In-depth characterisation of an infantile rat model of epileptic encephalopathy for testing disease-modifying treatments

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BACKGROUND

Epileptic encephalopaty is defined as a ”condition in which epileptic activity itself may contribute to severe cognitive and behavioral impairments above and beyond what might be expected from the underlying pathology alone and that this can worsen over time”.[1]

There is urgent need of animal models -which are still lacking- to study the pathological mechanisms ignited by unremitting seizures in the immature brain that lead to devastating sequelae including motor and cognitive disorders and epilepsy.

AIM

To characterized in-depth an infantile rat model of epileptic encephalopathy induced by *de novo* status epilepticus to test novel disease-modifying treatments

METHODS

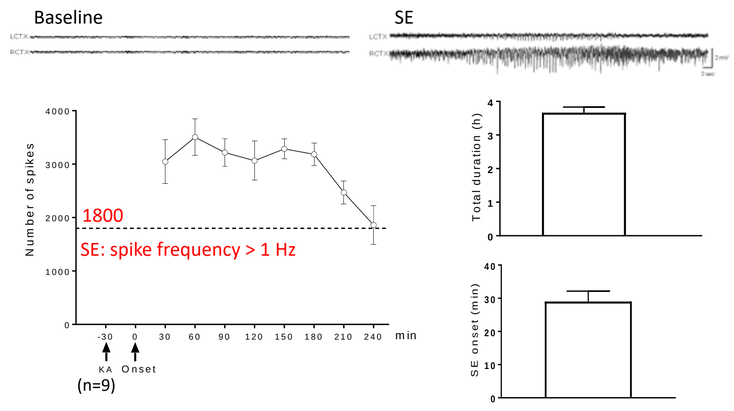
EXPERIMENTAL MODEL. Status epilepticus (SE) was induced in postnatal day 13 (P13) male Sprague Dawley rats by unilateral injection of kainic acid (KA; 2μg/0.2μl) in the amygdala (from *bregma*, mm: anteroposterior, -1.4; lateral, -4.9).[2,3]. Controls were age-matched rats injected with PBS instead of KA. Four distinct groups of rats were prepared depending of the aim of the experiment, as follows: **Group 1-EEG analysis of SE**: P12 rat pups were stereotaxically implanted under isoflurane anesthesia (1-3% isoflurane in a mixture of 70% N_2O-30% O_2) with an injection guide cannula positioned on top of *dura mater* for the intra-amygdala injection of KA, and bilateral cortical electrodes placed over the somatosensory cortex. The day after surgery, freely moving P13 rats were injected with KA after 30-min EEG baseline was established. SE was continuously video-EEG monitored for 4h. EEG analysis was done to assess SE severity and duration. **Group 2-Longitudinal study to monitor epilepsy and brain atrophy by MRI:** P13 rats were injected with KA and video-monitored for behavioral signs of SE (i.e. salivation, forelimb clonus, wild running and loss of posture) but not EEG recorded. SE-rats and their corresponding controls underwent T2-weighted MRI sequence to assess anatomic changes at PN22 and at 5 months post-SE (*ex-vivo* MRI). Rats were implanted with electrodes and video-EEG recorded for 2 weeks (24/7) at PN33 or PN65, and at 4.5 months post-SE to detect the frequency of spontaneous recurrent seizures. At the end of EEG recording, rats were killed and exposed to MRI, and their brain were used for histological analysis. **Group 3-Longitudinal study to monitor cognitive deficits:** Rats were exposed to SE as described for Group 3, and then tested to Morris water maze task at PN25 and PN75. Rats were then implanted with electrodes and video-EEG recorder for 2 weeks (24/7) at 4.5 months post-SE. At the end of EEG recording, rats were killed and exposed to MRI. Brains were used for histological analysis. **Group 4-Histological and biochemical analysis of neuroinflammation and oxidative stress:** Rats were exposed to SE as described for Group 3, and then killed 6, 24, and 72h, or 1 week post-SE to perform immunohistochemistry or RT-qPCR of neuroinflammatory and oxidative stress markers.

MRI ANALYSIS. RARE T2-weighted sequence of the whole brain (from the olfactory bulb to the cerebellum) was acquired using a 7T MRI. Rats were imaged under general anesthesia (1.4% isofluorane, in a mixture of 70%N2O-30%O2) and continuously monitored for changes in their respiratory rate. Body temperature was maintained at 36.5-37.5° C using a feed-back-regulated heating pad. The morphological images were obtained with a resolution of 130 x 130 x 130 μm3 (matrix = 231 x 96 x 138; FOV= 3 x 1.4 x 1.8 cm), repetition time of 2500 ms, effective echo time of 60 ms, and 1 average (total acquisition time: 34 min).

MORRIS WATER MAZE. A circular pool (diameter 150 cm, height 60 cm) was filled with water (25±1° C), and it was ideally divided in four quadrants. A squared platform was placed 1 cm below the water surface in the center of one of the quadrant. The platform was moved to a different quadrant during the second exposure to the behavioral test (PN75). The position of the platform was kept in the same quadrant throughout each behavioral test (PN25 and PN65). Each rat received one training session per day (4 swims) for 5 consecutive days. Each rat was allowed to swim until it found the platform or had swum unsuccessfully for 60 sec. In the latter case, the rat was guided to the platform by hand and its latency was recorded as 60 sec. After 10 sec rest on the platform, the rats was transferred to its home cage. The escape latency, i. e. the time to reach the hidden platform, was measured.[4]

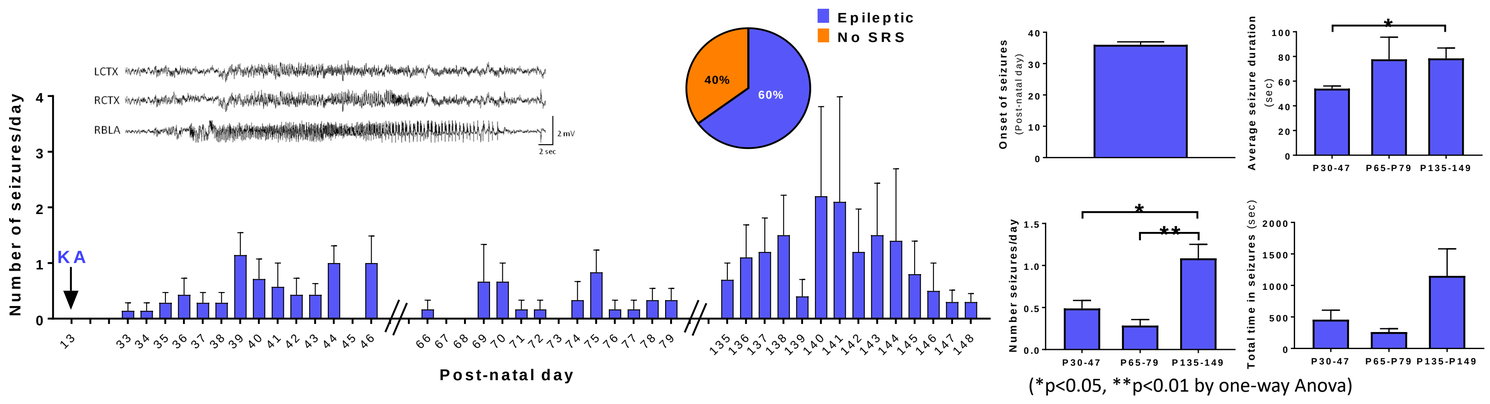
HISTOLOGICAL and RT-qPCR ANALYSES. Immunohistochemistry and evaluation of neuronal cell loss: Rats were transcardially perfused 6, 24 and 72 h post-SE with PBS followed by 4% PAF in PBS. Brains were post-fixed in PAF, cryoprotected and then frozen at -45° C. Coronal sections of the brain (40 μm) were cut in a cryostat. We performed immunohistochemistry (IHC) using specific markers to detect astrocyte (GFAP) and microglia (CD-11b) activation, and IL-1β. Nissl staining was used to quantify neuronal cell loss.[4,5] High-power non-overlapping fields (20X magnification) of the whole dorsal hippocampus were acquired, and the total number of Nissl-stained neurons was quantified. **RT-qPCR:** Rats were killed 24 h, 72 h and 1 week post-SE, the hippocampus ipsilateral to the injected amygdala was dissected out on ice, frozen and used for measuring GFAP, CD-11b, HMGB1 and Nrf2 mRNAs.

EEG analysis of status epilepticus (SE)



✓ SE develops ~30 min after KA injection lasting for ~4 h.
✓ During SE rat pups display motor seizures (masticatory movements, salivation, forelimb myoclonus, loss of posture, swimming motion).
✓ SE did not induce mortality.

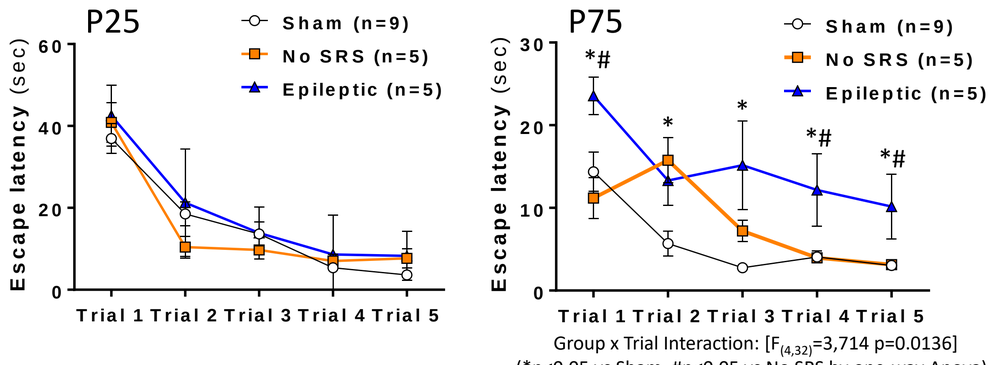
Longitudinal EEG analysis of epilepsy development



(*p<0.05, **p<0.01 by one-way Anova)

Epilepsy develops at around P36, i.e. 13 days after the induction of SE.
Epilepsy progression occurs between 1 and 5 months post-SE in some rats.
At 5 months of age (i.e. P148), 60% of SE-exposed rats develop spontaneous seizures.

Longitudinal analysis of cognitive deficits: Morris water maze test



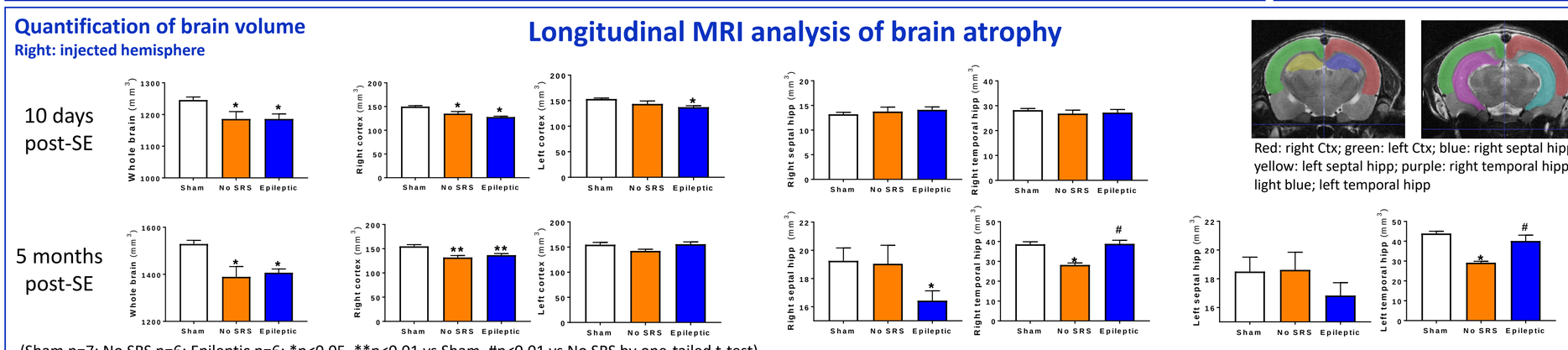
Group x Trial Interaction: [$F_{(4,32)}$=3,714 p=0.0136]
(*p<0.05 vs Sham, #p<0.05 vs No SRS by one-way Anova)

SE-exposed rats develop progressive memory deficits.
At P75, memory deficits are more pronounced in epileptic rats.

Quantification of brain volume

Right: injected hemisphere

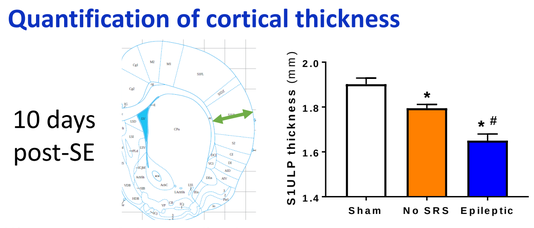
Longitudinal MRI analysis of brain atrophy



Red: right Ctx; green: left Ctx; blue: right septal hipp; yellow: left septal hipp; purple: right temporal hipp, light blue; left temporal hipp

(Sham n=7; No SRS n=6; Epileptic n=6; *p<0.05, **p<0.01 vs Sham, #p<0.01 vs No SRS by one-tailed t-test)

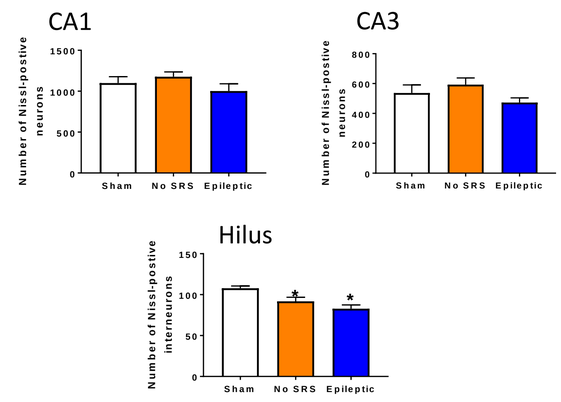
Quantification of cortical thickness



(Sham n=7; No SRS n=4; Epileptic n=4;
*p<0.05, **p<0.01 vs Sham, #p<0,01 vs No SRS by one-tailed t-test)

✓ SE-exposed rats show whole brain and right cortex atrophy at 10 days post-SE, independently on whether they will develop spontaneous recurrent seizures (SRS).
✓ The atrophy of the hippocampus progresses: at 5 months post-SE, epileptic rats show atrophy of the right septal hippocampus while rats without spontaneous seizures show bilateral atrophy of the temporal hippocampus.
✓ At 10 days post-SE, epileptic rats showed a significant reduction in the thickness of S1ULP as compared to rats without seizures and sham controls. S1ULP is a cortical region involved in the generation of spike-and-waves dischages.[6] No changes in other cortical regions (cingulate, retrosplenial granular, perirhinal, primary somatosensory cortices) were observed.

Neuronal cell loss in the hippocampus (5 months post-SE)

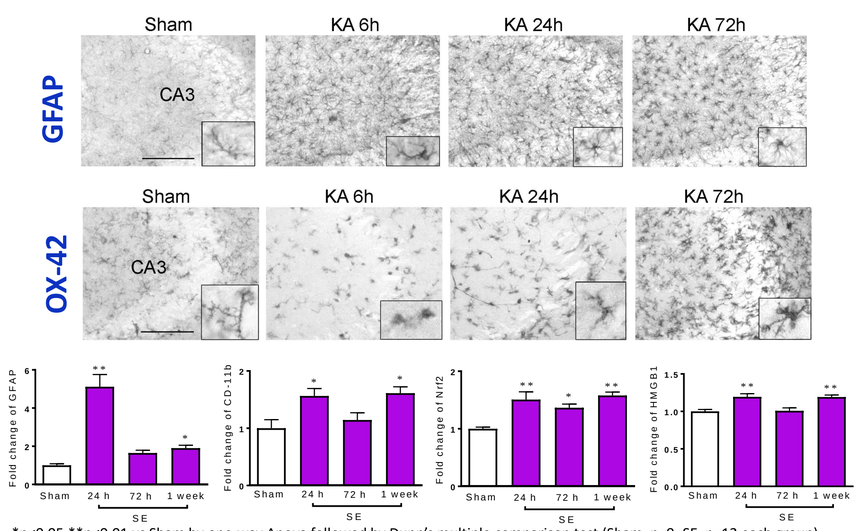


(Sham n=6; No Epilepsy (No SRS) n=4; Epilepsy n=5; *p<0.05 vs Sham by one-tailed t-test)

Epileptic and non epileptic rats develop similar neuronal cell loss in the hilus

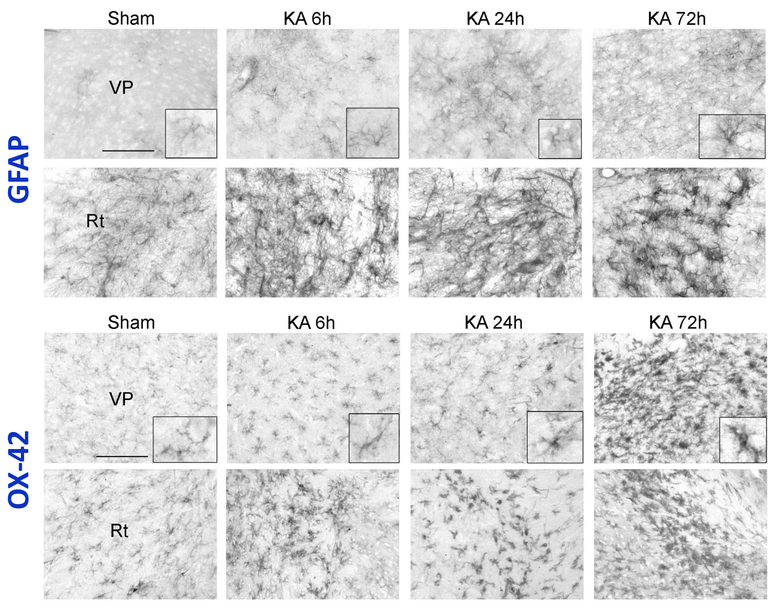
Histological and biochemical analysis of neuroinflammation and oxidative stress in the acute phase post-SE

Hippocampus



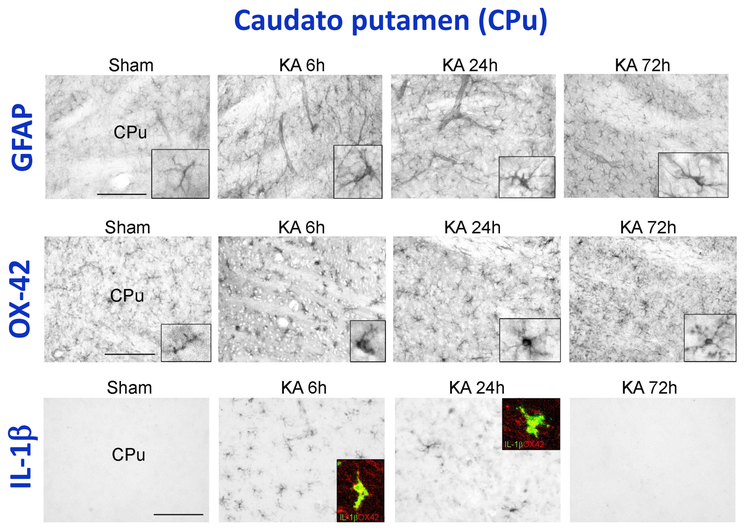
*p<0.05,**p<0.01 vs Sham by one-way Anova followed by Dunn’s multiple comparison test (Sham, n=9; SE, n=12 each group)

Thalamus



VP: ventroposterior thalamic nucleus; Rt: reticular thalamic nucleus

Caudato putamen (CPu)



✓ Astrocytes and microglia are activated in the hippocampus, thalamus, caudato putamen and cortex (*not shown*) at 6-72h post-SE. This activation is unilateral to the site of kainate injection at 6h, thereafter it becomes bilateral. IL-1β is induced in caudato putamen in microglia at 6-24h.
✓ RT-qPCR analysis showed an increase in mRNA levels of neuroinflammatory (GFAP, CD-11b, HMGB1) and oxidative stress (Nrf2) markers in the hippocampus 24h-7 days post-SE.

Summary

The rat model recapitulates some salient features of the clinical condition:
✓ age of animals (early childhood of human life)
✓ SE which evolves in healthy animals
✓ development of epilepsy
✓ cognitive decline and brain atrophy which worsen with epilepsy

Neuroinflammation and oxidative stess, two pathologic processes involved in the progression of epilepsy[7-9], develop in the aftermath of SE.
MRI parameters differentiate rats with and without spontaneous seizures.

Conclusions

This model can be used for mechanistic studies and for testing novel drugs.

Since the model provides rats with and without spontaneous seizures (although all animals are similarly injured), it can be exploited to identify biomarkers of epileptogenesis.

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