negative form of CLIP-170 in Chinese hamster ovary cells, CLIP-115 and CLIP-170 were shown to act redundantly as rescue factors via their N-terminal domains. Recently, CLIP-170 and CLIP-115 were both found to be enriched in the growth cones of cultured rat hippocampal neurons, and involved in initial neuronal polarization and axon formation (Neukirchen and Bradke, 2011).

A potential role for another CLIP-related protein in the nervous system has been suggested by the identification of CLIPR-59, or CLIP-related protein of 59 kDa (Clip3 – Mouse Genome Informatics), found to be strongly expressed in the brain. In contrast to CLIP-170 and CLIP-115, CLIPR-59 does not bind MT plus ends. The domains surrounding its two CAP-Gly domains, an N-terminal domain bearing ankyrin repeats and a C-terminal Golgi-targeting domain, inhibit MT interactions (Lallemand-Breitenbach et al., 2004) and CLIPR-59 has been proposed to active at endosome/TGN interface. A role for a TGN-localized MT-binding protein in neuronal cells may be related to the strong need of developing axons to sustain not only polarized intracellular trafficking but also dynamic exocytosis to ensure rapid reorganization of membrane during pathfinding and to establish proper synaptic connections.

In the present work, we therefore studied the function of CLIPR-59 in the development of the nervous system. We show that CLIPR-59 is particularly expressed in MNs, with an increased expression from early to late embryonic development. MNs are highly polarized and differentiated cells that must develop long axons. To
investigate the role of CLIPR-59 in vivo, we generated a KO mouse model and found that mutant mice die perinatally from respiratory defects. We detected mis-innervation of the diaphragm by phrenic nerves that arise from cervical MNs, with a degeneration of their distal axon terminals from E15.5 that leads to a lower density of nerve terminals at the NMJ at E18.5 in distal regions of the mutant diaphragm. Similar defects were observed in some muscles innervated by facial and spinal MNs. Our structural and ultrastructural results further indicate that CLIPR-59 depletion is associated with a premature or enhanced retraction of motor axons at the NMJ during mouse embryo development. This suggests that CLIPR-59 plays a crucial role in nerve terminal maintenance, possibly through protein/membrane trafficking or cytoskeleton remodeling at the NMJ.

MATERIALS AND METHODS
Generation of Clipr-59 mutant mice
Clipr-59 mutant mice were generated at the Mouse Clinical Institute (Strasbourg, France) via insertion of loxP sequences into introns 1 and 5 with a neomycin-resistance gene as a selective marker (Fig. 2A). The targeting vector was electroporated into embryonic stem (ES) cells. Breeding of these mice with mice universally expressing Cre recombinase lead to the generation of mice with one invalidated Clipr-59 gene (Clipr-59<sup>−/−</sup>). Clipr-59<sup>−/−</sup> mice were backcrossed to C57BL/6 mice before intercrossing heterozygous parents to obtain homozygous CLIPR-59-deficient mice (Clipr-59<sup>−/−</sup>). DNA was isolated from the tail and used for genotyping with the following primers: GCTCAGCTGTC-CCAGAGTTTGAC and GCATAACTCTGAGAGTTTGAGGCC; or AATCGGAAGAAG. Pregnant Swiss mice were purchased from Janvier Laboratories (Le Genest St Isle, France).

In situ hybridization and MN counts
Cryosections (20 µm) of brain and spinal cord were prepared from mouse embryos and in situ hybridization was performed as described previously (Causeret et al., 2004). The Clipr-59 probe was designed by PCR to precisely encompass the deleted region of CLIPR-59 cDNA in KO mice (nucleotides 374-889 in cDNA). The peripherin probe was kindly provided by M. M. Portier (Moncla et al., 1992). Cell counts were performed at E18.5, as described previously (Backer et al., 2007). Results are means of right and left counts (±s.e.m.) from at least four different embryos of each genotype.

Cell culture and immunolabeling
For primary neuronal cultures, the cervical region of spinal cord was dissected from E12.5 wild-type embryos according to Arce et al. (Arce et al., 1999). Cells were fixed in PBS containing 4% PFA and 10% sucrose for 15 minutes at room temperature. After washing in phosphate-buffered saline solution (PBS), autofluorescence was quenched with 50 mM NH₄Cl for 15 minutes at room temperature. After washing in phosphate-buffered saline solution (PBS), autofluorescence was quenched with 50 mM NH₄Cl for 20 minutes at room temperature. The primary antibodies used were anti-peripherin (Millipore: 1:2000), TUJ1 (Covance: 1:5000), anti-S-100 (DAKO, 1:200), anti-MuSK (serum 194T, 1:500) and anti-agrin (serum 205, 1:500), kindly provided by Dr. M. A. Ruegg (University of Basel, Switzerland). After extensive washing in PBS, samples were incubated with Cy3-coupled anti-rabbit IgG (Jackson ImmunoResearch, 1:1000), Alexa647-coupled anti-mouse IgG or Alexa488-coupled α-bungarotoxin (Invitrogen, 1:500). Apoptosis was detected in tissue cryosections using a cell death detection kit (Roche Applied Science). Tissues were mounted in Mowiol and analyzed using a Zeiss confocal laser scanning microscope and a 63× objective. For image analysis, series of optical sections of 0.5 µm acquired using the same microscope settings were quantified using the ImageJ software (100 synapses from three control and mutant embryos). For analysis of MuSK and agrin labeling on cryosections, the signal was expressed as total intensity normalized to the synapse area. Data are presented as the mean±s.e.m.

Electron microscopy on E15.5 and E18.5 diaphragms
Hemi-diaphragm preparations from E15.5 and E18.5 embryos were fixed in 2% PFA and 2% glutaraldehyde (Sigma) solution in PBS for 2 hours at room temperature. Samples from E15.5 and E18.5 were perfused with 2% PFA and post-fixed for 2 hours in 2% PFA at room temperature. Tissues were embedded in PBS containing 10% sucrose and 10% gelatin, and processed into 20 µm cryosections. Autofluorescence was quenched with 50 mM NH₄Cl for 20 minutes at room temperature. The primary antibodies used were anti-agrin (Novocastra, 1:500), Alexa488-coupled anti-mouse IgG or Alexa488-coupled α-bungarotoxin (Invitrogen, 1:500). Apoptosis was detected in tissue cryosections using a cell death detection kit (Roche Applied Science). Tissues were mounted in Mowiol and analyzed using a Zeiss confocal laser scanning microscope and a 63× objective. For image analysis, series of optical sections of 0.5 µm acquired using the same microscope settings were quantified using the ImageJ software (100 synapses from three control and mutant embryos). For analysis of MuSK and agrin labeling on cryosections, the signal was expressed as total intensity normalized to the synapse area. Data are presented as the mean±s.e.m.

RESULTS
In vivo CLIPR-59 expression during mouse development
According to an EST database (Unigene Cluster hs. 7357), Clipr-59 gene expression was ubiquitous but was highest in the nervous system. In northern blot analysis of adult mouse tissues using mouse Clipr-59 cDNA fragments, high levels of ~4 kb Clipr-59 transcripts were detected in brain and lower levels in other tissues (pancreas, kidney, skeletal muscle, liver, lung, placenta and heart) (Holly et al., 1997).
Goodson, personal communication (Notre Dame University, South Bend, IN, USA) (Perez et al., 2002). Using a systematic bioinformatic approach (Huminiecki et al., 2003), we also found that Clipr-59 was expressed at its highest levels in the brain compared with its expression levels in other tissues.

Specific expression of Clipr-59 in the mouse nervous system was further characterized using in situ hybridization with an antisense probe directed against Clipr-59 mRNA in brain and spinal cord cryosections [control in situ hybridization with a sense probe revealed no signal (data not shown)]. During development, Clipr-59 mRNA could be detected at low levels as early as E11.5 in the spinal and cranial MNs, including the V, VII, X and XII nuclei (Fig. 1A, arrowheads). The intensity of the mRNA signal increased in MN pools during embryonic development and slightly decreased in the adult (postnatal day 21, P21). Thus, Clipr-59 expression is finely and not ubiquitously expressed in the nervous system, as MNs show higher mRNA expression than surrounding cells. Peripherin mRNA is present at high levels in motor nuclei of cranial nerves (in particular the V, VII, X and XII nuclei), as well as in ventral horn MNs (Leonard et al., 1988), and accordingly we observed at E18.5 by in situ hybridization strong expression of peripherin in motoneuronal pools, where Clipr-59 signal was detected (Fig. 1B).

Western blot analysis of mouse tissues at E18.5 confirmed that Clipr-59 was highly expressed in different regions of the brain and spinal cord, but that expression was very low in other tissues, such as lung, heart and diaphragm (Fig. 1B). Moreover, CLIPR-59 protein levels increased progressively between E12.5 and E18.5 in hindbrain and spinal cord extracts (four- and twofold, respectively) (Fig. 1C).

We also examined the intracellular localization of CLIPR-59 in neuronal cells (Fig. 1D). Although only low levels of CLIPR-59 protein could be detected in HeLa cells, immunofluorescence experiments carried out previously in these cells identified the TGN as a principal localization site for CLIPR-59 (Perez et al., 2002). For these experiments, we used a new antibody raised against CLIPR-59 to stain E12.5 primary MNs dissociated either from the facial nucleus (VII) or from ventral spinal cord (cervical region), as in situ hybridization and western blot experiments detected high levels of Clipr-59 expression in these MN pools during mouse development. CLIPR-59 staining in MNs increased by 2.5±0.3-fold from 2 to 5 days in vitro, and it appeared concentrated in a tubulovesicular network in the cell body juxtaposed to GM130 staining, but also as punctate staining at the growth cone and to a lesser extent along the axon (Fig. 1D).

**CLIPR-59 deficiency in mice and perinatal death**

To investigate the role of CLIPR-59 in the mammalian nervous system, mice lacking CLIPR-59 were generated (Fig. 2A). In situ hybridization in brain cryosections from E18.5 embryos confirmed the absence of Clipr-59 expression in homozygous knockout mice (Clipr-59−/−, data not shown). Moreover, CLIPR-59 protein was not...
detected in spinal cord and cortex lysates from \textit{Clipr-59}−/− E18.5 embryos (Fig. 2B). No effect was observed in the expression of \textit{Clipr-170} and \textit{Clip-115} in the spinal cord of \textit{Clipr-59}−/− E18.5 embryos (Fig. 2B). \textit{Clipr-59}−/− mice are healthy and fertile but no homozygous mutants were identified at postnatal day 1 (P1) in the ten litters from mated \textit{Clipr-59}−/− mice. However, we observed no prenatal mortality, \textit{Clipr-59}−/− embryos being present in a normal Mendelian ratio at all developmental stages (Fig. 2C), suggesting that \textit{Clipr-59} deletion did not impair \textit{in utero} survival. Therefore, we focused our analysis on E18.5 embryos for all subsequent studies on \textit{Clipr-59}-deficient mice.

Upon attempts to resuscitate E18.5 embryos from mated \textit{Clipr-59}−/− mice, only homozygous mutants died shortly after the Cesarean section. Despite exhibiting normal gross morphologies at E18.5, responsiveness to mild pinches on their tails and legs, and having some gasps, \textit{Clipr-59}−/− embryos were unable to expand their lungs and rapidly became cyanosed (Fig. 2D): respiratory failure. As the diaphragm is innervated by phrenic nerves consisting of axons from MNs located in the cervical spinal cord (which strongly express \textit{Clipr-59}), we next analyzed diaphragm innervation in mutant (\textit{Clipr-59}−/−) and control (\textit{Clipr-59}+/+) embryos.

**Normal early development but incomplete innervation pattern of the E18.5 diaphragm in the absence of \textit{Clipr-59}**

To visualize phrenic nerve arborizations in whole-mounts of diaphragms from E12.5 to E18.5, we labeled the intermediate filament protein peripherin, which is expressed as early as E9.5 in MNs and in peripheral sensory neurons (Duprey and Paulin, 1995). During normal mouse development, axons of the phrenic nerve exit the cervical spinal cord and reach the diaphragm primordium at E12.5. Then each phrenic nerve divides into three main branches: the crural branch that innervates the crus (a muscle not involved in breathing movements), and the dorsal and ventral branches. Whole-mount immunostaining of peripherin indicated no significant differences in the innervation patterns of mutant and control diaphragms at E13.5 and E15.5 (data not shown and Fig. 3A). However, in later developmental stages of mutant embryos, a progressive loss of innervation was observed in the most distal parts of the main phrenic branches, in particular in the ventral region of the diaphragm (Fig. 3B, frame in 3C), and also, albeit with a reduced severity, in the dorsal region of the muscle (arrow in Fig. 3C and supplementary material Fig. S1). By E18.5, the ventral part, and to a lesser extent, the dorsal part of the diaphragm were not innervated in the mutants (Fig. 3C). However, postsynaptic nAChR clusters (labeled with α-bungarotoxin in green) could be observed at the center of the diaphragm muscle from both control and mutant E18.5 embryos (Fig. 3C). The lengths of the primary branches of the phrenic nerve were similar at E15.5 for control and mutant embryos (Fig. 3D), but significantly shorter in mutant embryos at E18.5 (Fig. 3E). In addition, the mean length of the major secondary branches of the right phrenic nerve was significantly longer than in control embryos at E18.5 (Fig. 3F). However, there was some disparity among individuals of the same genotype.

Analysis of the distribution of nAChR clusters revealed their confinement in a central band of the muscle in both mutant and control diaphragms at all stages between E15.5 and E18.5 (data not shown and Fig. 3C). A slight enlargement of the nAChR band was observed in the aneural part of the mutant diaphragm (frame in Fig. 3C), possibly owing to the loss of presynaptic nerve terminals in this region (Fig. 3G).

**Reduced contraction force of the diaphragm from \textit{Clipr-59}-deficient embryos at E18.5**

As we observed discrete defects in diaphragm innervation in \textit{Clipr-59}−/− embryos and breathing depends primarily on phrenic nerve-diaphragm activity, we next tested the ability of this muscle to contract in nerve/hemi-diaphragm preparations at E18.5. Through nerve stimulation, the maximal twitch tension in mutant hemidiaphragms was about half of that recorded in control muscles (Fig. 4A). However, when hemidiaphragms from mutant embryos were directly stimulated, the maximal contraction was not significantly different from that recorded in control muscles. Hence, in the absence of \textit{Clipr-59}, the target muscle retains its contractility capacity, whereas phrenic nerve-elicited contraction is greatly impaired. Next, we tested the influence of the stimulation frequency of single phrenic nerve pulses on isometric tension (Fig. 4B). No differences in the frequency-dependency of the nerve-elicited contractions were evident between mutant and control hemidiaphragms.

We further studied whether isometric tetanic tension could be sustained upon nerve stimulation at different frequencies and times of stimulation (Fig. 4C,D). Not only was the peak of the nerve-elicited tetanic contraction in mutants lower than in controls, but the fade of the mutant contractile response was more pronounced at 6 seconds stimulation than at 1.5 seconds. Thus, both the maximal amplitude and the maintenance of the contraction following nerve stimulation were greatly impaired in CLIPR-59-deficient hemidiaphragms.

By contrast, all muscles from mutant and control embryos contracted to the same extent when directly stimulated in the presence of d-tubocurarine, which blocks neuromuscular transmission (Fig. 4E,F). This suggests that only nerve-elicited
muscle contraction is altered in CLIPR-59-deficient mice, a deficiency probably caused, at least in part, by the innervation defects observed previously.

Abnormal motor innervation of other muscles in CLIPR-59-deficient mice at E18.5

To determine whether defects in muscle innervation by MN were diaphragm specific, we analyzed the innervation of other muscles in mutant embryos. Analysis of the innervation pattern of the intercostal muscles, which are also involved in breathing, did not reveal any defects in the mutant at E18.5 (data not shown). The intercostals and the diaphragm belong to different muscle classes: fast-synapsing (FaSyn) muscle and delayed-synapsing (DeSyn) muscle, respectively. These two classes of muscle exhibit intrinsically different features of focal nAChR clustering and differ in the rate at which they acquire the characteristic organization of the NMJ (Pun et al., 2002). Therefore, we next analyzed some cranial muscles, which are composed of both FaSyn and DeSyn muscles (Fig. 5A), and are innervated by branches of the cranial muscles, which are composed of both FaSyn and DeSyn the NMJ (Pun et al., 2002). Therefore, we next analyzed some

Altered NMJ stability in the distal part of the phrenic nerve in CLIPR-59-deficient embryos at E18.5

To further characterize NMJ alterations, we analyzed their morphology in the diaphragm from E18.5 embryos by confocal microscopy on whole-mount preparations stained with anti-peripherin antibodies and labeled with α-bungarotoxin. Quantification of individual nAChR clusters showed that the mean surface was larger in mutant than in control E18.5 diaphragms, especially in the ventral area of the muscle (supplementary material Fig. S3A). However, the total intensity of α-bungarotoxin labeling was similar (supplementary material Fig. S3B). These results suggest that the number of post-synaptic nAChR receptors was not affected in mutant diaphragms, but their organization in clusters was perturbed in the denervated region of the mutant diaphragm. However, in this ventral region of the mutant diaphragm, the localization and levels of the muscle specific kinase MuSK, a post-synaptic protein playing a central role in the formation of NMJs, were unaltered compared with control diaphragms (supplementary material Fig. S4). Moreover, the proportion of innervated synapses was reduced by 30% in the ventral part of mutant diaphragms, whereas it was similar to control in the medial part where NMJs appeared to be

Fig. 3. Innervation of the diaphragm is impaired in Clipr-59−/− embryos from E15.5 to E18.5. Anti-peripherin and α-bungarotoxin were used to label nerve intermediate filaments and nAChRs, respectively before macroscopic imaging of diaphragm whole mounts (orientation of the diaphragm: D, dorsal; V, ventral; R, right; L, left). (A) The innervation patterns of the diaphragms are similar for control and mutant embryos until E15.5, as the dorsal and ventral primary branches of the phrenic nerve reach both muscle extremities. (B) In the absence of CLIPR-59, the innervation pattern becomes incomplete from E15.5 until E18.5, in particular in the ventral region of the diaphragm muscle. (C) At E18.5, both ventral and dorsal branches of phrenic nerves do not reach the most distal part of the mutant diaphragm where clusters of nAChRs are normally distributed (arrows). (D) At E15.5, the dorsal and ventral nerve branches in embryos of all three genotypes exhibit no significant differences in length. (E) At E18.5 the ventral and dorsal primary branches of the phrenic nerve are both significantly shorter in the mutant. (F) In the right hemi-diaphragm, the lengths of the major secondary nerve branches are longer in Clipr-59−/− mice. (G) In the ventral part of the left hemi-diaphragm, the band of nAChR clusters is slightly but not significantly larger in mutants. Data are means±s.e.m. *P<0.05; **P<0.001; Mann-Whitney U test. NS, non-significant. Scale bars: 500 μm.
normal (supplementary material Fig. S3C). In both control and mutant diaphragms, presynaptic nerve terminals were observed facing the post-synaptic nAChR receptors in the core of the nerve branches (Fig. 6A, parts a and b, respectively). However, near the tip of nerve branches in mutant mice (Fig. 6Ad), the nerve frayed out and axons appeared less fasciculated and branched than in control mice (Fig. 6Ac), with shredded segments of axons (arrowhead), varicose terminals and unoccupied nAChR clusters (star).

We next examined perisynaptic Schwann cells using an anti-S-100 antibody along with a TuJ1 antibody to detect axonal tubulin (Fig. 6B). Upstream of the nerve tip, terminal Schwann cells could be observed capping NMJs in both control (Fig. 6Ba) and mutant (Fig. 6Bb) diaphragms. However at the nerve tips of mutant mice (Fig. 6Bd), axons were defasciculated, as indicated by tubulin staining (arrowhead). Schwann cells remained present and were capping the nerve terminals but their shape, identified by the staining (arrowhead), varicose terminals and unoccupied nAChR clusters significantly higher (mean value=5±0.7; n=41), whereas in the controls, the mean number of nerve terminals was significantly higher (mean value=5±0.7; n=67; P<0.05). Moreover, in ~10% NMJs of the mutant diaphragm, abnormal nerve terminals containing a reduced number of small clear synaptic vesicles were observed in terminals totally wrapped up in terminal Schwann cell extensions (Fig. 7D), a feature not observed in control NMJs. These may correspond to retracting nerve terminals that are being engulfed by Schwann cells. Thus, even if the tripartite composition of the NMJ was respected, nerve terminals appeared less numerous at NMJs in the ventral part of the mutant diaphragm muscle. This suggests a reduction in either the branching complexity of nerve terminals or the number of axons at NMJs in the absence of CLIPR-59.

NMJs in the ventral region of diaphragms were also imaged at E15.5 by electron microscopy (supplementary material Fig. S5). Nerve terminals (highlighted in red), capped by Schwann cells (highlighted in green), were observed in close proximity to α-bungarotoxin-labeled post-synaptic zones in both control and mutant samples (supplementary material Fig. S5Aa,Ab), indicating that NMJs were properly formed at E15.5. Figures of stacked nerve terminals or the number of axons at NMJs in the absence of CLIPR-59 were very similar. (F) The percentage of maximal contraction upon direct stimulation remains high after 1.5 and 6 seconds for diaphragms from either Clipr-59+/- or Clipr-59−/− embryos. Data are mean±s.e.m.
in the mutant, some nerve terminals (supplementary material Fig. S5Ad, white stars) contained fewer small clear synaptic vesicles when compared with control nerve terminals (supplementary material Fig. S5Ac), but still contained mitochondria (asterisks). Schwann cells were always present in all visualized NMJs of both mutant and control E15.5 diaphragms, and their long thin digitations were also observed facing α-bungarotoxin-labeled muscle membrane in the absence of nerve terminals, in control and mutant diaphragms (supplementary material Fig. S5Ae,f). Such immature organization was no longer observed at E18.5 (Fig. 7). These Schwann cell extensions were also detected using S-100 immunolabeling on cryosections of E15.5 diaphragms (supplementary material Fig. S5Ba,b, white arrows). No apoptotic figures were detected by TUNEL staining in S-100-positive cells imaged in cryosections of the ventral region of diaphragms from both control and mutant E15.5 embryos, confirming the ultrastructural observations.

Next, we examined whether MN cell bodies were also affected by CLIPR-59 deficiency. We counted the number of facial and spinal MNs on cervical sections in brain and spinal cord cryosections after in situ hybridization with an anti-peripherin probe (Fig. 8A). At E18.5, no differences in both facial and cervical MN cell body numbers were detected between mutant and control embryos (Fig. 8B). Thus, at this developmental stage in mutant embryos, there were no signs of MN loss in these two pools despite losses of innervation by the facial and spinal nerves. Consistently, immunofluorescence labeling of active caspase 3 on brain and spinal cord cryosections did not reveal any significant differences between control and mutant E18.5 embryos (data not shown). Hence, no increase in apoptosis could be observed at late developmental stages in CLIPR-59-deficient embryos.

**DISCUSSION**

We report here that *Clipr-59* is especially expressed in motoneuronal pools. The phenotypic and functional characterization of the innervation of different muscles in *Clipr-59* KO mouse reveals that CLIPR-59 is necessary for the stabilization of NMJs and the prevention of motor axon retraction during late embryogenesis.

**Clipr-59 expression levels increase along embryonic development and MN differentiation**

*Clipr-59* expression in the mouse is spatially restricted, in particular to some MN pools in the brain and spinal cord. *Clip-115* mRNA and protein were also detected mostly in the brain, in particular in the inferior olive nucleus, hippocampus, cortex and cerebellum (De Zeeuw et al., 1997). In contrast, *Clip-170* expression is ubiquitous in the adult rat (Akhmanova et al., 2005).

In mouse, *Clipr-59* expression levels increase from E11.5 until birth, whereas those of *Clip-115* expression remain low from E10.5
through birth, and become very high during the first postnatal days (De Zeeuw et al., 1997). The increasing levels of Clipr-59 expression were also observed in vitro in primary MN cultures from E12.5 embryos, similarly to what has been described in adipocytes (Ding and Du, 2009). Thus, Clipr-59 expression seems to be enhanced as cell differentiation occurs and its increased expression between E12.5 and birth could be correlated with a possible role during embryogenesis. Interestingly, the temporal increase in phenotypic defects observed in Clipr-59 KO mice between E15.5 and birth could be correlated with a possible role during embryogenesis. Interestingly, the temporal increase in phenotypic defects observed in Clipr-59 KO mice between E15.5 and birth could be correlated with a possible role during embryogenesis. CLIPR-59 is involved in the proper and timely maintenance of muscle motor innervation during late embryogenesis

Although CLIPR-59 deficiency is not lethal during embryonic development, mutant mice die at birth from respiratory failure. From this phenotype and the developmental expression profile of Clipr-59 in cervical MNs, we focused on analyzing the innervation pattern of the diaphragm from E12.5, when the phrenic nerve reaches the diaphragm primordium and branches. The defects observed in diaphragm innervation could be due to axon extension defects, to axon-guidance defects or to synapse-maintenance defects. Unlike the readily apparent lack of innervation at E13.5 observed in diaphragms from mice lacking the Unc5c netrin receptor (Burgess et al., 2006), axonal projection and pathfinding by phrenic MNs appeared normal in CLIPR-59 mutants until E15.5. From E16.5 to E18.5, motor innervation became incomplete in the most distal regions of the mutant diaphragm, and phrenic branches were significantly shorter than normal. However, aneural nAChRs were still clustered in a central band that was not significantly broader in the mutant than in the control. This observation is more consistent with a retraction of pre-existing phrenic axons or a loss of synaptic connections, as occurs in neuronal neuregulin 1 mutant mice (Yang et al., 2001), than with a defect in the guidance or elaboration of the nerve.

The analyses of other muscles revealed that some facial MN projections showed similar axonal retractions, but as early as E15.5, whereas lower spinal MN projections were affected but to a less extent than phrenic MN ones at E18.5. Altogether, these different delays in the appearance of MN axon retractions parallel the time course of MN maturation along the rostrocaudal axis. It could suggest that CLIPR-59 is involved, at specific stages of embryonic
development, in the projection of MNs towards their target muscle, possibly by preventing the premature withdrawal of polyneuronal innervation. Indeed, polyneuronal innervation of diaphragm muscle fibers could represent a developmental strategy during perinatal period to allow fractional and selective recruitment of motor units as synapse elimination proceeds. In mouse, phrenic MNs are recruited as soon as E12.5 by rhythmic motor patterns generated in the spinal cord, and by E15.5 rhythmic fetal respiratory movements are already occurring (Greer and Funk, 2005). However, the influence of these synaptic inputs to phrenic MNs on trophic support or dendritic arborization during embryonic development is not yet clearly determined, and we cannot so far exclude an additional effect of CLIPR-59 deficiency on those rhythmogenic networks. As CLIPR-59 deficiency does not lead to embryonic death, the rate of NMJ innervation and activity during embryogenesis would be sufficient to ensure basic functions required for embryo survival, but the first breathing at birth could not be supported in the absence of CLIPR-59 as the near complete recruitment of diaphragm motor units would be necessary to inflate the lungs and sustain ventilation. In E18.5 Clipr-59 mutant embryos, as in mice lacking rapsyn or agrin which are key components of NMJs involved in nAChR clustering, lower maximal nerve-induced contraction was detected in mutant diaphragms, whereas their contractile ability was not different from controls when the muscles were stimulated directly (Banks et al., 2003). Hence, the weak nerve-elicited muscle contraction is likely to be due to impaired neurotransmission in the Clipr-59 mutant. The analysis of the present model seems to reveal a key step in MN development that would underline the strict requirement of multi-innervation maintenance during late embryogenesis until birth. Although the purpose of having a higher number of nerve terminals at the NMJs at birth than postnatally is not yet fully characterized, it will be of interest to analyze its role in the initial breathing and lung expansion at birth, and for other motor movements in newborns.

**NMJs in Clipr-59 mutants are lost distally and selectively in different skeletal muscles**

In E18.5 mutant diaphragms, axons at the end of the phrenic nerve were fewer and defasciculated with shedding segments and swelling tips close to aneural nAChR clusters. These axonal structures may be representative of retraction bulbs, typically observed during axon branch removal at developing synapses. They are characterized by disorganized MT network in contrast to the typical bundling of MT in growth cones (Bishop et al., 2004; Ertürk et al., 2007). The particular morphology of the terminal Schwann cells at the tip of the phrenic nerve in mutant embryos could be due to the engulfment

**Fig. 7. The ultrastructure is modified in some NMJs of E18.5 mutant diaphragms.** Presynaptic nerve terminals and terminal Schwann cells were artificially colored in light red and green, respectively. (A) Bundle of nerve terminals capped by a Schwann cell process in a control NMJ. Numerous pre-synaptic synaptic vesicles and some mitochondria (asterisks) are present in nerve terminals. (B-C) Clipr-59 mutant NMJs showing either the chain-like arrangement of nerve terminals (B), or the single arrangement of the terminal (C) covered by thin Schwann cell processes. Both types of nerve terminals exhibit small clear synaptic vesicle accumulation and mitochondria. (D) Clipr-59 mutant NMJ exhibiting abnormal nerve terminals (stars), totally wrapped up in Schwann cell processes containing few synaptic vesicles. Scale bars: 1 μm.

**Fig. 8. The number of facial and cervical MN cell bodies is similar in control and mutant embryos at E18.5.** (A) In situ hybridization with anti-peripherin probe on brain and spinal cord cryosections from E18.5 embryos. Scale bar: 100 μm. (B) Cell number is not significantly changed in the facial nucleus and in the cervical MN pools of mutants. Data are mean±s.e.m. NS, not significant.
of axonal membrane remnants. Ultrastructural observations of NMJs in this area of the diaphragm revealed that the number of nerve terminals was quite reduced in the absence of CLIPR-59 compared with the control, and that some nerve terminals devoid of vesicles were visualized enwrapped in Schwann cell extensions. Similar defects in some NMJs in E15.5 diaphragms, revealed at the ultrastructural but not at the macroscopic level, could be responsible for the onset of nerve terminal retraction that leads to a more pronounced phenotype of mis-innervation at E18.5. Conversely, intercostal muscles were not detectably affected in Clipr-59−/− embryos at E18.5. Similar differences in defect severity between phrenic and intercostal innervation were also observed in ErbB2- (Lin et al., 2000) and in DINE-deficient mice (Nagata et al., 2010), which could suggest that the deeper the final motor branches are into a muscle, the more severely affected the muscle innervation is. Another hypothesis is that CLIPR-59 deficiency differentially affects motor innervation according to the skeletal muscle type, such that DeSyn muscle (i.e. diaphragm, LALc) is more severely affected than FaSyn muscle (i.e. intercostals, LALc).

Indeed, we hypothesize that the expression level of CLIPR-59 may not be crucial in the selective impairment of some motor units, but could indicate the specific involvement of CLIPR-59 in these types of motor units, because of their specific physiology. Interestingly, the perinatal defects associated with CLIPR-59 deficiency are similar to the early symptoms of animals with SMN deficiency (Grandic et al., 2004) and are more severe than FaSyn muscle (i.e. intercostals, LALc).

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Fig. S1. Innervation of the dorsal part of the diaphragm is also impaired in *Clipr-59*−/− embryos from E15.5 to E18.5. Whole-mount histochemistry was performed on diaphragms using anti-peripherin to label embryonic nerve intermediate filaments and α-bungarotoxin to label nAChRs before macroscopic imaging (orientation of the diaphragm: D, dorsal; V, ventral; R, right; L, left). (A) The innervation patterns of the diaphragms are similar for control and for CLIPR-59-deficient embryos until E15.5, as the dorsal and ventral primary branches of the phrenic nerve reach both muscle extremities. (B) At E18.5, both ventral and dorsal branches of phrenic nerves do not reach the most distal part of the mutant diaphragm. (C) In the magnification of the dorsal region of the diaphragm muscle, the innervation pattern in the mutant becomes incomplete from E15.5 until E18.5. Scale bar: 500 µm.
Fig. S2. Innervation defects in hindlimb muscles are less extended than in diaphragm of Clipr-59⁻/⁻ embryos at E18.5. Whole-mount histochemistry was performed on dissected hindlimb muscles using anti-peripherin to label embryonic nerve intermediate filaments before macroscopic imaging. To facilitate the visualization and comparison of the innervation, the nerve trunk is highlighted by a broken red line. (A, B) In E18.5 mutant embryos, the innervation pattern is moderately altered in two fast-twitch muscles, (A) the tibialis anterior and (B) the extensor digitorum longus (EDL). (C) In the slow-twitch muscle soleus, only slight innervation defects can be detected in the mutant at E18.5. Scale bar: 500 µm.

Fig. S3. Post-synaptic nAChRs are slightly less clustered in the denervated part of the mutant diaphragms at E18.5. Post-synaptic nAChRs were labeled with α-bungarotoxin in whole-mount diaphragm preparations and then imaged by confocal microscopy. (A-C) Measurement of (A) nAChR cluster surface, (B) α-Bungarotoxin fluorescence signal intensity and (C) percentage of innervated synapses were performed in the ventral and medial parts of the diaphragm at E18.5. Data are mean±s.e.m. *P<0.05; **P<0.001; Mann-Whitney U test. NS, non significant.
Fig. S4. Post-synaptic MuSK and neutrally secreted agrin are normally present at NMJs in E18.5 mutant diaphragms. Postsynaptic nAChRs and neuronal tubulin were labeled with α-bungarotoxin and Tuj1 antibody, respectively, and with either anti-MuSK or anti-agrin antibodies in diaphragm cryosections before imaging by confocal microscopy. (A) MuSK (in red) colocalized with nAChRs (in green) either at the core (a, b) or the tip (c, d) of the nerve ventral branch in both control and mutant diaphragms. (B, C) Measurement of (B) MuSK and (C) agrin fluorescent signal intensity at NMJs in the ventral part of E18.5 diaphragms. Data are mean±s.e.m. Mann-Whitney U test. NS, non-significant. Scale bar: 10 µm.
Fig. S5. At E15.5, some defects are already apparent at the ultrastructural level in few NMJs in the ventral part of mutant diaphragm muscle. (A) Longitudinal ultrathin sections were cut through muscle fibers of the ventral region of diaphragm of E15.5 embryos. NMJs were detected by labeling nAChRs with biotinylated α-bungarotoxin and streptavidin coupled to gold particles. Presynaptic nerve terminals and terminal Schwann cells are artificially colored in light red and green, respectively. In both control and mutant diaphragms, nerve terminals containing pre-synaptic vesicles and mitochondria (asterisks), and capped by large Schwann cells are observed at NMJ (a, b). However, in Clipr-59 mutant, in some NMJs (stars in d) the nerve terminal composition appeared abnormal with few vesicles accumulating (but still some mitochondria, asterisks). The presence of Schwann cell processes in the synaptic cleft between presynaptic and post-synaptic components (arrowhead), and enwrapping nerve terminals could suggest their engulfment by Schwann cells. These Schwann digitations were observed to a lower extent in the synaptic cleft of some NMJs of control samples (c), and also in regions devoid of nerve terminals (d and e). (B) Using anti-S-100 antibody on E15.5 diaphragm cryosections, similar Schwann extensions were evidenced (arrow) by light microscopy in both control and mutant samples (a and b, respectively). Scale bars: 1 µm in A; 10 µm B.