

Research paper

Prolonged deficit of low gamma oscillations in the peri-infarct cortex of mice after stroke

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ABSTRACT

Days and weeks after an ischemic stroke, the peri-infarct area adjacent to the necrotic tissue exhibits very intense synaptic reorganization aimed at regaining lost functions. In order to enhance functional recovery, it is important to understand the mechanisms supporting neural repair and neuroplasticity in the cortex surrounding the lesion. Brain oscillations of the local field potential (LFP) are rhythmic fluctuations of neuronal excitability that synchronize neuronal activity to organize information processing and plasticity. Although the oscillatory activity of the brain has been probed after stroke in both animals and humans using electroencephalography (EEG), the latter is ineffective to precisely map the oscillatory changes in the peri-infarct zone where synaptic plasticity potential is high. Here, we worked on the hypothesis that the brain oscillatory system is altered in the surviving peri-infarct cortex, which may slow down the functional repair and reduce the recovery. In order to document the relevance of this hypothesis, oscillatory power was measured at various distances from the necrotic core at 7 and 21 days after a permanent cortical ischemia induced in mice. Delta and theta oscillations remained at a normal power in the peri-infarct cortex, in contrast to low gamma oscillations that displayed a gradual decrease, when approaching the border of the lesion. A broadband increase of power was also observed in the homotopic contralateral sites. Thus, the proximal peri-infarct cortex could become a target of therapeutic interventions applied to correct the oscillatory regimen in order to boost post-stroke functional recovery.

1. Introduction

Stroke remains a devastating brain pathology for which there is no therapy able to increase the magnitude of functional recovery. In the sub-acute and chronic stage following a focal brain ischemia, neuronal plasticity possibly leads to a regain of lost functions. The wiring of new circuits uses both established and *de novo* cellular materials, from spirogenesis to axonal sprouting (Nudo and Milliken, 1996; Nudo et al., 1996; Florence et al., 1998; Stroemer et al., 1998; Carmichael et al., 2001; Brown et al., 2009; Murphy and Corbett, 2009; Ueno et al., 2012). The reorganization of neuronal networks potentially occurs in any structure involved in the relearning of a behavior. Intense plastic changes take place especially in the cortex adjacent to the ischemic lesion, the so-called peri-infarct cortex, where neurons are well alive but

neural circuits are partially damaged (Stroemer et al., 1995; Brown et al., 2007; Murphy and Corbett, 2009). There is an increasing number of studies showing how the somatosensory-motor cortical activities of the affected limbs are progressively transferred and reorganized in the peri-infarct area (Dijkhuizen et al., 1999; Tombari et al., 2004; Brown et al., 2009; Wang et al., 2009; Carmichael, 2012; Sharma and Cohen, 2012). Progress from basic research also suggests that cellular and molecular mechanisms involved in assembling neurons after stroke are similar to those identified during learning and memory formation in physiological context (e.g. long-term change of synaptic strength) (Cooke and Bliss, 2006; Chervyakov et al., 2015; Yu et al., 2019). However, the peri-infarct cortex is under the influence of various pathophysiological processes such as chronic inflammation and glial reactivity. It is not yet clear how and to what extent these micro-

Abbreviations: EEG, electroencephalogram; GFAP, glial fibrillary acidic protein; LFP, local field potential; LTP, long term potentiation; MCAO, middle cerebral artery occlusion.

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environmental conditions interfere with neuronal reconnection (Sochocka et al., 2017; Skaper et al., 2018). For instance, neuronal excitability, a determining factor for neuronal communication and synaptic plasticity, is reduced in the peri-infarct area, which has been demonstrated to limit functional recovery (Clarkson et al., 2010; Carmichael, 2012). Thus, a therapeutic goal to optimize recovery after acute brain damage is to normalize the conditions of neuronal communication.

Neural oscillations are rhythmic fluctuations of the brain electrical field potential (including membrane potential of neurons) that can be measured with extracellular electrodes placed into the cortex (local field potential, LFP) or with external electrodes placed over the scalp (electroencephalography, EEG). Several discrete frequency bands generated by different oscillators have been identified, from slow rhythms (e.g. delta band, 1–3 Hz) to fast rhythms (e.g. gamma band, 30–80 Hz). Each rhythm is more or less expressed depending on the brain state (i.e. wake vs. sleep) and the ongoing sensory, motor or cognitive activity. The fundamental role of these rhythmic fluctuations of neuronal excitability is to regulate action potentials trafficking by synchronizing the firing of multiple neuronal assemblies distributed across brain regions (Buzsáki, 2006). Interestingly, an increasing number of studies show the potential importance of oscillations in neuronal plasticity (Zarnadze et al., 2016; Womelsdorf and Hoffman, 2018). For instance, reduction of theta (3–7 Hz) and gamma (30–80 Hz) activity has been correlated with decreased long term potentiation (LTP) (Huerta and Lisman, 1993; Wespatat et al., 2004; Stephan et al., 2009; Kalweit et al., 2017; Kalemaki et al., 2018). Indeed, theta and gamma wave-bands are precisely tuned to dictate a timing of collective neuronal discharges that match the temporality of synaptic plasticity mechanisms, such as LTP or spike timing dependent plasticity (STDP) (Engel et al., 1992; König et al., 1996; Magee and Johnston, 1997; Bi and Poo, 1998; Harris et al., 2003; Buzsáki and Draguhn, 2004; Wespatat et al., 2004; Harris et al., 2005; Nishiyama et al., 2010). Logically, the modification of network connections allowing functional recovery after a stroke requires that homeostatic mechanisms such as the maintenance of neuronal oscillatory activity stick to their operating range (Llinás et al., 2005; Schnitzler and Gross, 2005; Buzsáki, 2006). Several tools are tested with the aim to precisely tune the oscillatory spectrum of the pathological brain by the mean of pharmacologic, optogenetic, transcranial magnetic, direct current or rhythmic sensory stimulation methods (Guerra et al., 2018; Lozano-Soldevilla, 2018; Ramanathan et al., 2018; Zheng et al., 2020). Therefore, it is important to document the oscillatory conditions of the repairing cortex after stroke. In human, measuring the rhythmic activity of the post-stroke cortex is not new (Giaquinto et al., 1994; Zhang et al., 2013; Carino-Escobar et al., 2019) and in most cases the purpose was to find an early biomarker able to predict the quality of recovery (Pfurtscheller, 1981; Van Huffelen et al., 1984; Tecchio et al., 2005; Laaksonen et al., 2013; Zhang et al., 2013; Nicolo et al., 2015; Rabiller et al., 2015). However, these studies were carried out with EEG or magnetoencephalography (MEG), for which spatial resolution is too low to probe the ~2 mm peri-infarct boundary extending from the edge of the core (Ohab et al., 2006; Brown et al., 2007). Consequently, little is known about the spatial extent of neural oscillatory changes around the necrotic neuronal mass. The aim of the present work was thus to describe how the oscillatory activity of the peri-infarct cortex evolves, one and three weeks after a focal cortical ischemia in mice.

2. Material and methods

2.1. Study approval

Experiments, approved by the Ethics Committee for Animal Research of Normandy (CENOMEXA) and the French ministry of higher education, research and innovation, were conducted by authorized investigators in accordance with the recommendations of the European Community Council Directive 2010/63/UE of September 22.2010 on

the protection of animals used for scientific purposes. All procedures were undertaken and reported in accordance to the ARRIVE (Animal Research: Reporting *In Vivo* Experiments) guidelines.

2.2. Stroke model

For these studies, 8 to 12-week-old (20–25 g) male C57BL/6 J mice were purchased from Janvier Laboratories. Anesthesia was induced with 5% isoflurane in an induction chamber. Following the loss of righting reflex, the mouse was rapidly transferred to a nose cone mask, and maintained with isoflurane (2–2.5%) delivered at 1 L/min in oxygen enriched air and 0.15 mg/kg of buprenorphine (Par Sterile Products) was injected i.p. Spontaneous breathing frequency was kept over 0.5 Hz and body temperature was strictly maintained at 37 ± 0.2 °C throughout the surgery. Focal ischemia was induced by the permanent occlusion of the left middle cerebral artery as reported previously (Welsh et al., 1987; Nawashiro et al., 1997). Briefly, a skin incision was made between the orbit and ear. Under an operating microscope, an incision was made, dividing the temporal muscle, and the left lateral aspect of the skull was exposed by reflecting the temporal muscle and surrounding soft tissue. The distal course of the middle cerebral artery was then visible through the translucent skull. A small burr-hole craniectomy was performed with a dental drill. The left middle cerebral artery was electrocoagulated by bipolar diathermy. The muscle and soft tissue were replaced, and the incision was sutured. In this model, ischemia is restricted to the neocortex. An analgesic (buprenorphine) was administered on the day of the surgery (0.015 mg/kg, s.c.) and on subsequent 2 days.

2.3. *In vivo* electrophysiology

Seven or 21 days after the occlusion of the middle cerebral artery, anesthesia was induced with 5% isoflurane in an induction chamber. Following the loss of righting reflex, the mouse was rapidly transferred to a nose cone mask and maintained with isoflurane (2–2.5%) delivered at 1 L/min in oxygen enriched air. A calibrated isoflurane dispenser with consistent and constant oxygen pressure was used to ensure reliable and reproducible delivery of specific isoflurane concentrations. Animal was placed in a stereotaxic frame (Kopf Instrument), and 0.15 mg/kg of buprenorphine (Par Sterile Products) was injected i.p. and the eyes were protected with ophthalmic gel. Breathing frequency was maintained over 0.5 Hz and body temperature was strictly maintained at 37 ± 0.2 °C throughout the surgery using a feedback-controlled heating pad. The head was shaved and disinfected with iodine, the cranium was exposed, and 3 small holes were drilled in the parietal bone and the dura-matter was incised with care to leave the cortex intact. Three Teflon-coated silver wire electrodes, 100 µm in diameter, were lowered into the cortex until layer 4. Two electrodes were placed in the ischemic ipsilateral hemisphere at varying distances (<3 mm) from the putative lesion border. The third electrode was placed in the contralateral hemisphere in homotopic position with the distal ipsilateral electrode. The 3 electrodes were secured to the skull with some dental cement (Paladur, DentalMedical). Two other electrodes were implanted in the cerebellum for reference and ground readings. After the surgical procedure, isoflurane was reduced to $1.1 \pm 0.1\%$ for a resting period of 45–60 min followed by the recording period. Fifteen minutes of recording were performed twice with each electrode resulting in 6 different readings overall. At the end, anesthesia was elevated to 5% for a 5 min period followed by an intracardiac injection of saturated KCl solution inducing heart arrest.

2.4. Data acquisition and analysis

All *in vivo* recordings were done in a Faraday chamber and used an amplifier PowerLab 8/35 (AD-Instrument). Raw data were acquired with Labchart software (AD Instrument). The extracellular signals were amplified (10000×), bandpass filtered (0.1 Hz to 100 Hz) for the local

field potential (LFP) and acquired continuously at 4 kHz. In addition, a notch filter was added to eliminate the 50 Hz band noise. For spectral analysis of oscillatory patterns (epoch of 15 min), a modified version of the multitaper FFT MATLAB package by Mitra and Pesaran (1999) was used: FFT window size of 4 s, three to five tapers, frequency bins = 0.15 Hz, no overlap between successive windows, time bandwidth = 3 (Mitra and Pesaran, 1999; Quilichini et al., 2010).

2.5. Measurement of infarct-electrodes distance

Electrode were placed *a priori*, in a cortical area supposed to be the peri-infarcted cortex, based on the topology and the reproducibility of our MCAO procedure. The verification of the exact position of each electrode relative to the lesion was realized *a posteriori*, as follows. After the recording, under deep anesthesia, mice were killed, and 1 μ L of black ink was slowly injected using a micropipette into the site of each ipsilateral electrode. The brains were removed rapidly and frozen in cooled isopentane at -65°C for 10 s. Whole brains were cut in 20- μ m-thick sections with a cryostat (Leica CM3050), and 1/5 serial sections were collected on a glass slide and stained by thionine. Slides were scanned at a high resolution and imported into ImageJ. The Euclidian distance between ink spots and the closer lesion border was calculated.

2.6. Immunofluorescent labeling of GFAP

Reactive astrogliosis was assessed by immunofluorescent labeling for GFAP at 7 and 21 days post stroke. Brains were sectioned and every 5th section (20 μ m thick) was collected and stored in cryopreservation solution until used. Sections were rinsed in buffered saline and transferred to 1% BSA in tris-buffered saline (TBS) for 10 min at room temperature, followed by a second TBS rinse. The sections were blocked for 30 min in TBS containing 2% donkey serum with 0.3% Triton X-100 before being incubated in TBS with 2% donkey serum and 0.3% triton X-100 containing the primary antibody rabbit GFAP, 1:600 (ref Z033401-2, Agilent Dako) for 24 h at 4°C . Ensuing incubation with primary antibody, sections were washed three times in TBS followed by incubation for 2 h at room temperature in TBS with 2% normal donkey serum and 0.3% triton X-100 containing the fluorescent secondary antibody (Donkey anti rabbit Alexa-488, 1:300, A-21206, Invitrogen) and finally by the nuclear counter stain DAPI (1:1000, Sigma-Aldrich) in TBS for 5 min at room temperature. Images were taken with a Leica SP8 microscope, where two sections from each animal ($n = 3$) were included in the analysis. Quantification of the signal intensity of GFAP-like immunoreactivity was assessed with ImageJ using the *plot profile* tool over a region of interest drawn from the interhemispheric fissure to the edge of the lesion. The limit of the glially defined peri-infarct cortex corresponds to the beginning of a statistical difference ($P < 0,05$) between the fluorescence signal intensity in the ipsilateral cortex and the homotopic contralateral cortex.

2.7. Statistics

Data are presented as mean \pm SEM. All statistics were performed using Prism software (Graphpad). A paired Student's *t*-test was used for pairwise comparisons.

3. Results

Cerebral ischemia was induced in mice using a variation of the well-characterized Tamura model (Tamura et al., 1981) consisting in a permanent occlusion of a distal trunk of the middle cerebral artery. This procedure generated a focal lesion while sham operated animals didn't present any lesion. In order to visualize the extent of the pathophysiological alteration of the surviving cortex adjacent to the necrotic core, the cellular reactivity of astrocytes, an endogenous biomarker for brain diseases, was investigated. Upregulation of GFAP is generally considered

as a reliable maker for reactive astrocytes (Escartin et al., 2019). The immunostaining of GFAP showed a gradual decrease in intensity as we move away from the stroke border (Fig. 1). At day 7 post-stroke, the glial scar was identified in a $315 \pm 12 \mu\text{m}$ ($n = 6$ mice) zone surrounding the necrotic core, where the up expression of GFAP was most intense and a long leading process of each astrocyte extended in the direction of the infarct (Fig. 1A). Further away, a second peripheral area extending up to 1802 μm from the edge of the lesion, was defined by a significant GFAP overexpression relative to the homotopic contralateral cortex ($n = 3$ mice; boundary defined when $P < 0,05$; Fig. 1C). In this territory, astrocytes displayed protoplasmic shape without preferred orientation of their processes. Beyond, GFAP expression was no more different from its expression in the contralateral cortex (Fig. 1A and C). At day 21, the glial scar was narrower ($163 \pm 3 \mu\text{m}$; $n = 6$ mice) but overall, the glially-defined peri-infarct area was more extended (2210 μm ; boundary defined when $P < 0,05$; Fig. 1C).

To test the hypothesis of an alteration of neural oscillatory activity around the cortical infarction, 3 electrodes were implanted in the cortex of the mouse brain, 7 or 21 days after MCAO. Two electrodes (E1 and E2) were placed in cortical layer 4 at various distances from the expected location of the lesion border (Fig. 2A and B). At the time of electrodes implantation the exact location of the cortical lesion was not known, but based on the reproducibility of our model in term of size ($8.5 \pm 0.8 \text{ mm}^3$ at 48 h, $n = 20$ mice) and location (Fig. 2C), we managed to target the peri-infarct cortex with good accuracy (Fig. 2D). The third electrode (E3) was placed in the layer 4 of the contralateral hemisphere, in mirror position with the nearest electrode from the lesion. In sham animals, two electrodes were placed in mirror position, in the layer 4 of the barrel field cortex. After 45–60 min of rest under isoflurane anesthesia ($1.1 \pm 0.1\%$) and during which body temperature was strictly kept at $37 \pm 0.2^{\circ}\text{C}$, each recording was done twice during 15 min at 7 days or 21 days post-stroke. In such condition, the whitened power spectrum of LFP activity shows 3 distinct peaks at $1.8 \pm 0.8 \text{ Hz}$, $4.5 \pm 0.9 \text{ Hz}$ and $36.4 \pm 1.1 \text{ Hz}$, corresponding respectively to the delta (1–3 Hz), the theta (4–7 Hz) and the low gamma (30–50 Hz) waveband (Fig. 2E). The other wavebands (alpha, beta, high gamma) presented no peak and were considered inactive. Sham operated animals didn't show any LFP spectrum power difference between the ipsilateral and the contralateral hemisphere ($P > 0,05$ for the three wavebands at both 7 and 21 days post-stroke, $n = 4$ animals, Fig. 2E). Irrespective to their distance from the infarct border, averaging the power spectrum recorded by all ipsilateral electrodes showed a slight depression of the broadband cortical oscillatory power at day 7 post-stroke, compared with sham animal, albeit not significant ($P > 0,05$ for the 3 wavebands studied; $n = 8$ ipsilateral electrodes from 4 mice, Fig. 2E). In contrast, the contralateral hemisphere showed a global increase in power, relative to sham animal. As a result, at 7 days, there was a significant difference of the theta and the low gamma waveband power between the contralateral and the ipsilateral ($66.8 \pm 0.5 \text{ dB}$ vs. $63.3 \pm 1.8 \text{ dB}$ for theta, $P < 0,01$; 72.5 ± 1.1 vs. 67.3 ± 1.5 for low gamma, $P < 0,05$; $n = 8$ ipsilateral electrodes from 4 mice Fig. 2E). At day 21 post-stroke, the ipsilateral power spectrum (irrespective to electrodes position) moved toward normalization relative to sham (Fig. 2F), while the LFP power of the contralateral cortex remained significantly increased for the delta ($P < 0,01$), the theta ($P < 0,05$) and the low gamma wavebands relative to the ipsilateral LFP power ($P < 0,05$; $n = 5$ contralateral electrodes and $n = 10$ ipsilateral electrodes from 5 mice, Fig. 2F and G).

To investigate the spatial relation between the oscillatory activity and the extent of the glially defined peri-infarct area, the scar border-to-electrodes distances were measured precisely by histological analysis, using ink labeling as a marker of the electrode sites (Fig. 2B). No significant correlation between the ipsilateral LFP power and the distance from the infarct border was found for the delta and the theta waveband at 7 or 21 days post-stroke (7 days: $P > 0,05$, $n = 8$ electrodes from 4 mice; 21 days: $P > 0,05$, $n = 10$ electrodes from 5 mice; Fig. 3A and B). However, for the low gamma waveband (30–50 Hz), there was a

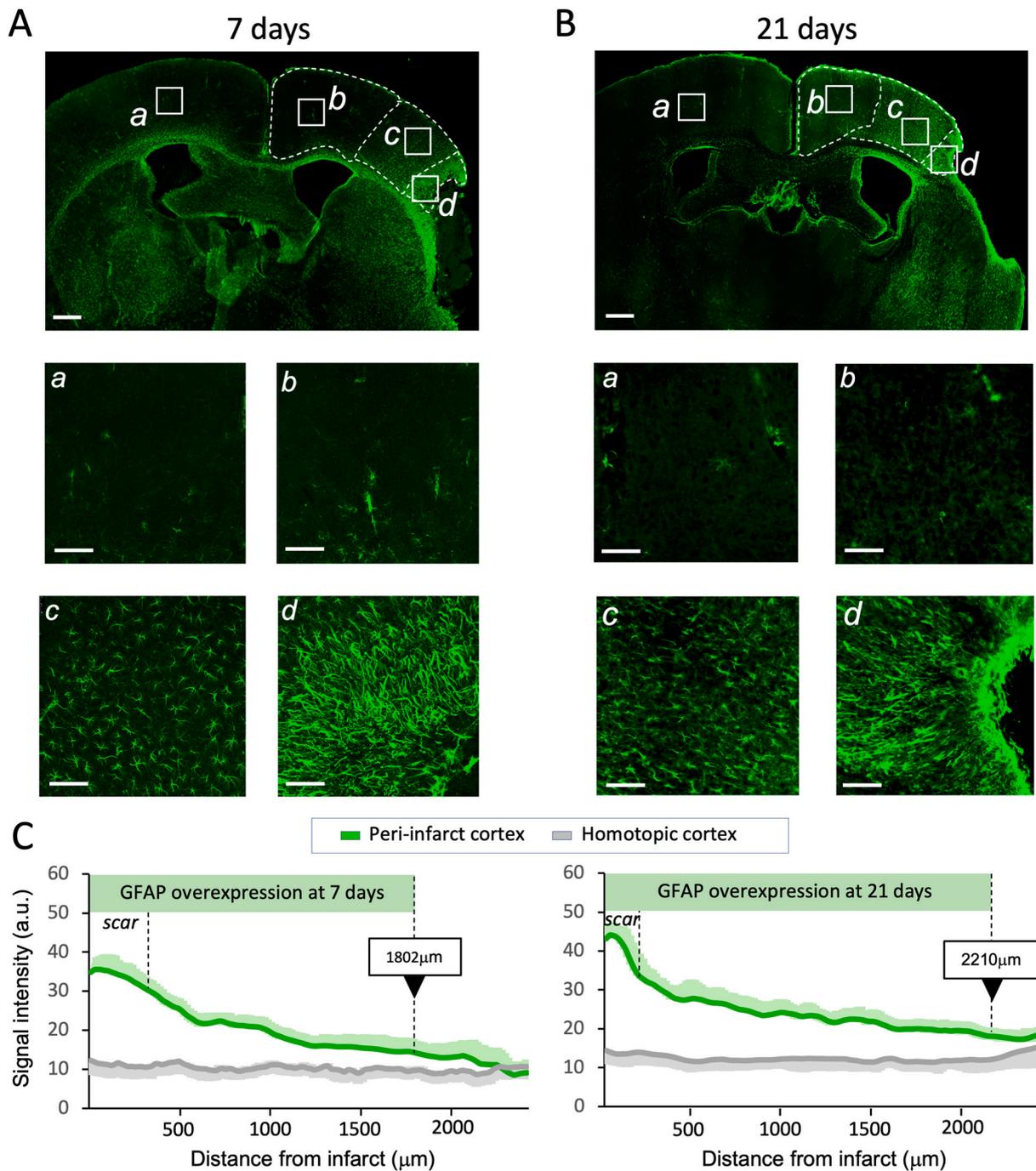


Fig. 1. Astroglial identification of the peri-infarct cortex. GFAP immunostaining of a coronal section of the mouse brain 7 days (A) and 21 days (B) after MCAO, scale bar, 400 μm . Four regions of interest were identified: a. the contralateral cortex where GFAP immunoreactivity is low; b. the distal ipsilateral cortex where the level of GFAP expression is as low as in the contralateral cortex; c. the proximal ipsilateral cortex where astrocytes are strongly GFAP-positive; d. the border of the infarction, the glial scar, where astrocytes express high level of GFAP with a long leading process oriented toward the lesion (or the cavity); scale bars of a,b,c,d: 100 μm . C. Quantification of the signal intensity of GFAP-like immunoreactivity in the peri-infarct cortex (green) and the contralateral homotopic cortex (grey). The distal limit of the GFAP overexpression zone extends until the end of the statistical significance of the signal intensity of GFAP-like immunoreactivity relative to the contralateral side (Euclidian length of each zone; limit when $P < 0.05$; $n = 3$ mice per time point).

significant positive relationship between LFP power and distance to the infarct border at both 7 and 21 days post-stroke (7 days: $r(6) = 0.912$; $P < 0.05$, $n = 8$ electrodes from 4 mice; 21 days: $r(8) = 0.752$; $P < 0.05$, $n = 10$ electrodes from 5 mice; Fig. 3A and B). The relationship was best described by a power function (7 days: $y = 49.776x^{0.043}$; 21 days: $y = 43.674x^{0.059}$) which equation was used to build a visual model showing the spatial extent of the low gamma depression relative to the average location and size of the ischemic lesion (Fig. 4).

4. Discussion

The main finding of this study is that the cortex surrounding an ischemic lesion undergoes a long-lasting deficit in low gamma (30–50 Hz) oscillatory power, the latter being an emerging neurophysiological determinant of neural communication and plasticity.

In human, the highest potential for recovery is observed within the first 3 months after stroke (Biernaskie et al., 2004). In rodent models of

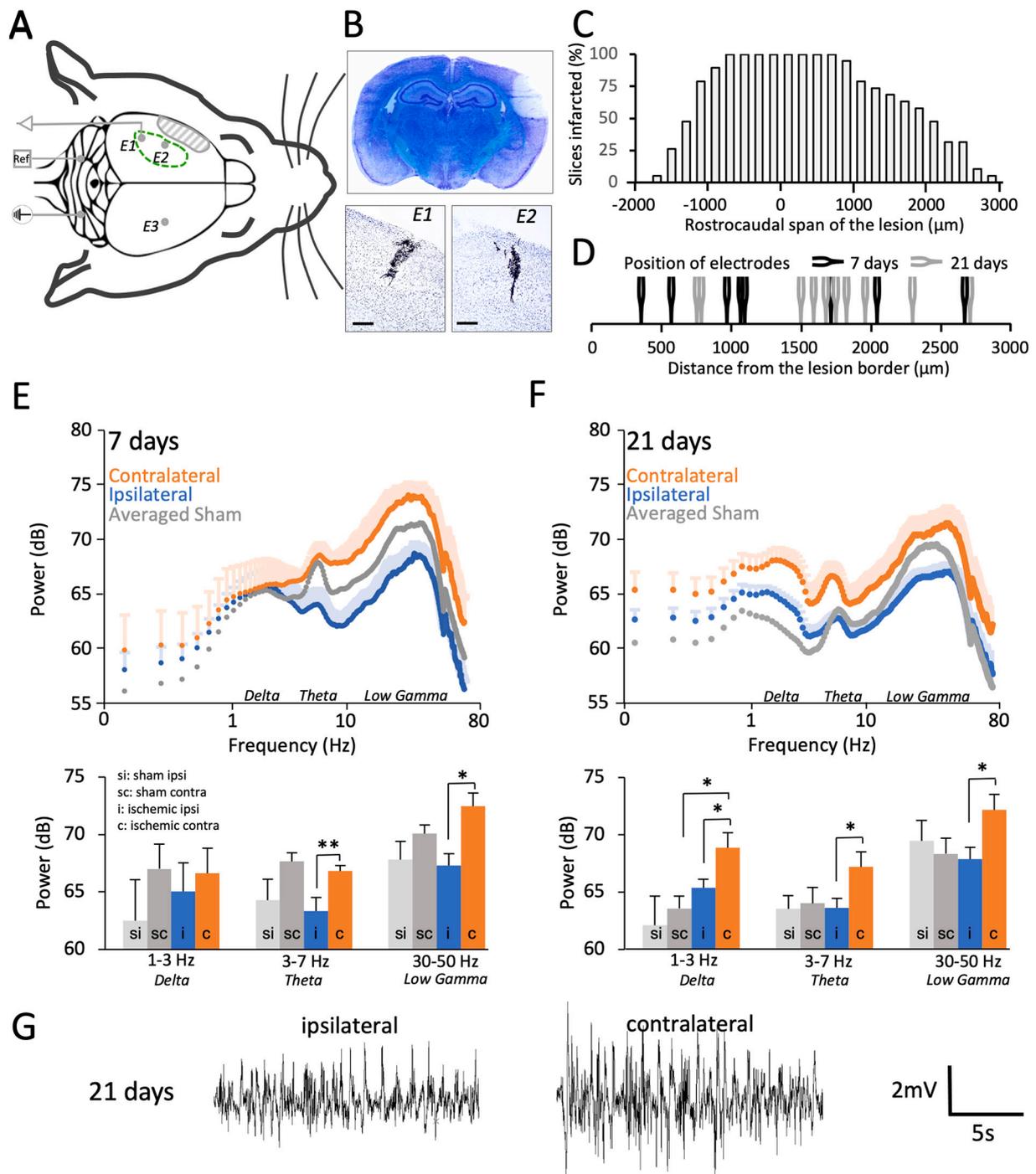


Fig. 2. Spectral analysis of the LFP activity of the peri-infarct cortex. **A.** Experimental arrangement. Three electrodes were implanted for sequential recordings of 15 min in the ipsilateral cortex (E1 and E2) and in the contralateral cortex (E3); R: reference electrode. **B.** A representative ischemic lesion 48 h after the MCAO procedure. The cortical position of E1 and E2 electrodes was marked by a local micro-injection of black ink (scale bar: 100 μm). **C.** Profile of the ischemic lesion at 48 h ($n = 20$). In the horizontal axis, the zero value represent the brain slice where the lesion area (mm^2) reaches a maxima. Most of lesions were circumscribed in a cortical territory of 2000 μm . **D.** Relative position of all electrodes used in the study, at 7 days (black) and 21 days (grey). Whiten power spectrum (1–80 Hz) obtains at 7 days (**E**) and 21 days (**F**) in sham and ischemic animal. Note the three distinct peaks corresponding to the frequencies of delta, theta and low gamma waveband. To clarify the graphical representation of the spectrum in **E** and **F**, the ipsi- and contra-lateral power spectrums of sham animals (grey dots) were averaged and presented without error bars. The power quantification of each waveband is reported in the respective histogram below (i: ischemic side; c: contralateral side; s: sham). Comparisons between hemispheres or groups are reported by (*) when significant ($* P < 0.05$; $** P < 0.01$; 7 days: $n = 8$ recordings from 4 ischemic animals at 7 days post-stroke and $n = 10$ recordings from 5 animals at 21 days post-stroke). Sham animals: $n = 4$ animals per time point). **G.** Representative raw trace (1–80 Hz band pass filtered) of the LFP activity of the ipsilateral and contralateral cortex recorded 21 days after MCAO.

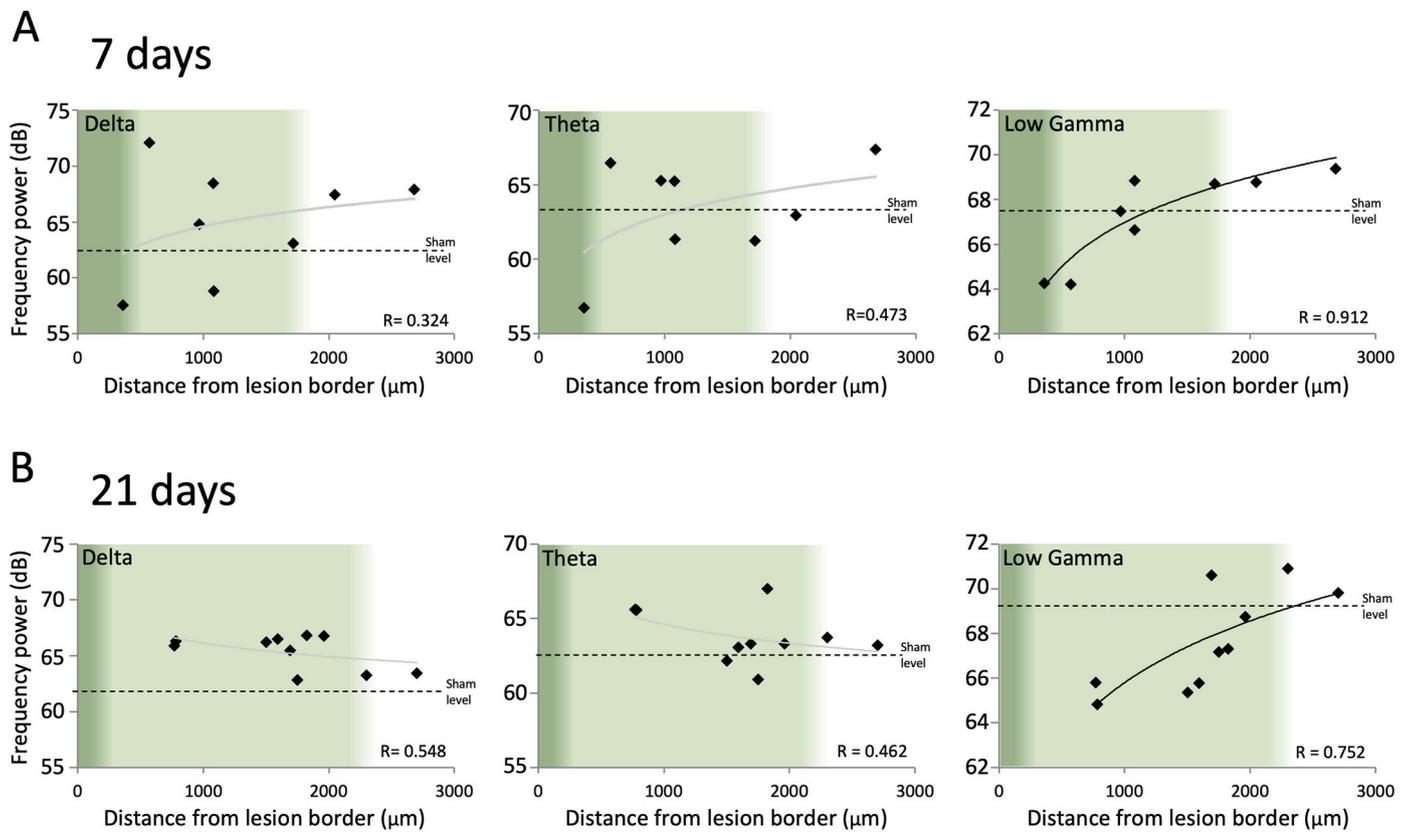


Fig. 3. Analysis of LFP power change relative to the distance from the cortical infarct. At each time point, (A: 7 days; B: 21 days) LFP power and the distance between peri-infarct electrodes and the lesion border were plotted to test the hypothesis of a correlation. No correlation was found for delta and theta. However, the power of low gamma oscillations (30–50 Hz) showed a strong correlation with the distance from the infarct border. The green background indicates the limits of the astroglial scar (dark green) and the peri-infarct zone (light green) as measured and reported in Fig. 1.

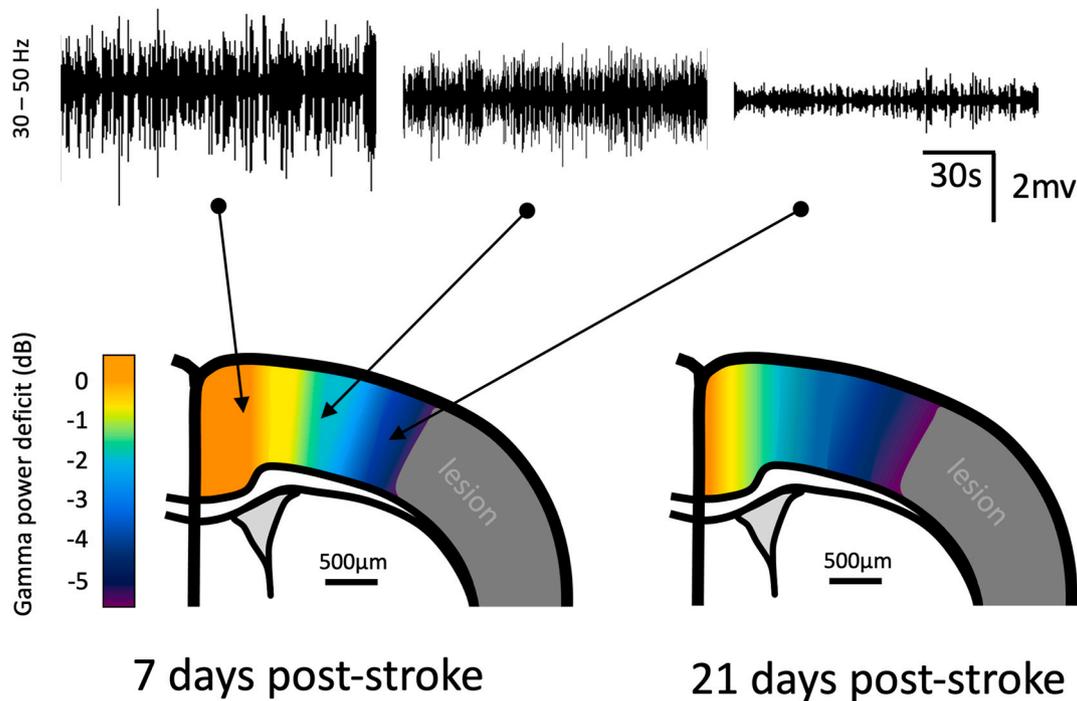


Fig. 4. Model of low gamma deficit in the cortical environment of an ischemic lesion. Based on the 2 power functions best describing the significant correlations obtained in Fig. 3, a spatial modelization of low gamma power deficit in the peri-infarcted cortex was drawn. Top: three examples of raw LFP band-pass filtered (30–50 Hz) recorded at various distances from the infarction, 7 and 21 days after MCAO.

focal cerebral ischemia, this critical period of plasticity corresponds to the first 4 weeks, after which functional recovery gains are no more significant (Dijkhuizen et al., 2001; Brown et al., 2007).

We chose to study the spontaneous oscillatory activity of the repairing cortex under anesthesia to avoid the stochastic changes of the oscillatory pattern associated with the awake state and to favor the stability and the reproducibility of an internally driven regimen (Lustig et al., 2016). Isoflurane is a well-known depressor of cortical activity (Land et al., 2012), however at ~1%, we systematically observed a LFP oscillation pattern composed of three peaks reminiscent of the delta, theta and gamma frequencies in the awake mice. In agreement with Aksenov et al., the beta band (12–30 Hz), associated with wakefulness, was largely inactivated by light isoflurane anesthesia (Aksenov et al., 2019). Our experimental design is therefore not suited to study the oscillatory activity of the post-stroke cortex in the beta range. Interestingly, a recent study by Hillman et al., conducted in the awake mouse 2 to 6 weeks following prefrontal cortex (PFC) bilateral stroke, reports that beta oscillations power is actually enhanced in the PFC during open field task (Hillman et al., 2019). This illustrates the importance of examining state-dependent dynamics during specific cognitive or motor tasks. Nevertheless, when comparing studies, a particular attention should be exercised in the relative location of the three players: the oscillator (underlying generator), the electrode and the lesion. Multiple combinations of sites can be tested. In this study, we focused our attention to the relative place of the recording site and the lesion site without stimulation.

We found no clear differences with control animals for delta and theta power at 7 and 21 days post-stroke in the neighborhood of the lesion. Neither the necrotic environment nor the disruption of local neural network seems to prevent peri-infarct neural networks to oscillate at these frequencies. This is consistent with the observation of Ramanathan et al. in the peri-infarct cortex of both anesthetized and awake resting mice, showing that cortical low frequency oscillations (LFO, 1–4 Hz) power is similar to the pre-ischemic level (Ramanathan et al., 2018). The authors also showed that the brief bout of LFO power accompanying a skilled upper-limb task is however severely dampened after stroke.

Regarding low gamma oscillations, there was no significant change when averaging their power over the entire peri-infarcted zone. However, our detailed topological analysis revealed an accelerating collapse of their power when approaching the lesion border. The extent of the deficit spanned 2 mm away from the glial scar, a distance matching many previous measurement of the peri-infarct cortex in the rodent brain (Brown et al., 2007). In the human brain, the extent of the peri-infarct cortex is not proportionally bigger, but it represents an important volume of grey matter with high plasticity potential (Funck et al., 2017). As for the relevance of 2 mm of cortex, it represents the equivalent distance of 5 to 6 cortical columns in mice (Tischbirek et al., 2019). Moreover, cortical motor microcircuits are functional units organized in territory of 100 μm receiving local inputs from ~500 μm away (Amirikian and Georgopoulos, 2003). Of note, plastic reorganization of neurons starts readily after the edge of the glial scar, that is, in the present case, ~160 μm from the necrotic core (Brown et al., 2007). These topological considerations emphasize the potential importance of this 2 mm strip of cortex for post-stroke functional recovery.

What is the origin of the selective depression of cortical low gamma rhythm around the consolidated lesion? Seven and 21 days after stroke, peri-infarct neurons are still under the influence of inflammatory processes and glial reactivity. It could be argued that cell swelling or water content in the tissue changes its conductance in a magnitude such as gamma oscillations are less detected. This is however unlikely as several studies verified that the cortical tissue conductivity tested with an intracortical electrode show weak frequency dependence similar to cerebrospinal fluid (Logothetis and Wandell, 2004; Miceli et al., 2017). Moreover, as suggested by Miceli et al. (2017), the filtering properties of the tissue itself should be a minor factor in shaping the LFP. Therefore,

the origin of low gamma depression in the periphery of the stroke lesion should be searched in the light of cell and neural network properties. Gamma oscillations are generated sporadically by local groups of cortical neurons spatially confined into the volume of a putative column (Steriade et al., 1996) that is approximately 250 μm in diameter (Tischbirek et al., 2019) beyond which the amplitude of a gamma oscillation decreases rapidly with distance (Sirota et al., 2008). Possibly, and in agreement with several studies suggesting patchy selective neuronal death into the surviving cortex, several weeks after the consolidation of the ischemic lesion, the number of neurons required to generate enough gamma power is not met in this zone (Baron, 2005; Guadagno et al., 2008).

Two other considerations can serve as food for thought regarding the origin of low gamma deficit. First, gamma oscillations are known to emerge from the interaction of parvalbumin interneurons and principal cells (Buzsáki and Wang, 2012). A selective reduction of these interneurons in the ipsilateral perilesional cortex has been associated with an improved plasticity and training-induced functional recovery (Zeiler et al., 2013; Alia et al., 2016). Future studies on the specific survival of these interneurons (Baron, 2005) and the integrity of their perineuronal net (Härtig et al., 2017), will help to interpret the present observation. Second, several demonstrations have been made in the last decade showing that the hypoexcitability of peri-lesional neurons can be corrected by antagonists of GABA_A receptors-mediated tonic inhibition to boost functional recovery (Clarkson et al., 2010). Whether this excess of tonic inhibition can dampen the power of gamma oscillations is not clear (Farrant and Nusser, 2005). Outside of the cortex at least, increasing tonic inhibition can reduce the power of gamma oscillations in hippocampal CA3 slices (Towers et al., 2004). Interestingly, astrocytes have been found to be the primary cause of the excess of tonic inhibition observed after stroke in the peri-infarct cortex (Ek Lie et al., 2019). Furthermore, the involvement of astrocytes in the control of gamma oscillation (but not the other frequency bands) have recently been proposed (Lines et al., 2020). In the present study, the symmetrical profile of GFAP overexpression and low gamma deficit along the peri-infarct cortex is striking and calls for further investigations to test the hypothesis that reactive astrocytes depress the power of low gamma.

Little is known about gamma oscillation changes after stroke, since most studies have been done using EEG or EcoG with low spatial resolution and poor detection of frequencies above 30 Hz (Rabiller et al., 2015; Lake et al., 2016). Here we found that low gamma power is strongly and persistently depressed in a cortical area that closely matches with the peri-infarct zone described as a primary reservoir of neuronal plasticity. Further studies taking into account the topologic profile of gamma depression around the infarction should examine whether gamma power alteration correlates with recovery. Since gamma abnormalities have been associated with many brain disorders of very different pathophysiologic background (Woo et al., 2010), it is tempting to consider that it is simply an epiphenomenon resulting from perturbation of cerebral cortical network functions, only useful as a good sensitive clinical readout (Woo et al., 2010). However, the role of gamma oscillations in synaptic plasticity is increasingly pushed forward. Synaptic strengthening or weakening required to build new neuronal networks as a result of learning –and most likely of *re-learning* after a brain lesion– is an activity-dependent process driven by the principle of temporal coincidence of pre- and post-synaptic firing (Hebb, 1949). Oscillation of neuronal membrane potential at the gamma frequency allows synchronized neuronal firing within a temporal window that is optimal for STDP process (Engel et al., 1992; König et al., 1996; Magee and Johnston, 1997; Bi and Poo, 1998; Harris et al., 2003; Buzsáki and Draguhn, 2004; Wespapat et al., 2004; Harris et al., 2005). In other words, under a gamma rhythm of oscillation, the probability to associate pertinent information to assemble a neuronal circuit, increases. In support of the role of gamma oscillation in plasticity, several studies have demonstrated that the power of hippocampal gamma oscillation during learning predicts the quality of the recall (Sederberg et al., 2003;

Headley and Paré, 2017). More compelling demonstrations are certainly necessary to prove a causal role of gamma oscillations in cortical synaptic plasticity and it remains to be shown that gamma deficit is actually associated with poor plasticity and functional recovery (Zheng et al., 2020). But based on this concept, a lot of efforts are being carried out to stimulate the human brain with transcranial alternative electric current (tACS) at a specific frequency supposed to entrain natural oscillations and boost network plasticity (see Bland and Sale, 2019 for a recent update). While many challenges are still ahead to understand the neurobiology behind the observed effect, encouraging data suggest that tACS delivered at gamma frequency can be used to improve motor performance in humans (Guerra et al., 2018).

The cease of inputs originating from the necrotic cortex causes a functional imbalance in many regions of the brain, not necessarily directly connected to dead neurons. This phenomenon named diaschisis, describes changes of neuronal activity that positively or negatively contribute to the reorganization of brain circuits (Reggia, 2004). One of the most obvious expression of diaschisis after a cortical stroke is the activity change of the homotopic contralateral area. Both clinical and pre-clinical studies have shown hyperactivity in the contralateral cortex due to disinhibition (Andrews, 1991; Dijkhuizen et al., 2001; Tombari et al., 2004; Brown et al., 2009; Cramer et al., 2011). However, this increase in “activity”, whether measured by an increase of firing rate, excitability or neurovascular signaling is not necessarily accompanied by an increase of neuronal synchronization and therefore of oscillatory power. In the present study, we found an increase of the broadband LFP power of the contralateral cortex, mostly 3 weeks after stroke in mice. The origin of this power increase is unlikely due to a genuine enhancement of the activity of each frequency-band oscillator but most likely due to an enlargement of the neuronal population entrained into these rhythms, because 1/ while the homotopic contralateral cortex displays an increased power in delta and theta wavebands, the peri-infarct cortex displays no change in delta and theta power at 21 days, irrespective to the distance to the lesion, suggesting that theta and delta subcortical oscillators deliver stable inputs; 2/ it is well known that a stroke induced transcallosal disinhibition is amplified by a down-regulation of GABA receptor (Buchkremer-Ratzmann et al., 1996; Kokinovic and Medini, 2018) and a concomitant up regulation of NMDA receptor (Qü et al., 1998) in the contralesional cortex. Whether the increase of oscillatory power in the contralateral hemisphere is associated with favorable or unfavorable recovery, remains to be clarified (Marshall et al., 2000; Silasi and Murphy, 2014; Kokinovic and Medini, 2018).

In conclusion, the present work leads to the hypothesis that low gamma deficit may slow down the process of cortical synaptic reorganization occurring during the period of post-stroke recovery. Accordingly, this result argues for the usefulness of therapeutic intervention aimed specifically at boosting cortical low gamma oscillations in order to enhance post-stroke functional recovery.

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Author contributions

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Methodology, Validation, Resources, Writing, Visualization, Supervision, Funding Acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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