Autonomic reflex plasticity associates with time-dependent SUDEP susceptibility in a murine model with hyperactive stress circuits

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ABSTRACT

Sudden unexpected death in Epilepsy (SUDEP) is the leading cause of death in patients with Epilepsy. Although SUDEP results from cardiorespiratory arrest, it's underlaying mechanisms are poorly understood. Considering the significant association between stress-related disorders and Epilepsy, we hypothesized that stress exaggerates autonomic reflexes critical in cardiorespiratory function and that these exaggerated reflexes increase susceptibility to SUDEP. Experiments were performed using a novel mouse model of SUDEP where chronic hyperactivity of central corticotropin-releasing hormone (CRH) neurons (*Kcc2/Crh*) predisposes mice to SUDEP in the weeks following seizure induction based on the ventral intrahippocampal kainate (vIHKA) model of chronic Epilepsy. In our study, the vIHKA model was employed in both wild-type (WT) and *Kcc2/Crh* mice while they were monitored with EEG and ECG using in vivo telemetry and underwent terminal autonomic reflex testing at time points when mortality peaked and plateaued. A resting tachycardia developed by one week following vIHKA injection but subsided by day 30 in both WT and *Kcc2/Crh* mice. During spontaneous seizures, *Kcc2/Crh* mice had more pronounced reflex-like ictal bradycardias compared to WT controls that notably occurred just prior to seizure termination. vIHKA injection promoted time-dependent exaggeration of autonomic reflexes, with *Kcc2/Crh* mice exhibiting robust autonomic disturbances compared to WT controls, including a pronounced serotonin-mediated Bezold Jarisch reflex. Taken together, our findings indicate that increased autonomic disturbance burden parallels time-dependent SUDEP susceptibility in mice with hyperactive stress circuits.

INTRODUCTION

Sudden unexpected death in Epilepsy (SUDEP) is a significant health burden representing the most common cause of death outside of trauma or accident in patients with Epilepsy (Tomson et al., 2005). Seizure events are often temporally linked to SUDEP whereas more global long-term pathophysiological remodeling is also suspected (Pathak et al., 2025). Cardiorespiratory dysfunction is strongly implicated in SUDEP as severe bradycardia and apnea are observed at seizure termination, or immediately post-ictal, in patients that succumb (Ryvlin, Nashef, Lhatoo, et al., 2013). Similar severe bradycardia and apneas also appear in individuals that eventually succumb to SUDEP (Lamrani et al., 2023), suggesting a predictive causal capacity of these cardiorespiratory disturbances for patients at risk. While these epidemiological factors are being established, diagnostic and interventional patient care for SUDEP remain a critical health need.

Animals models provide a mechanistic approach to understanding how dysfunction of cardiorespiratory control circuits drives clinical presentation and mortality in SUDEP. Most transgenic animal model investigations into mechanisms of SUDEP include mutations known to impact neurodevelopment and intrinsic cardiac excitability (Gu et al., 2024). Stress signaling is an additional important component to Epilepsy and SUDEP. Stress increases the probability of seizure generation and worsens seizure severity (Moore et al., 2014; Si et al., 2024). There is also a significant comorbidity between stress-related disorders and Epilepsy with individuals with both Epilepsy and stress-related disorders succumbing to SUDEP at higher rates than those with Epilepsy alone (Sawyer & Escayg, 2010). These studies implicate interaction between central stress circuits and autonomic brainstem motor output as a critical mechanism of SUDEP that is distinct from pathological changes in neurodevelopment and intrinsic cardiac excitability.

At the apex of central stress circuits, CRH neurons in the paraventricular nucleus of the hypothalamus (PVN^{Crh}) are of particular interest. For example, multiple chemical convulsant models of Epilepsy demonstrate robust, dose dependent, chronic increases in serum corticosterone as a marker of chronic stress activation (Hooper et al., 2018; O'Toole et al., 2014). PVN^{Crh} neuron activity is also significantly elevated by spontaneous seizures across convulsant models as demonstrated by in vivo and in vitro approaches (O'Toole et al., 2014). To link SUDEP with stress and autonomic dysfunction, this study tested mice with hypothalamic–pituitary–adrenal (HPA) axis hyperactivity via genetic loss of K+/Cl− cotransporter (KCC2) in corticotropin-releasing hormone (CRH) neurons (*Kcc2/Crh* mice). Chronic Temporal Lobe Epilepsy (TLE) was modeled in *Kcc2/Crh* mice by ventral intrahippocampal kainate administration (vIHKA) (Basu et al., 2024; Zeidler et al., 2018).

Here, *Kcc2/Crh* mice given TLE by vIHKA showed a dramatic increase in long-term susceptibility to SUDEP thus prompting further mechanistic investigation (Basu et al., 2024). PVN^{Crh} neurons send their densest descending brainstem projection to the critical cardiorespiratory regulating region known as nucleus of the solitary tract (nTS) which is the terminal field of most cardiorespiratory sensory afferents (Lee et al., 2013; Moga et al., 1990; Ruyle et al., 2023; Wang et al., 2019) Both isoforms of the CRH receptor are present in nTS (Wang et al., 2018) and excitation of nTS projecting PVN^{Crh} neurons can increase heart rate (HR) (Wang et al., 2019) and modulate cardiorespiratory reflex responsivity (Ruyle et al., 2023). Since abnormal autonomic responsivity is suggested to increase SUDEP susceptibility (Budde et al., 2020; Nakase et al., 2016; Stewart et al., 2017), we hypothesized that elevated CRH neuron activity in mice with spontaneous seizures results in autonomic reflex disturbances that promote SUDEP. To test this, we utilized a combination of chronic electrocardiogram (ECG) and electroencephalogram (EEG) telemetry recordings with acute autonomic reflex testing before and following TLE induction in our unique bi-transgenic *Kcc2/Crh* mice compared to WT controls.

MATERIALS AND METHODS

Animals

All animal procedures were performed in accordance with NIH standards, ARRIVE guidelines for the care and use of laboratory animals, and approval by the University of Missouri Animal Care and Use Committee (ACUC). $Kcc2^{f/f}$ (WT) and *Kcc2/Crh* mice (both sexes; 8-35 weeks of age) were initially acquired as a gift in kind (Dr. Jamie Maguire)(Basu et al., 2024; Melon et al., 2018) to establish a live colony. Animals had *ad libitum* access to food and water and were housed under 12h light – 12h dark conditions.

Telemetry implantation for recordings of electroencephalogram (EEG) and electrocardiogram (ECG)

Mice were implanted with HD-X02 (Data Science International) telemetry devices to examine changes in resting HR (via electrocardiogram, ECG), as well as changes in HR during spontaneous seizures (recorded with electroencephalogram, EEG) over time. Mice were anesthetized with isoflurane in oxygen (4% induction, then maintained at 2%) to effect (lack of toe pinch). Surgical sites were aseptically prepared, and mice placed on a heating pad for supplemental heat. A transverse incision was made through the skin on the dorsal flank. Using blunt tipped scissors, a subcutaneous pocket was created and the implant inserted. One set of bipotential leads was tunneled to two ventral incision sites and placed in a Lead II ECG configuration. Leads were secured in

place and incision site closed with 5–0 silk suture. Mice were then placed in a stereotaxic apparatus in sternal recumbency. An incision was made along the dorsal midline and bipotential leads were tunneled to the incision in the scalp. Two burr holes were made into the skull (one ~1mm anterior to bregma and ~1mm to the right of midline and the other at ~2 mm posterior to bregma and ~1mm to the left of midline). EEG screws (0-80 X 1/16, PlasticsOne, Roanoke, VA) were then inserted and secured to the skull with biopotential leads attached. Dental acrylic was applied to cover screws. Incisions were closed with either 5-0 silk suture or wound clips (FST). Mice were given subcutaneous pain medication (Buprenorphine extended release, Ethiqa XR, 1mg/kg) and placed back in their home cage with supplemental heat and monitored postoperatively. Wound clips/sutures were removed 10-14 days after surgery.

Seizure induction via ventral intrahippocampal kainic acid microinjection

The ventral intrahippocampal kainic acid (vIHKA) model, an established model of temporal lobe Epilepsy, was used to generate chronically epileptic mice as previously described (Basu et al., 2024; Zeidler et al., 2018). Briefly, mice were anesthetized with a ketamine/xylazine cocktail (100mg/kg ketamine; 10mg/kg xylazine) and aseptically prepared for stereotaxic surgery as detailed above. A burr hole was made at established coordinates (ventral hippocampus; -3.6mm from bregma, 2.8mm from midline)(Basu et al., 2024; Paxinos & Franklin, 2001). A 34 gauge needle (WPI) attached to a 10uL Hamilton syringe was then lowered into the ventral hippocampus (-2.8mm from surface) and kainic acid (KA; Millipore Sigma, 20mM, 100nL) or sterile saline (100nL; 0.9%) was microinjected using a microsyringe pump (UltraMicroPump3 and SMARTouch Controller, WPI) at a rate of 1.7ul/sec. The needle was then slowly withdrawn. Incisions were closed with VetBond (3M) tissue adhesive or 5-0 silk suture. Mice were given warmed subcutaneous fluids (1 mL, 0.9% Saline) and pain medication (Buprenorphine extended release, Ethiqa XR, 1mg/kg) and placed back in their home cage with supplemental heat and monitored twice daily for duration of study. Seizures were not pharmacologically terminated, and *status epilepticus* was observed upon waking.

ECG and EEG Telemetry

Mice were allowed to recover from the telemetry implant surgery and then acclimated for at least three days prior to telemetry recordings. Animals were then recorded for one day (at least a week after telemetry implant surgery) to obtain baseline measurements (prior to KA or saline injections). This recording occurred between the hours of 10:00 and 17:00 h in all cohorts, and animals were singly housed during this time with water and food available *ab libitum*.

After KA or saline hippocampal injection, telemeter implanted mice were recorded weekly (day 7, 14, 21, 28) for ECG and EEG. To note, two WT mice (1 saline injected, 1

KA-injected) were not recorded on day 28 due to issues with the telemeters, not SUDEP. Signals from telemetry probes were acquired at a sampling frequency of 1 kHz using the DSITalker interface (Cambridge Electronic Design Limited) connected to MX2 PhysioTel telemetry hardware (Data Sciences Inc.)

Autonomic reflex testing

All autonomic reflex testing was performed using a jugular catheter tunneled into the right atria as previously detailed (Strain et al., 2023). Briefly, a jugular catheter was placed under urethane anesthesia (1500 mg/kg w/supplemental doses as needed) immediately before autonomic reflex testing. Surgical sites were aseptically prepared. A midline incision and blunt dissection was completed to visualize the right external jugular vein with a surgical microscope. The jugular vein was gently lifted with curved forceps, and two small sutures placed underneath. The cranial suture was used to ligate the jugular vein. Using fine spring scissors, a small incision was made into the jugular vein and a beveled catheter (polyethylene tubing; PE10; Intramedic, 427401) containing saline was inserted and secured with suture.

<u>For Baroreflex:</u>

In experiments where baroreflex was assessed, blood pressure (BP) and HR were recorded using HDX11 telemetry probes. Briefly, a transverse incision was made through the skin on the dorsal flank. A subcutaneous pocket was created via blunt dissection. Bipotential leads and catheter were tunneled, using a trocar, to the ventral incision site on the neck. The ECG leads were further tunneled and secured in a Lead II ECG configuration. The carotid artery was isolated using blunt force dissection and three sutures placed underneath the artery. The cranial suture was ligated to the carotid artery just proximal to the carotid bifurcation. To allow placement of the catheter, the most distal suture was used to temporarily occlude blood flow. Using the 25-gauge needle, the artery was pierced, and catheter inserted. The middle suture was secured and occlusion suture released. The catheter was then advanced towards the aortic arch. The middle and occlusion suture were tightened and incisions closed with suture. Sodium nitroprusside (SNP, 600ug/kg) was infused (0.04 mL/min; 1mg/mL) into the jugular vein to decrease BP. Phenylephrine (PE, 15mg/kg) was infused (0.04 mL/min, 25mg/mL)(Karlen-Amarante et al., 2012) to increase BP.

<u>For Bezold Jarisch Reflex (BJR):</u>

In experiments where the BJR was assessed, HR was recorded either via previously implanted HDX02 probe (animals that underwent chronic telemetry recordings) or needle electrodes inserted into each forepaw in a lead I ECG configuration. ECG recordings were AC amplified (1000x; CED 1902 amplifier, Cambridge Electronic Design, Cambridge, UK), band pass filtered (1-1000Hz) and digitized at 1 kHz (CED

Power 1401, Cambridge Electronic Design, Cambridge, UK). Phenylbiguanide (50ug/kg), a serotonin type 2 receptor (5HT3R) agonist, was infused (1mL/min, 0.1mg/mL) via the jugular catheter to elicit the BJR. In a subset of mice, animals were tested to ensure autonomic contributions by subsequently administration of the sympathetic antagonists, atenolol (10 mg/kg, I.P.) and parasympathetic antagonist, scopolamine (1 mg/kg, I.P) and rerunning the BJR. At least 15 minutes was allowed between repeated testing to eliminate tachyphylaxis and allow for full antagonist effects.

Chronic muscarinic blockade

In a subset of KA-injected *Kcc2/Crh* mice, an osmotic mini pump (Alzet Model 1004) containing methyscopolamine was implanted four days after seizure induction to test the capacity for chronic parasympathetic blockade to prevent SUDEP mortality. Briefly, mice were anesthetized with isoflurane in oxygen (4% induction, then maintained at 2%) to effect (lack of toe pinch) and aseptically prepared for implantation as detailed for telemeters. A transverse incision was made through the skin on the dorsal flank. Using blunt tipped scissors, a subcutaneous pocket was created. The pocket was then irrigated with sterile saline and a mini pump containing methylscopolamine (12mg/kg/day, n=10) was inserted. The site was then closed with wound clips (FST). Mice were given pain medication cocktail (buprenorphine 0.1 mg/kg and carprofen 10 mg/kg) and placed back in their home cage with supplemental heat and monitored postoperatively. Wound clips were removed a week after surgery.

Immunohistochemistry

For immunohistochemical analysis, mice were deeply anesthetized with isoflurane or urethane (if following reflex testing) until the toe-pinch reflex was absent. Mice were decapitated and brains removed and bisected down the midline. Brains were fixed by submerging in 2.5% PFA for 24 hours and then cryoprotected in 20% sucrose for 24 hours followed by 30% sucrose for 24 hours. Hippocampal sections were cut at 30 µm in the coronal plane with a cryostat (Leica CM1860). Serial sections through the ventral hippocampus were rinsed with PBS (pH 7.4). Nonspecific immunoreactivity was blocked with 5% normal donkey serum (Jackson Immunoresearch, ref#017-000-121) in PBS + Triton (0.3%). ZnT3 was identified with primary rabbit anti-Znt3(1:100, Synaptic Systems) followed by secondary donkey anti-rabbit 488 Alexa Fluor (1:200, Invitrogen). Slices were mounted using DAPI mounting media. Tissue from all groups were run in parallel with the same antibody cocktails. Images were acquired under identical parameters, including exposure time and illumination intensity. Further processing of brightness and contrast were performed identically for figure presentation. Negative controls were run without primary antibody. All imaging was done with a fluorescence microscope (BZ-X800 Keyence, Itasca, Illinois) using filters appropriate for the two fluorescent dyes.

Drugs

(-)Scopolamine methyl bromide, (R)-(-)- Phenylephrine hydrochloride, Atenolol, and Sodium nitroprusside dihydrate were from Sigma-Aldrich (St Louis, MO, USA). 1-Phenylbiguanide hydrochloride was from Combi-Blocks (San Diego, CA, USA).

Data analysis

For analysis of mortality, only animals that were taken out to endpoint (28 days) or were found dead in their cage (presumed SUDEP) were included. Animals were checked twice daily for mortality.

All HR recordings were analyzed offline in Spike2 software. Resting HR was averaged from a stable two-hour recording period at least two hours after the animals were placed in the recording room. Collected EEG data was analyzed using SeizyML for spontaneous seizure onset and termination (Antonoudiou et al., 2025). Time from seizure onset to termination was used to determine seizure duration. For analysis of changes in HR during seizures, a significant change in HR was considered if HR changed (increased or decreased) by > 5% of HR during the seizure. As a tachycardia often occurred before the onset of the seizure, the baseline period was sampled for 60 secs during the preictal period. For qualitative representation of the grouped average HR during seizures, a stimulation histogram was generated in Spike2 triggered by seizure termination. Beats were binned into 1 sec intervals.

For analysis of BJR, HR was averaged 30 sec prior to phenylbiguanide infusion and then again in two, two second bins. The minimum of the first two bins was selected to represent BJR magnitude. For analysis of HR and BP during sodium nitroprusside infusion, BP and HR were averaged for one minute before infusion to represent baseline. HR and BP were then averaged for 10 sec at the end of the infusion to represent the “early” response. Right before PE administration (~30-45 sec after SNP infusion), HR and BP were averaged for 10 secs to represent the “late” response. Both early and late BP and HR values were subtracted from baseline values to capture the biphasic HR response to SNP. To analyze HR and BP changes with PE administration, binned averages (0.5 sec duration) of BP and HR were sampled over time during PE infusion. Change in HR by Change in BP was then fitted with a modified WYSIWYG Boltzmann sigmoidal equation (Heusser et al., 2021) which generated V50 (as an index of BP set point) and slope (as an index of baroreflex sensitivity) values. The change in BP with PE administration was calculated as the difference before PE infusion and an average BP over 10 sec at the peak of the PE-induced BP response. For terminal reflex testing and/or in vivo telemetry, animals with baseline HR and/or BP two standard deviations above or below means seen in control groups were excluded from analysis.

For immunohistochemical analysis, ventral hippocampus was identified with the use of a mouse brain stereotaxic atlas and DAPI immunoreactivity (Paxinos & Franklin, 2001). Mossy fiber sprouting and dentate granule cell density were quantified in ImageJ (version 1.54f). For each slice, the entire granule cell layer and molecular layer of the dentate gyrus were labeled as a region of interest (ROI) and mean intensity of the ROI was calculated. Mean fluorescence intensity of the ROI was averaged across two sections to quantify mossy fiber sprouting for each animal. The cell counter function in ImageJ was used to manually count cells (DAPI+) in a region (containing at least 50 cells) of the dentate gyrus in the upper blade, with a ROI around the counted cells used to determine area. Cell density was quantified as number of cells per area. The experimenter was blinded to treatment during analysis.

Statistics

Data are presented as mean ± s.d. unless otherwise stated or shown as individual points and means to highlight individual responses. When two groups of independent samples were compared, a two-tailed unpaired t-test was used. In experiments with one main effect, a one-way ANOVA, with or without repeated measures (when appropriate), was used to test for the main effect. One-way ANOVA was followed up with Tukey's multiple comparisons test. In experiments with two main effects, a two-way ANOVA, with or without repeated measures (when appropriate), was used to test the two main effects and the interaction effect. Two-way ANOVA was followed up with Tukey's multiple comparisons test unless otherwise specified. To analyze repeated-measures data with missing values (HR over time w/SUDEP mortality), a mixed effects model was used and followed up with Tukey's multiple comparisons test. Significance was accepted when $P < 0.05$. All analyses were performed using GraphPad Prism (v10.5.0, San Diego, CA, USA).

RESULTS

Resting HR before and after vIHKA injection

To examine the interaction between CRH neuron hyperexcitability and seizures on resting HR, we recorded HR in both *Kcc2*/*Crh* and WT mice using ECG telemetry at various time points following vIHKA injection. Before hippocampal injection of saline or KA (Fig. 1A), there was no difference in resting HR between *Kcc2*/*Crh* (532.1 ± 55.0 BPM, n=23) and WT (555.8 ± 49.5 BPM, n=13, p=0.2071, unpaired t-test) mice. Following hippocampal injection, a mixed effects model revealed a significant interaction between group and time on resting HR ($F(10.09, 92.45) = 1.974$; p=0.0445). Specifically, HR was elevated in both WT (ΔHR, 26.1 ± 12.1 BPM, n=6) and *Kcc2/Crh* (ΔHR, 43.6 ± 44.1 BPM, n=14) mice on day 7 following KA injection compared to prior to injection (WT: p=0.0169; *Kcc2/Crh*: p=0.0190; Tukey's post hoc) and saline-injected *Kcc2/Crh* sham controls (ΔHR, -11.2 ± 30.0 BPM, n=8; vs WT day 7: p=0.0415, Tukey's

post hoc; vs *Kcc2/Crh day 7*: p=0.0127, Tukey's post hoc) (Fig. 1B, C). Interestingly, on day 14, HR remained significantly elevated only in KA-injected *Kcc2/Crh* mice (ΔHR, 53.8 ± 32.0 BPM, n=11; p=0.0169, Tukey's post hoc) compared to prior to injection (Fig. 1C). There were no significant differences in resting HR among any group on day 21 or 28 (Tukey's post hoc). To determine if the magnitude of the resting tachycardia was predictive of SUDEP susceptibility, we plotted individual KA-injected *Kcc2*/*Crh* mice that died, against the average resting HR of KA-injected *Kcc2*/*Crh* mice that survived to endpoint (Fig. 1D). We did not observe any qualitative relationship between the magnitude of resting tachycardia and those that died or survived to endpoint, suggesting the severity of resting tachycardia is not predictive of SUDEP susceptibility. Taken together, both KA-injected groups have resting tachycardia shortly after seizure induction that resolves over time. Further, resting tachycardia does not appear to be predictive of SUDEP but likely contributes to total autonomic disturbance burden.

Changes in HR during spontaneous seizures

To examine the impact of CRH neuron hyperexcitability on control of HR during seizures, we recorded spontaneous seizures in both *Kcc2*/*Crh* and WT mice using EEG and ECG telemetry recordings (Fig. 2). In agreement with prior studies (Basu et al., 2024), we observed no significant difference in average seizure duration between *Kcc2*/*Crh* (31.3 ±13.4 sec, n=8 seizures) and WT mice(38.5 ±9.5 sec, n=6 seizures; p= 0.2871, unpaired t-test). In both *Kcc2/Crh* and WT mice, HR often (12/14 seizures) increased at the start or immediately before (*Kcc2/Crh*: -7.0 ± 7.2 sec, n=7; WT: -8.2 ± 5.4 sec, n=5) seizure onset (Fig. 2G). Average ictal HR was predominately (4/6 WT seizures and 5/8 Kcc2/Crh seizures) increased relative to the preictal period, with no difference between genotypes (WT: ΔHR, 36.75 ± 59.80 BPM, n=6; Kcc2/Crh: ΔHR, 3.91 ± 87.92 BPM, n=8, p=0.4476, unpaired t-test, Fig. 2D).

However, during seizures (n=11/14), HR fluctuated between periods of tachycardia and bradycardia, with a subset of seizures only having tachycardia (3/14 seizures). To better quantify nuanced fluctuations in HR during seizures, we segregated ictal HR time series into periods of ictal tachycardia and bradycardia. Magnitude (Fig. 2E) and duration (Fig. 2F) of ictal tachycardia were similar between *Kcc2/Crh* (ΔHR, 65.6 ± 54.9 BPM, n=8; 16.3 ± 20.0 sec, n=8) and WT (ΔHR, 75.2 ± 61.72 BPM, n=6, p=0.7629, unpaired t-test; 13.5 ± 12.3 sec, n=6, p=0.7721, unpaired t-test) mice, with preictal tachycardia magnitude no different across groups (WT: 62.4 ± 24.5 BPM, n=4 v.s *Kcc2/Crh*: 77.8 ± 56.2 BPM, n=6; p= 0.6245, unpaired t-test; data not shown). However, *Kcc2/Crh* mice had both significantly longer duration (11.6 ±3.3 sec, n=6, Fig. 2I) and greater magnitude of ictal bradycardia (ΔHR: -208.1 ± 63.5 BPM, n=6 Fig. 2H) than WT (7.2 ± 2.2 sec, n=5, p=0.0350, unpaired t-test; ΔHR, -113.2 ± 53.0 BPM, n=5, p=0.0264, unpaired t-test). Qualitatively, ictal bradycardia occurred most prominently right before seizure termination in both *Kcc2/Crh* and WT mice (Fig 2B, C).

Effect of Epilepsy and hyperactive CRH neurons on baroreflex function

Since baroreflex is a critical, gold standard reflex for regulating cardiac function (Salah et al., 2025; Schreihofer & Guyenet, 2002), we chose to investigate both high and low pressure baroreflex responsivity at 10 and 30 days after KA injection or in saline-injected sham controls. To investigate reflex changes in HR mediated by high pressure baroreceptors, we infused phenylephrine (PE), an alpha-adrenergic agonist, again into the right jugular vein (Fig. 3). PE infusion increased BP at all time points across all groups, with one-way ANOVA revealing no significant differences in the magnitude of the pressor response between groups (PE Δ BP, Table 1, Fig. 3C). A modified-Boltzmann equation (Heusser et al., 2021) was used to relate PE-mediated increases in BP to baroreflex mediated decreases in HR (inset with colored background in example traces Fig 3A & B). Two-way ANOVA showed a specific main effect of time post hippocampal injection ($F(2, 25) = 4.243$, $p=0.0259$) on the slope of the resulting curve i.e., baroreflex sensitivity (Fig. 3E). Collapsing across genotype, baroreflex sensitivity was not significantly different (-17.3 ± 1.8 BPM/mmHg, n=5 *Kcc2/Crh*, n= 5 WT) 10 days after KA injection, compared to saline-injected controls (-12.0 ± 3.9 BPM/mmHg, n=5 *Kcc2/Crh*, n= 5 WT, p=0.2400, Tukey's post hoc). Interestingly, at day 30 collapsed groups had significantly decreased baroreflex sensitivity (-7.9 ± 5.2 BPM/mmHg, n=6 *Kcc2/Crh*, n=5 WT, ; Fig. 3A right) compared to day 10 (p=0.0168, Tukey's post hoc), but not saline-injected controls (p=0.4246, Tukey's post hoc). Thus, regardless of genotype, baroreflex blunting occurs 30 days after KA injection that works to bring baroreflex sensitivity closer to baseline values.

Similar to baroreflex sensitivity, two-way ANOVA showed a specific main effect of time post vIHKA injection ($F(2, 25) = 4.407$, $p=0.0229$) on the operating point (V50), which represents the arterial pressure at which pressure disturbances are effectively buffered by reflex response (Fig. 3D). Collapsing across genotype, V50 was not significantly different (115.7 ± 1.1 mmHg, n=5 *Kcc2/Crh*, n= 5 WT) 10 days after vIHKA injection, compared to saline-injected controls (116.9 ± 1.9 mmHg, n=5 Kcc2/Crh, n= 5 WT, p=0.9967, Tukey's post hoc). At day 30 vIHKA groups had significantly increased V50 (132.3 ± 8.4 mmHg, n=6 *Kcc2/Crh*, n=5 WT, Fig. 3A right) compared to vIHKA groups at day 10 (p=0.0412, Tukey's post hoc), but not saline-injected controls (p=0.0635, Tukey's post hoc). Thus, regardless of genotype the operating point of baroreflex is increased 30 days after vIHKA injection.

To evaluate low pressure baroreceptors, we infused sodium nitroprusside (SNP), a nitric oxide donor, in the right jugular vein (Fig. 4). Two-way ANOVA showed a significant main effect on time following SNP infusion on BP ($F(2, 56) = 537.6$; $p<0.001$) as pressure fell quickly and plateaued in all groups and this change was similar across all genotypes (Table 1, Fig. 4C).

Group	Treatment	Baseline BP	SNP Δ BP Early	SNP Δ BP Late	PE Δ BP
Kcc2$^{f/f}$	Saline	89.8 ± 11.3 (6)	-40.6 ± 9.8 (6) †	-44.6 ± 9.4 (6) †	81.1 ± 17.4 (5)
	10 days post KA	87.8 ± 12.9 (5)	-40.5 ± 10.2 (5) †	-48.2 ± 8.3 (5) †	95.2 ± 8.4 (5)
	30 days post KA	87.9 ± 11.8 (6)	-36.1 ± 8.0 (6) †	-38.4 ± 8.1 (6) †	104.2 ± 11.6 (5)
Kcc2/Crh	Saline	81.9 ± 16.1 (5)	-36.3 ± 9.1 (5) †	-40.0 ± 6.8 (5) †	91.75 ± 14.7 (5)
	10 days post KA	86.6 ± 7.8 (5)	-33.1 ± 10.9 (5) †	-35.3 ± 11.2 (5) †	89.3 ± 17.6 (5)
	30 days post KA	92.2 ± 9.9 (6)	-37.1 ± 9.9 (6) †	-39.6 ± 9.1 (6) †	87.1 ± 12.4 (6)

Data are presented as mean ± SD (n); Baseline is 1 min prior to SNP infusion, SNP early is the avg BP over 10 secs immediately following SNP infusion, SNP late is avg BP over 10 sec immediately prior to PE infusion, PE BP is 10 secs of peak BP during PE infusion. SNP early and late are relative to baseline and change in BP with PE is relative to SNP late.
†P<0.05, relative to baseline, Tukey's post hoc

For HR changes, however, two-way ANOVA revealed a significant interaction between group and SNP-mediated changes in HR (p=0.0038; F(10,54)=3.059; Fig. 4D). During the early phase, HR did not significantly change from either prior to SNP infusion or between genotypes. During the "late" response, HR increased in saline-injected *Kcc2/Crh* mice (ΔHR, 10.6 ± 10.3 BPM, n=5; Fig. 4B left) but decreased (e.g. a paradoxical bradycardia) in saline-injected WT controls (ΔHR, -6.3 ±8.4 BPM, n=6; Fig. 4A left). However, these qualitative changes were not significantly different from each other. On day 10 following KA injection, the "late" paradoxical bradycardia occurred in both WT (ΔHR, -31.3 ± 27.7 BPM, n=5; Fig. 4A middle) and *Kcc2/Crh* mice (ΔHR, -15.8 ± 21.9 BPM, n=5; Fig. 4B middle), with the magnitude of "late" HR significantly greater than "late" HR in respective saline-injected group controls (WT: p=0.0432; *Kcc2/Crh*: p=0.0386; Tukey's post hoc; Fig. 4D). While all mice continued to exhibit paradoxical bradycardia at Day 30, the magnitude of this response was attenuated at 30 days in KA-injected WT (ΔHR, -2.4 ± 18.6 BPM, n=6; Fig. 4A right) compared to KA-injected WT mice on day 10 (WT: Late, d30 vs d10, p=0.0114, Tukey's post hoc). In contrast, there was no change in paradoxical bradycardia in KA-injected *Kcc2/Crh* mice on day 30 (ΔHR, -32.9 ± 31.7 BPM, n=6; p=0.3189, Tukey's post hoc, Fig. 4B right) compared to KA-injected *Kcc2/Crh* mice on day 10. Finally, paradoxical bradycardia in KA-injected *Kcc2/Crh* mice on day 30 was significantly greater than KA-injected WT mice on day 30 (p=0.0030; Tukey's post hoc). Taken together, paradoxical bradycardia is exaggerated 10 days after vIHKA injection in both mice with and without hyperactive

CRH neurons. By day 30, this paradoxical bradycardia is attenuated in vIHKA WT, but remains exaggerated in vIHKA *Kcc2/Crh* mice.

To quantify the relationship between changes in BP and HR, we plotted change in HR over change in BP in the early and late phase (Fig 4E). Two-way ANOVA revealed significant interaction between group and SNP-mediated changes in the ratio of ∆HR/∆BP (p=0.0473; F(5,27)=2.612; Fig. 4E). At no time was ∆HR/∆BP during the "early" phase different between genotype or across time. At day 10, ∆HR/∆BP during the "late" phase was no different than saline-treated groups in both *Kcc2/Crh* (Sal: -0.24 ± 0.27 BPM/mmHg, n=5 v.s vIHKA: 0.74 ± 1.28 BPM/mmHg, n=5, p=0.0544, Tukey's post hoc) and WT (Sal: 0.15 ± 0.19 BPM/mmHg, n=6 v.s vIHKA: 0.65 ± 0.57 BPM/mmHg, n=5, p= 0.8375, Tukey's post hoc). Furthermore, *Kcc2/Crh* and WT with vIHKA were also not different from each other at day 10 (p>0.9999, Tukey's post hoc) or day 30 (*Kcc2/Crh*: 0.76 ± 0.65 BPM/mmHg, n=6 v.s WT: 0.05 ± 0.51 BPM/mmHg, n=6, p= 0.2595, Tukey's post hoc). Notably, at day 30, "late" phase ∆HR/∆BP of *Kcc2/Crh* mice was significantly greater than ∆HR/∆BP of saline injected *Kcc2/Crh* controls (p=0.0315, Tukey's post hoc).

Effect of Epilepsy and hyperactive CRH neurons on the BJR

As dysfunction of serotonergic signaling is implicated in the pathophysiology of SUDEP (Richerson & Buchanan, 2011), we investigated the BJR (Fig. 5), a cardioinhibitory reflex triggered by cardiopulmonary vagal afferents containing serotonin type 3 receptors (5HT3R). Accordingly, the BJR can be triggered by right jugular administration of phenylbiguanide (PBG), a 5HT3R agonist. A repeated-measures one-way ANOVA confirmed administration of phenylbiguanide (PBG), a 5HT3R agonist, elicited the expected BJR bradycardia (ΔHR, -251.9 ± 155.5 BPM, n=6) (Verberne & Guyenet, 1992). This PBG-dependent bradycardia was vagally mediated since IP administration of atenolol had no effect on reflex bradycardia (ΔHR, -286.6 ± 90.88 BPM, n=6, p=0.6729, Tukey's post hoc), but administration of scopolamine eliminated it (ΔHR, -42.00 ± 9.8 BPM, n=6, p=0.0441versus no drugs and p=0.0023 versus atenolol, Tukey's post hoc, Fig. 5A & B).

PBG-mediated reflex bradycardia was not different between saline-injected WT (ΔHR, -181.8 ± 111.5 BPM, n=7; Fig. 5C left) and saline-injected *Kcc2-Crh* (ΔHR, -189.7 ± 119.9 BPM, n=11; Fig. 5D left; p=0.8806, Tukey's post hoc). Two-way ANOVA revealed a significant interaction between time post vIHKA injection and genotype (F(2, 41) = 3.343; p=0.0452) on PBG-mediated reflex bradycardia (Fig. 5E). In WT mice, PBG-mediated reflex bradycardia was not different either by injection or day. In *Kcc2/Crh* mice, the magnitude of BJR was significantly increased at day 10 (ΔHR, -390.3 ± 77.1 BPM, n=9, Fig. 5D middle) compared to KA-injected WT at day 10 (ΔHR, -183.0 ± 123.1 BPM, n=6; p=0.0007, Tukey's post hoc, Fig. 5C middle) and saline-injected *Kcc2/Crh*

(p=0.0005, Tukey's post hoc, Fig. 5D left) mice as well as *Kcc2/Crh* mice on day 30 (ΔHR, -222.8 ± 114.9 BPM, n=8 p=0.0074, Tukey's post hoc, Fig. 5D right). *Kcc2/Crh* mice on day 30 (p=0.0074, Tukey's post hoc) were not significantly different than KA-injected WT mice on day 30 (ΔHR, -120.4 ± 92.9 BPM; n=6, p=0.0864, Tukey's post hoc, Fig. 5C right). Taken together, there is a selective increase in BJR magnitude 10 days after KA injection in mice with hyperactive CRH neurons, that is not observed in WT mice.

Chronic muscarinic blockade reduces SUDEP susceptibility in epileptic mice with CRH neuron hyperactivity

To confirm SUDEP susceptibility in our model, a subset of vIHKA injected WT and *Kcc2/Crh* mice were monitored for mortality for 28 days. Aligning with prior studies (Basu et al., 2024), 9/22 (41%) KA-injected *Kcc2*/*Crh* mice died with peak mortality occurring around the first week following injection (Fig. 5F blue). In contrast, KA-injected WT mice had no mortality (0/12 mice died) (Fig. 5F gray). To determine the impact of vagal bradycardia on SUDEP mortality, mice were chronically treated with peripherally restricted methylscopolamine. Indeed, muscarinic blockade attenuated (3/10, 30%, mice died, Fig 5F orange) SUDEP mortality.

Changes in hippocampal morphology following vIHKA injection

Hippocampal mossy fiber sprouting (MFS) and dentate granule (DG) cell dispersion are hallmark pathological changes observed in both preclinical models of Epilepsy and in patients with Epilepsy (Sutula & Dudek, 2007). To confirm the severity of these pathological changes did not change in our model (Basu et al., 2024), we performed immunohistochemistry (Fig. 6) to quantify MFS and DGCD 10 and 30 days after KA or saline injection. Two-way ANOVA revealed a significant main effect of time post injection on MFS (F (2, 28) = 25.13; P<0.001). Independent of genotype, we observed a significant increase in MFS on day 10 (19.8 ± 3.4 MFI, n=5 WT, n=4 *Kcc2/Crh*) and day 30 (20.2 ± 1.1 MFI, n=5 WT, n=10 *Kcc2/Crh*)of vIHKA injection compared to saline injected controls (11.5 ± 1.3 MFI, n=5 WT, n=4 *Kcc2/Crh*, p<0.001 and p<0.0001 respectively, Tukey's post hoc, Fig. 6C). There was no change in MFS between day 10 and day 30 (p=0.97, Tukey's post hoc).

Similar to MFS, a two-way ANOVA revealed a significant main effect of time post vIHKA on DG cell dispersion (F (2, 28) = 66.34; p<0.001). Independent of genotype, DG cell dispersion (0.80 ± 0.07 cells/area, n=5 WT, n=4 *Kcc2/Crh*) on day 10 and day 30 (0.57 ± 0.01 cells/area, n=5 WT, n=10 *Kcc2/Crh* mice n=10) was increased compared to saline-injected controls (1.18 ± 0.03 cells/area, n=6 WT, n=4 *Kcc2/Crh,* p<0.001 for both, Tukey's post hoc, Fig. 6B). Additionally, DG cell dispersion was significantly increased at day 30, compared to day 10 (p<0.001, Tukey's post hoc). Taken together, hallmark pathological features of Epilepsy are significantly increased shortly after seizure

induction, with DG cell dispersion worsening as Epilepsy progresses in the following weeks.

DISCUSSION

The present study examined the impact of CRH neuron hyperexcitability on autonomic control of HR in a novel mouse model of SUDEP using chronic EEG and ECG telemetry recordings, terminal autonomic reflex testing, and immunohistochemistry. We found that experimental TLE promotes a resting tachycardia in both *Kcc2/Crh* and WT that subsides in both groups (Fig. 1). Regardless of genotype, spontaneous seizures were punctuated by rapid changes in HR, including tachycardic and bradycardic-periods, with robust bradycardias appearing at seizure termination (Fig. 2). Despite no changes in the magnitude of tachycardiac periods, bradycardias during spontaneous seizures in *Kcc2/Crh* mice were more severe compared to WT mice. Finally, experimental TLE led to time-dependent plasticity of autonomic reflexes, specifically increased BJR and prolonged augmentation of “low pressure” baroreflex in *Kcc2/Crh* mice compared to WT (Fig 3-5). This exaggerated BJR, and diminished capacity to attenuate paradoxical bradycardia, fit in magnitude and timing to drive increased severity of ictal bradycardia and SUDEP susceptibility. These findings support further investigation into the mechanistic underpinnings of SUDEP including its relationships with stress signaling.

HR changes over time

In the present study, resting HR was not different between WT and *Kcc2/Crh* mice prior to vlHKA (Fig 1A). However, central administration of CRH (Fisher et al., 1983; Nijsen et al., 2000) and optogenetic stimulation of CRH neurons (Wang et al., 2019) increases HR. Therefore, the present lack of change in resting HR might be inconsistent with expected HR from CRH neuron hyperactivity in *Kcc2/Crh* mice based on these previous acute stimulation studies. However, a number of factors may be contributing to these HR responses. Most notable, our model utilizes a developmental strategy to knock down the expression of *Kcc2* in CRH neurons. It remains possible that CRH neurons in *Kcc2/Crh* mice have a compensatory change that minimizes the loss of this gene product. For example, recent evidence implicates excitatory amino acid transporter 3 (EAAT3) function in the establishment of glutamate-dependent GABA synaptic strengthening in PVN neurons (the CRH population most prominently implicated in both autonomic and stress response regulation), which protects PVN from excitotoxicity and be responsible for PVN adaptability (Yamaguchi et al., 2024). It remains possible then that a developmental modification in EAAT3 expression could alleviate pressures associated with Kcc2 loss and allow for relative homeostatic regulation of PVN^{CRH} neurons activity. Such a homeostatic regulation of PVN^{CRH} neurons would increase their probability of remaining in a “hard off” state with little to no basal firing (Gao et al., 2017; Lovick & Coote, 1988; Savic et al., 2022). This aligns well with lack of elevated plasma

corticosterone at baseline in *Kcc2/Crh* mice compared to WT since elevated PVN^{CRH} neuron activity should increase this signal (Basu et al., 2024).

TLE induction in *Kcc2/Crh* mice does induce chronic elevated corticosterone relative to WT mice given this same induction protocol (Basu et al., 2024). Here following TLE induction, both *Kcc2/Crh* and WT mice developed a resting tachycardia that resolved in the following weeks. This is consistent with previous work. Homeostatic challenges are known to alter activity of PVN, including activity related to stress axis activation (Palkovits, 2000). In particular, previous work demonstrates that regardless of model or genotype, seizures activate the HPA axis, including increased activation of PVN^{CRH} neurons and elevated corticosterone levels (O'Toole et al., 2014). Therefore, it remains possible that seizure related disturbances are sufficient to overcome any inhibitory mechanisms limiting activity of PVN^{CRH} neurons. In line then with no differences in resting HR before vIHKA, compensatory changes may also occur in PVN^{CRH} neurons of *Kcc2/Crh* and WT following TLE induction to return resting HR to baseline by day 30 since number of daily seizures, average seizure duration, or seizure burden does not change during this time (Basu et al., 2024). Although faster interictal HR is observed in patients with various types of epilepsy (Sevcencu & Struijk, 2010), whether this results from epilepsy itself or is influenced by treatment with antiepileptic drugs is poorly understood. Accordingly, patients with Epilepsy chronically treated with anti-seizure medication have higher interictal HR than newly diagnosed, non-treated patients, suggesting Epilepsy treatment, and not chronic Epilepsy induces resting tachycardia (Manka-Gaca et al., 2016). Therefore, it remains possible that the resolution of acute tachycardia in patients with Epilepsy is confounded by use of antiepileptic drugs.

HR responses during spontaneous seizures

Ictal tachycardia is a common change in HR reported during seizures (Eggleston et al., 2014). In our study, we observed an increase in HR in both *Kcc2/Crh* and WT mice during spontaneous seizures. This increase in HR began immediately pre-ictal, or directly at seizure onset, aligning with several reports in humans (Mayer et al., 2004; Zijlmans et al., 2002). There was no difference in this seizure-induced tachycardia across genotypes, suggesting it does not play a role in the generation of SUDEP mortality. Interestingly, these pre-ictal tachycardias are theorized to activate sensory interoceptive afferents (Hsueh et al., 2023) related to increased HR and play a role in the capacity of some patients with Epilepsy to predict imminent seizures (Mackay et al., 2017).

In both *Kcc2/Crh* and WT mice, this ictal tachycardia during spontaneous seizures was interrupted by transient drops in HR that began prior (~10 sec) to seizure termination. These ictal bradycardic-episodes were longer with greater magnitudes in *Kcc2/Crh* mice

than WT, which aligns with previous work using genetic models of SUDEP (Dhaibar et al., 2019; Paulhus & Glasscock, 2025; Trosclair et al., 2020). In patients with Epilepsy, ictal bradycardia or “ictal bradycardia syndrome” is less commonly reported. However, most observed seizures with tachycardia are not generalized tonic clonic seizures (Ryvlin, Nashef, Lhatoo, et al., 2013) which is often associated with SUDEP leading some to advocate that recordings of small subsets of seizures might not be enough to confirm (or reject) ictal bradycardia (Hampel et al., 2017). Critically, robust bradycardic events were confirmed as part of the SUDEP terminal sequence in the MORTEMUS study (Ryvlin, Nashef, Lhatoo, et al., 2013), primarily associate with temporal lobe seizures (Britton et al., 2006) and link to increased SUDEP risk (Rugg-Gunn et al., 2004). Patients with epilepsy and observed ictal bradycardia are also at a 40% risk of presenting with ictal bradycardia in subsequent seizures, suggesting that robust bradycardias are a consistent pathology in a subset of patients (Hampel et al., 2017). Taken together, it is conceivable that increased severity of ictal bradycardia in *Kcc2/Crh* mice promotes SUDEP susceptibility and could serve as a biomarker for SUDEP risk in patients with Epilepsy. Targeted intervention to blunt ictal bradycardia may hold promise in reducing SUDEP at least in some patients.

Baroreflex sensory afferent regulatory circuits as potential mechanism for poor HR control in Kcc2/Crh mice

Although high pressure baroreflex blunting can be found in patients with temporal lobe Epilepsy (Dutsch et al., 2006), there is no consistent predictable impact of Epilepsy on BP (Nass et al., 2019). Similarly, our present study found only a mild blunting of “high pressure” baroreflex (e.g. reduced sensitivity and higher set point) 30 days after TLE induction. This is consistent with other animal models of seizures where limited or no change in baroreflex is observed, including an audiogenic seizure model (Fazan et al., 2011) and amygdala kindling (Kaya et al., 2005; Sakamoto et al., 2015). While differences between human patients and animal models could be species dependent, the chronic use of anti-seizure mediations in patients with Epilepsy confounds modulation of BP (Persson et al., 2003). Whether reduced baroreflex sensitivity in patients with Epilepsy occurs from Epilepsy itself or results from anti-seizure medication should be further explored. Regardless, minor “high pressure” baroreflex blunting here was not specific to *Kcc2/Crh* mice, and therefore is unlikely to be a major contributing factor for the development SUDEP.

While infusion of PE elicits responses related to “high pressure” baroreceptors, infusion of SNP results in hypotension and blood pooling that when sufficiently severe stimulates “low pressure” baroreceptors located in the atria, ventricles, and pulmonary vessels. Activation of these interoceptive afferents produces a “paradoxical” bradycardia

(Heesch, 1999; Kuipers et al., 1984; Oberg & Thoren, 1972). This phenomenon mirrors HR responses during the decompensated phase of hemorrhagic shock (Little et al., 1995; Schadt, 1989; Souza et al., 2022) and is common in hypotensive trauma patients (Demetriades et al., 1998). In our experiments, TLE produced severe paradoxical bradycardia in both WT and *Kcc2/Crh* mice 10 days after induction. The magnitude of this response is corrected only in WT mice by day 30; and therefore, this robust paradoxical bradycardia could be a contributing factor for the cardiac arrest seen during SUDEP. Since WT mice present with paradoxical bradycardia at day 10, but do not exhibit SUDEP events, the system's ability to resolve increased “low pressure” baroreflex circuit sensitivity may be an important step in cardiorespiratory collapse with SUDEP.

Are peripheral serotonin-dependent sensory afferent circuits (i.e. BJR) a mechanism for robust ictal bradycardias in KCC2/Crh mice?

Although serotonergic signaling is theorized to play a significant role in SUDEP (Richerson & Buchanan, 2011), this study is one of the first, to our knowledge, to examine the role for peripheral serotonergic signaling in SUDEP-related cardiorespiratory dysfunction. First reported in 1867, activation of cardiopulmonary sensory vagal afferents containing serotonin type 3 receptors (5-HT3Rs) produce a triad of physiological responses consisting of a parasympathetically-mediated bradycardia, apnea, and hypotension known as the BJR (Cramer, 1915; Jarisch & Richter, 1939). Not only are these the triad of cardiorespiratory events seen during SUDEP (Bozorgi et al., 2013; Ryvlin, Nashef, Lhatoo, et al., 2013), an exaggerated BJR can trigger cardiorespiratory collapse (Jackson et al., 2024; Ou et al., 2004; Poulsen & Jellinge, 2024; So et al., 2013). Critically, *Kcc2/Crh* mice, but not WT, had time dependent exaggeration of BJR that peaked when population mortality was highest and subsequently attenuated when population mortality plateaued. Although our report is the first to link BJR to SUDEP, serum serotonin levels are elevated following generalized seizures (Murugesan et al., 2018), likely via release from activated platelets (Cloutier et al., 2018). Additionally, individual SUDEP case reports indicate increases in parasympathetic activity including triggered bradycardia during terminal SUDEP events (Jeppesen et al., 2019), providing further evidence that activation of the parasympathetic-mediated bradycardia during the BJR is clinically relevant. This increased BJR responsivity could also trigger the exaggerated ‘low pressure’ baroreflex thereby further complicating homeostasis. Therefore, the magnitude and timing of increased BJR in *Kcc2/Crh* mice suggests a critical role in the generation of robust bradycardia during spontaneous seizures that could link to sudden death.

Chronic inhibition of vagal motor output (the driver of BJR reflex bradycardia) improved mortality by 10% in Kcc2/Crh mice. Although this improvement provides some hope for patients at high risk for SUDEP with no treatment options, additional avenues of

investigation remain. In addition to bradycardia, the BJR induces a significant apnea and depressor response. Since SUDEP events include all of these physiological responses, it remains possible that elimination of one can only prevent mortality in certain incidences or in specific individuals. Additionally, similar to models proposed for other sudden death (e.g. sudden infant death syndrome) (Kinney et al., 2009), SUDEP could result from “a perfect storm” of multiplicative homeostatic risk factors. Theoretically, for example, since the BJR results in a depressor response, if severe enough it could trigger “low pressure” baroreflex-mediated paradoxical bradycardia. Unlike BJR-mediated bradycardia, this “low pressure” baroreflex-mediated paradoxical bradycardic reflex response is mediated by sympathetic reflex circuits (Souza et al., 2022) and would not be blocked by the scopolamine used here. Therefore, we suggest that the bradycardia from BJR activation alone is sufficient to trigger SUDEP in ~10% of *Kcc2/Crh* mice. However, the apnea and depressor response may either contribute alone in other cases, or are triggers for secondary reflex responses that also contribute to SUDEP. BJR reflex responsivity could serve as a biomarker for patients at highest risk for SUDEP; patients who would benefit from increased vigilance in monitoring. Future directions could further examine how reflex circuits are modulated singly and in combination and whether they could serve as biomarkers in SUDEP.

Future Directions

Although the present study does not exclusively focus on mortality during seizure, our report of HR during spontaneous seizure events supports the emerging body of work suggesting physiological events during non-fatal seizures can predict SUDEP risk (Lamrani et al., 2023; Ryvlin, Nashef, & Tomson, 2013; Schuele et al., 2011). It remains to be determined if ictal events during fatal and non-fatal spontaneous seizures are different and future studies could help clarify any distinctions. We also limited our examination to HR (and not respiration or BP). Whether exaggerated BJR-mediated HR response co-occurs with greater magnitude BJR-mediated apnea and hypotension remains to be determined. Finally, the cascade of stress signaling and cardiorespiratory disturbances examined here could have forms of state-dependency during both ictal and interictal periods.

The precise functional role of BJR activation during seizures warrants additional studies. A recent report suggested that in addition to the classic triad of physiological responses, BJR activation transiently decreases EEG power (Lovelace et al., 2023)(Lovelace et al., 2023). Initiation of ictal asystole also associates with early seizure termination in patients (Moseley et al., 2011; Schuele et al., 2010) and suppression of cerebral electrical activity (Rossetti et al., 2005). We observed the most prominent bradycardia at the end of seizures (Fig 2). Therefore, it's possible BJR activation during seizures promotes seizure termination and/or post-ictal EEG suppression. However, continued activation and strengthening of the BJR could ultimately prove too much. A role then of

excessive BJR activation to help facilitate seizure control and arousal that leads to negative plasticity would be supported by at least the “two-hit” pathomechanism theory of SUDEP (Mueller et al., 2018).

Conclusions:

TLE increased susceptibility to SUDEP in Kcc2/Crh mice and induced significant alternations in their cardiac function, namely an early resting tachycardia and modification of baroreflex parameters. TLE in the context of hyperactive PVN^{Crh} neurons, increases abnormal cardiac homeostatic regulation by exaggerating BJR-mediated bradycardia and “low pressure” baroreflex-mediated paradoxical bradycardia. These increased bradycardiac responses are suited triggers for increased severity of ictal bradycardia seen in TLE mice with increased stress signaling (*Kcc2/Crh*). Ictal activation of these improperly weighted reflexes could result in the cardiorespiratory collapse seen during SUDEP. Together, results here provide novel mechanisms of SUDEP in the context of hyperactive stress central circuits. Future research can expand whether preventing the activation of one or more autonomic reflexes during seizures can decrease SUDEP susceptibility.

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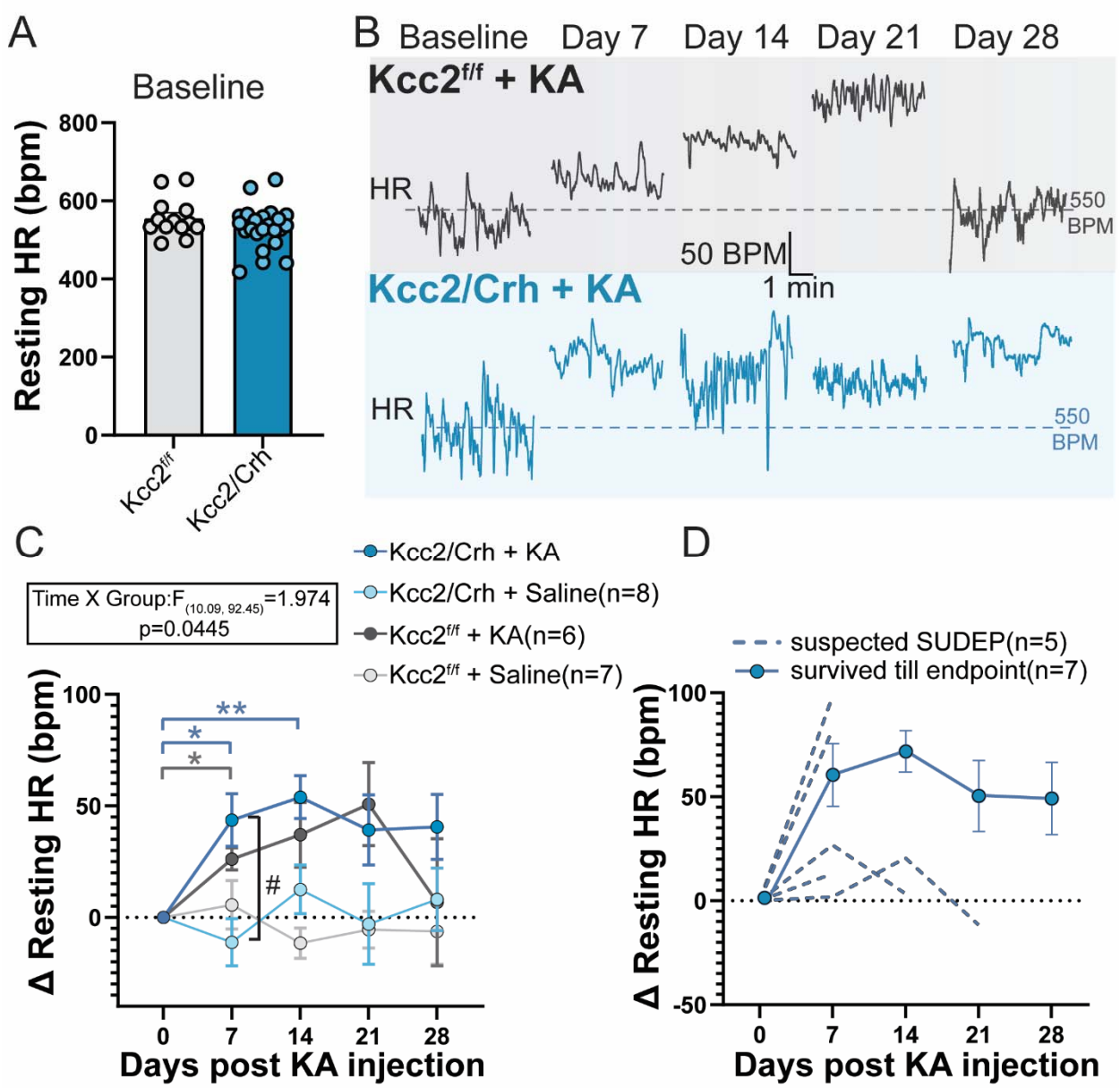

Fig 1. Mice have resting tachycardia shortly after KA injection. A) Resting HR is no different between WT (gray, Kcc2$^{f/f}$) and mice with hyperactive stress circuits (blue, *Kcc2/Crh*) prior to hippocampal injection. B) Example HR traces from mice with and without hyperactive stress circuits with telemeters that were monitored weekly following KA injection. C) Resting HR was significantly elevated 7 days after KA injection in both mice with and without hyperactive stress circuits. HR remained elevated in mice with hyperactive stress circuits but not WT, 14 days after KA injection. D) Mice with hyperactive stress circuits that died follow KA injection are plotted individually (dashed lines). The average HR over time of mice with hyperactive stress circuits that survive to endpoint are plotted together (solid line). There appears to be no relationship between

magnitude of resting tachycardia and SUDEP susceptibility. Symbols are group means ± SEM, $p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ compared to day 0 by mixed effects model and Tukey's post-hoc test, $\#p < 0.05$ compared to sham control by mixed effects model and Tukey's post-hoc test.

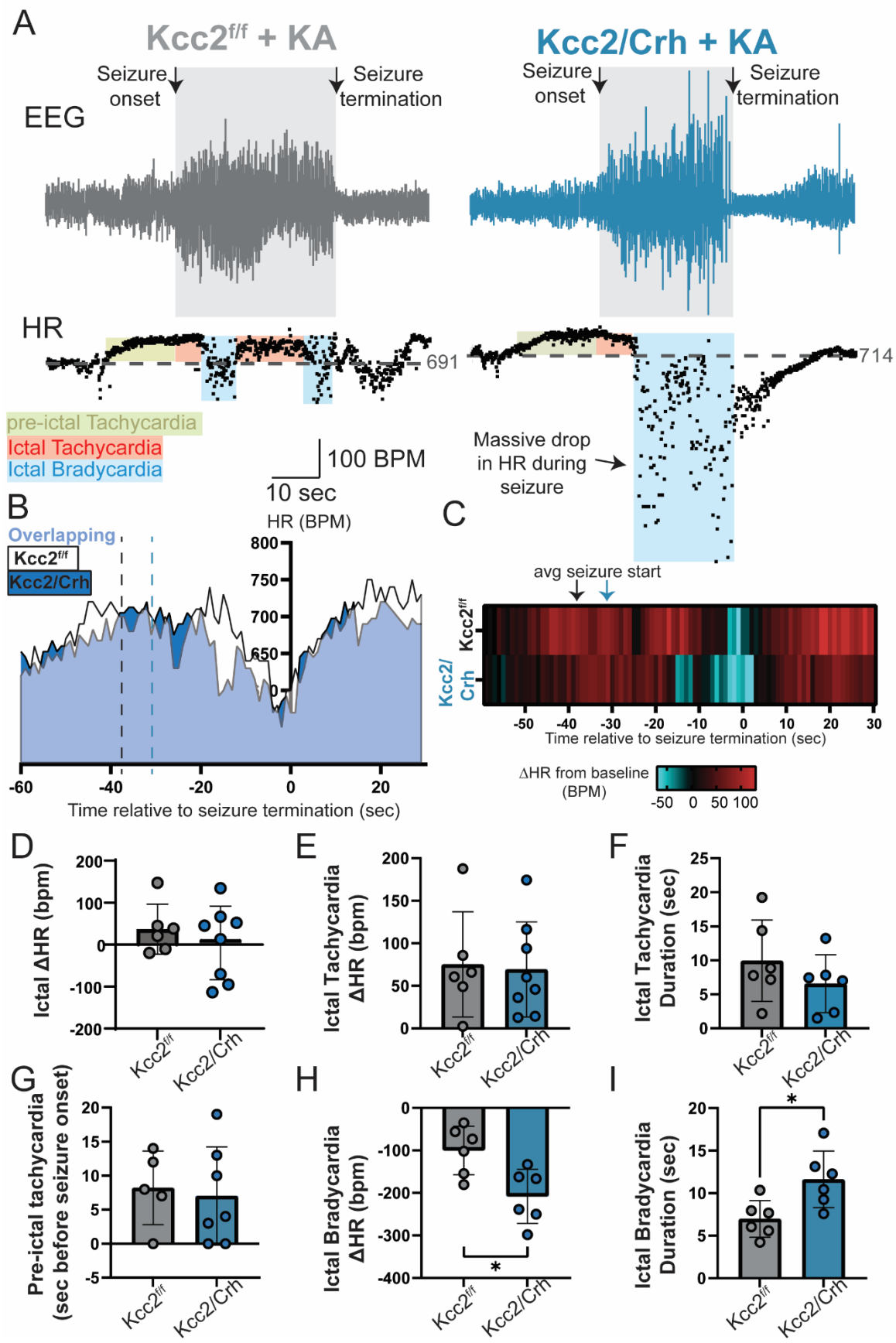
A
Kcc2f/f + KA
Kcc2/Crh + KA
Seizure onset
Seizure termination
EEG
HR
691
714
pre-ictal Tachycardia
Ictal Tachycardia
Ictal Bradycardia
100 BPM
10 sec
Massive drop in HR during seizure
B
Overlapping
Kcc2f/f
Kcc2/Crh
HR (BPM)
Time relative to seizure termination (sec)
C
avg seizure start
Time relative to seizure termination (sec)
ΔHR from baseline (BPM)
D
Ictal ΔHR (bpm)
E
Ictal Tachycardia ΔHR (bpm)
F
Ictal Tachycardia Duration (sec)
G
Pre-ictal tachycardia (sec before seizure onset)
H
Ictal Bradycardia ΔHR (bpm)
I
Ictal Bradycardia Duration (sec)

Fig 2. Mice with hyperactive CRH neurons have greater ictal bradycardia than WT mice. A) example telemetry recordings of EEG (top) and heart rate (HR, bottom) during a spontaneous seizure in WT (left, gray) and *Kcc2/Crh* (right, blue) mice. Prior to seizure onset, HR began to rise (pre-ictal tachycardia, light green). During the seizure, elevated HR (ictal tachycardia, red) was interrupted by transient drops in HR (blue). *Kcc2/Crh* mice showed severe drops in HR during seizures. B) Qualitative representation of grouped average HR in reference to seizure termination. HR during seizures in WT (white shading) and *Kcc2/Crh* (Blue shading) were similar with *Kcc2/Crh* mice having more pronounced drops in HR right before seizure termination. C) Heatmap depicting grouped average change in HR relative to baseline in reference to seizure termination. *Kcc2/Crh* mice had a more pronounced drop in HR right before seizure termination. D-I, Summary data of mean ictal HR, ictal tachycardia magnitude, ictal tachycardia duration, pre-ictal tachycardia time of onset, ictal bradycardia magnitude, and ictal bradycardia duration. *Kcc2/Crh* mice had significantly greater magnitude and duration of ictal bradycardia compared to WT mice. Bars are group means ± SD,* $p < 0.05$ by unpaired t test.

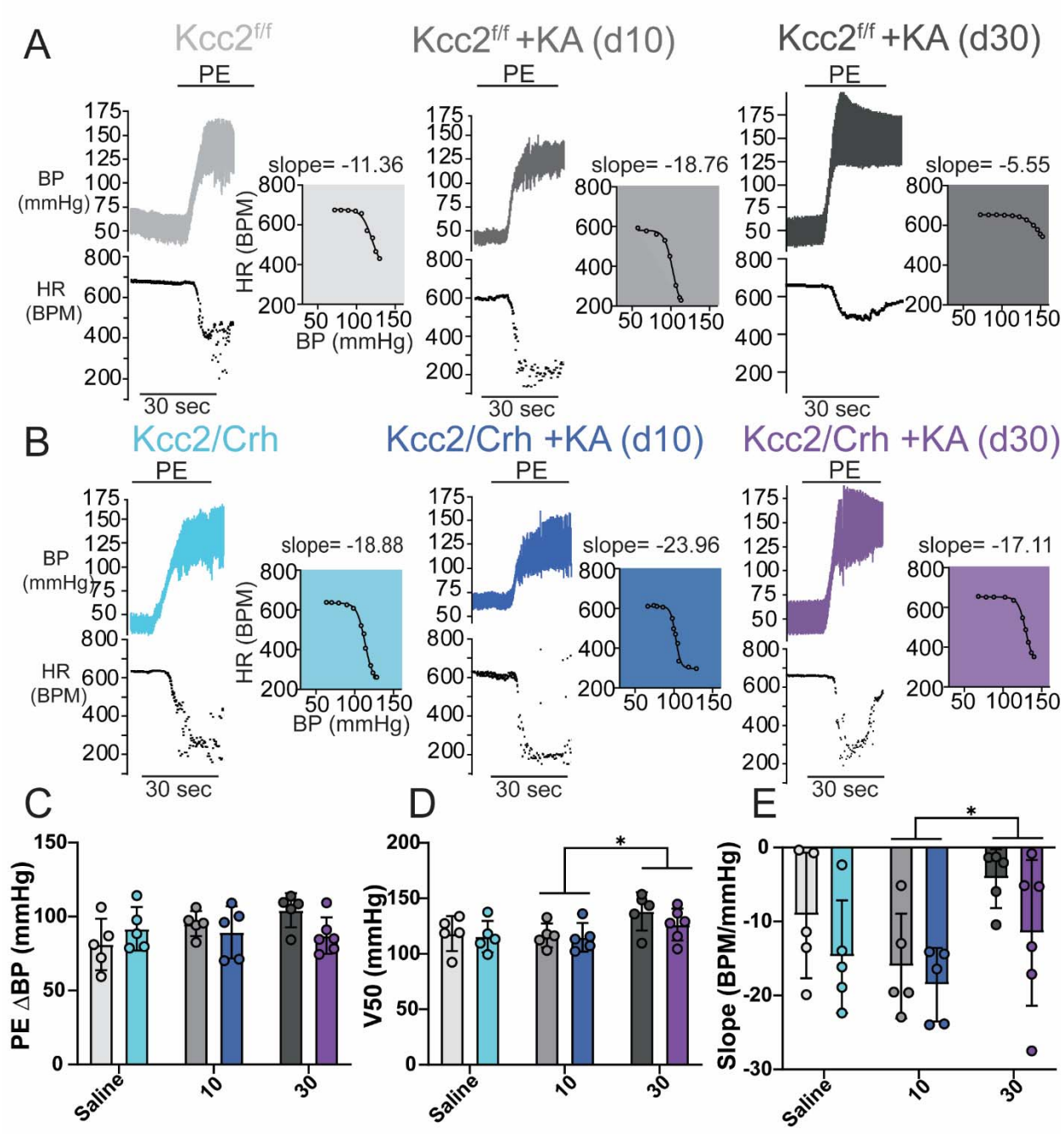
A
Kcc2f/f
Kcc2f/f +KA (d10)
Kcc2f/f +KA (d30)
PE
BP (mmHg)
HR (BPM)
30 sec
slope= -11.36
slope= -18.76
slope= -5.55
HR (BPM)
BP (mmHg)
B
Kcc2/Crh
Kcc2/Crh +KA (d10)
Kcc2/Crh +KA (d30)
slope= -18.88
slope= -23.96
slope= -17.11
C
PE ΔBP (mmHg)
D
V50 (mmHg)
E
Slope (BPM/mmHg)
Saline
10
30
*

Fig 3. WT mice have blunted baroreflex sensitivity 30 days after KA injection. A) Example blood pressure (BP, top) and heart rate (HR, bottom) recordings during jugular infusion of phenylephrine (PE) in WT (*Kcc2*$^{f/f}$) mice at 10 (middle, medium gray) and 30 (right, dark gray) days post KA or in saline-microinjected controls (left, light gray). B) Example BP (top) and HR (bottom) recordings during jugular infusion of PE in *Kcc2/Crh* mice either at 10 (middle, dark blue) and 30 (right, purple) days post KA or in saline-microinjected controls (left, light blue). In all experiments, infusion of PE caused a significant increase in BP and drop in HR. C) Summary data of PE-mediated increase in BP. D) Summary data of baroreflex set-point (V50). E) Summary data of baroreflex sensitivity that was determined via the slope of resulting curve from fit with modified Boltzmann equation. On day 30, baroreflex sensitivity was significantly blunted and V50 significantly increased compared to day 10, independent of genotype. Bars are group means ± SD, * $p < 0.05$ by two-way Anova and Tukey's post-hoc test.

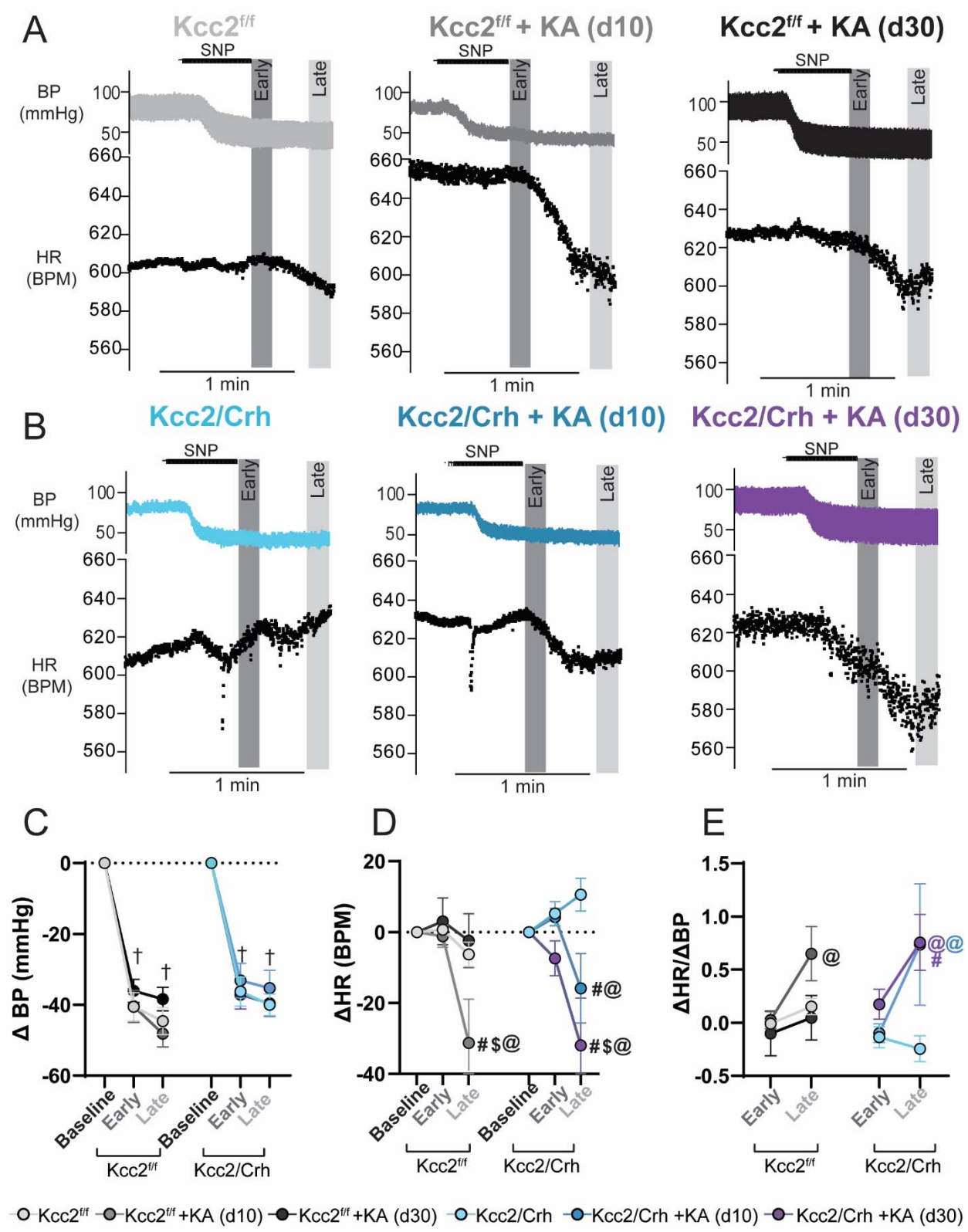
A
Kcc2f/f
Kcc2f/f + KA (d10)
Kcc2f/f + KA (d30)
SNP
Early
Late
BP (mmHg)
HR (BPM)
1 min
B
Kcc2/Crh
Kcc2/Crh + KA (d10)
Kcc2/Crh + KA (d30)
C
Δ BP (mmHg)
Baseline
Kcc2f/f
Kcc2/Crh
D
ΔHR (BPM)
#$@
#@
E
ΔHR/ΔBP
@
@@
#
Kcc2f/f
Kcc2f/f +KA (d10)
Kcc2f/f +KA (d30)
Kcc2/Crh
Kcc2/Crh +KA (d10)
Kcc2/Crh +KA (d30)

Fig 4. KA injection promotes robust time-dependent changes in paradoxical bradycardia. A) Example blood pressure (BP, top) and heart rate (HR, bottom) recordings during jugular infusion of sodium nitroprusside (SNP) in WT (*Kcc2*$^{f/f}$) mice at 10 (middle, medium gray) and 30 (right, dark gray) days post KA injection or in saline-injected controls (left, light gray). B) Example BP (top) and HR (bottom) recordings during jugular infusion of SNP in *Kcc2/Crh* mice either at 10 (middle, dark blue) and 30 (right, purple) days post KA injection or in saline-injected controls (left, light blue). In all experiments, infusion of SNP caused a decrease in BP. Changes in HR tended to occur in a biphasic manner, where an initial (early) increase in HR was often followed by a fall in HR (late). C) Summary data showing a significant and sustained drop in BP occurred following jugular infusion of SNP. D) Summary data of SNP-mediated change in HR, with WT mice having paradoxical bradycardia on day 10, and *Kcc2/Crh* mice having paradoxical bradycardia on both day 10 and day 30. E) Summary data of change in HR over change in BP shows HR changes more for a given change in BP in the late phase on day 10 in WT mice and day 10 and 30 in *Kcc2/Crh* mice. Symbols are group means ± SEM, † $p < 0.05$ compared to group baseline, # $p < 0.05$ compared to saline-injected sham control at the same time point, @ $p < 0.05$ compared to “early” in group, $ $p < 0.05$ compared to late WT d30; Analysis by repeated measures two-way ANOVA and Tukey’s post hoc.

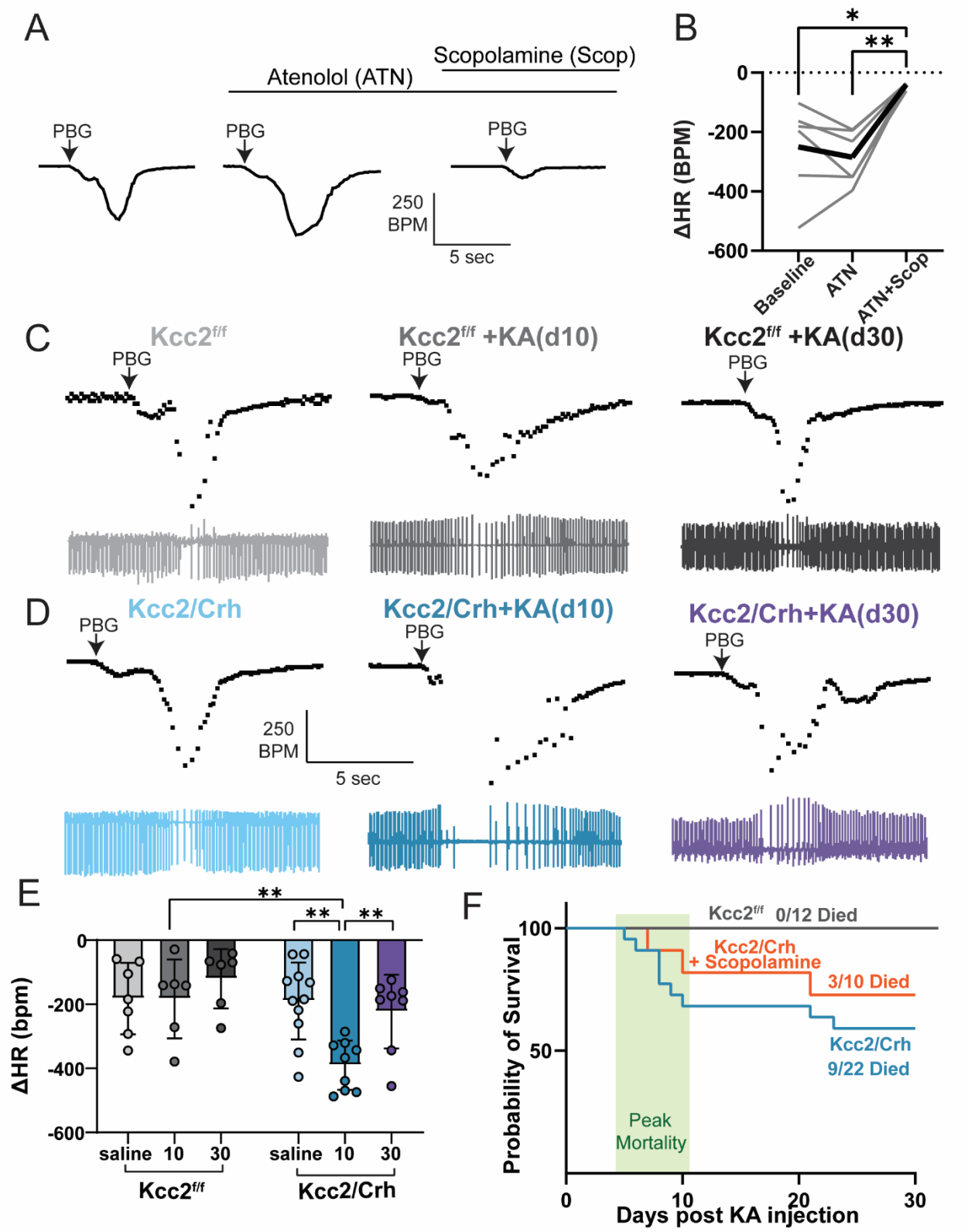
A
Atenolol (ATN)
Scopolamine (Scop)
PBG
PBG
PBG
250
BPM
5 sec
B
*
**
0
-200
-400
-600
ΔHR (BPM)
Baseline
ATN
ATN+Scop
C
Kcc2f/f
Kcc2f/f +KA(d10)
Kcc2f/f +KA(d30)
PBG
PBG
PBG
D
Kcc2/Crh
Kcc2/Crh+KA(d10)
Kcc2/Crh+KA(d30)
PBG
PBG
PBG
250
BPM
5 sec
E
**
**
**
0
-200
-400
-600
ΔHR (bpm)
saline
10
30
saline
10
30
Kcc2f/f
Kcc2/Crh
F
Kcc2f/f 0/12 Died
Kcc2/Crh
+ Scopolamine
3/10 Died
Kcc2/Crh
9/22 Died
Peak
Mortality
100
50
Probability of Survival
0
10
20
30
Days post KA injection

Fig 5. KA injection promotes robust time-dependent increase in BJR in mice with hyperactive CRH neurons, which contributes to a subset of SUDEP mortality. A) Example trace showing jugular infusion of phenylbiguanide (PBG) elicits the Bezold Jarisch Reflex (BJR), which is characterized by a transient decrease in heart rate (HR). The BJR is not blocked by IP administration of atenolol, but subsequent administration of scopolamine blocks the BJR. B) Summary data (bold line is average, individuals in small gray lines) showing the BJR is significantly decreased with administration of scopolamine and atenolol compared to atenolol alone or baseline by repeated measures one-way ANOVA with Tukey's post hoc test. C) Example ECG traces (bottom) with derived HR (top) during jugular infusion of PBG to elicit the BJR in WT (*Kcc2*$^{f/f}$, gray) at 10 (medium gray) and 30 (dark gray) days post KA injection or in saline injected controls (light gray). D) Example ECG traces(bottom) with derived HR (top) during jugular infusion of PBG to elicit the BJR in mice with hyperactive CRH neurons (*Kcc2/Crh*) at 10 (dark blue) and 30 (purple) days post KA injection or in saline-injected controls (light blue). E) Summary data of BJR-mediated change in HR over time. Two-way ANOVA and Tukey's post hoc revealed that *Kcc2/Crh* mice have a selective exaggeration of the BJR on day 10 that is attenuated on day 30.F) Following KA injection, 9/22 mice with hyperactive stress circuits died suddenly, with a peak in mortality occurring about a week post injection. WT mice are not susceptible to SUDEP (0/12 died). Chronic treatment with methylscopolamine attenuated SUDEP mortality (3/10 died) . Bars are group means ± SD, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

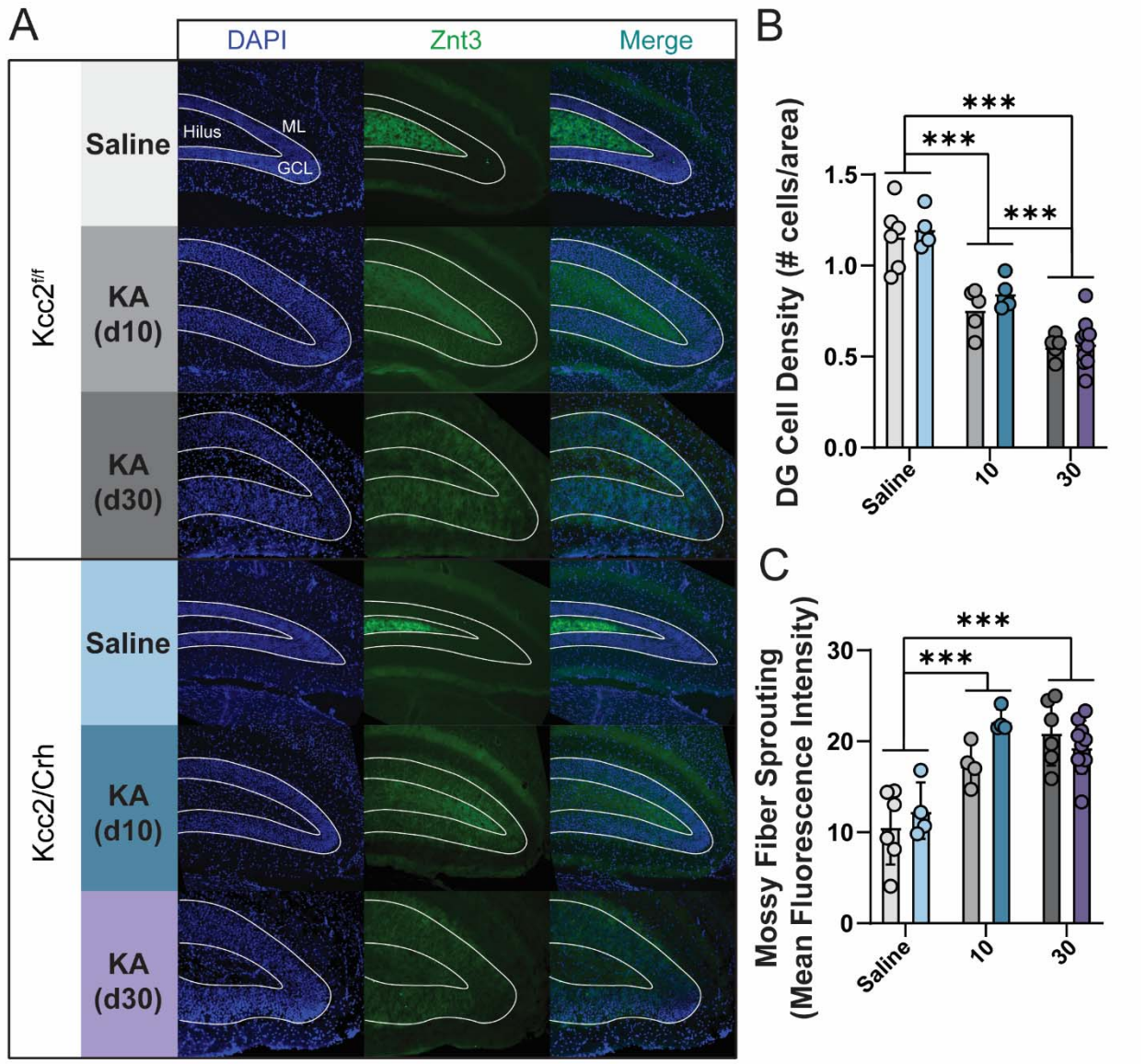

Fig 6. Hippocampal KA injection induces hallmark pathological features of Epilepsy in mice. A) Representative coronal sections of the hippocampus collected from WT mice (Kcc2$^{f/f}$) and mice with hyperactive stress circuits (Kcc2/Crh) at 10 and 30 days post KA injection, or in sham controls that were injected with saline in the hippocampus. DAPI (blue) stained cell nuclei and was used to quantify dentate granule (DG) cell dispersion (inverse of cell density). Znt3 (green) stained zinc rich mossy fibers which, in normal conditions, project through the hilus. Znt3 was used to quantify mossy fiber sprouting (MFS), or the sprouting of mossy fibers onto other dentate granule cells in the granule cell layer (GCL) and into the molecular layer (ML). B) Summary Data showing a significant increase in DG cell dispersion on day 10 compared to saline-injected controls, independent of genotype. On day 30, DG cell dispersion remained greater than saline-injected controls in collapsed groups. Finally, collapsed groups had

significantly increased DG cell dispersion on day 30 compared to day 10. C) Summary data showing a significant increase in MFS following KA injection. MFS on day 10 and 30 was significantly increased compared to saline-injected controls, independent of group. Bars are group means ± SD, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ by two-way ANOVA with Tukey's post hoc.

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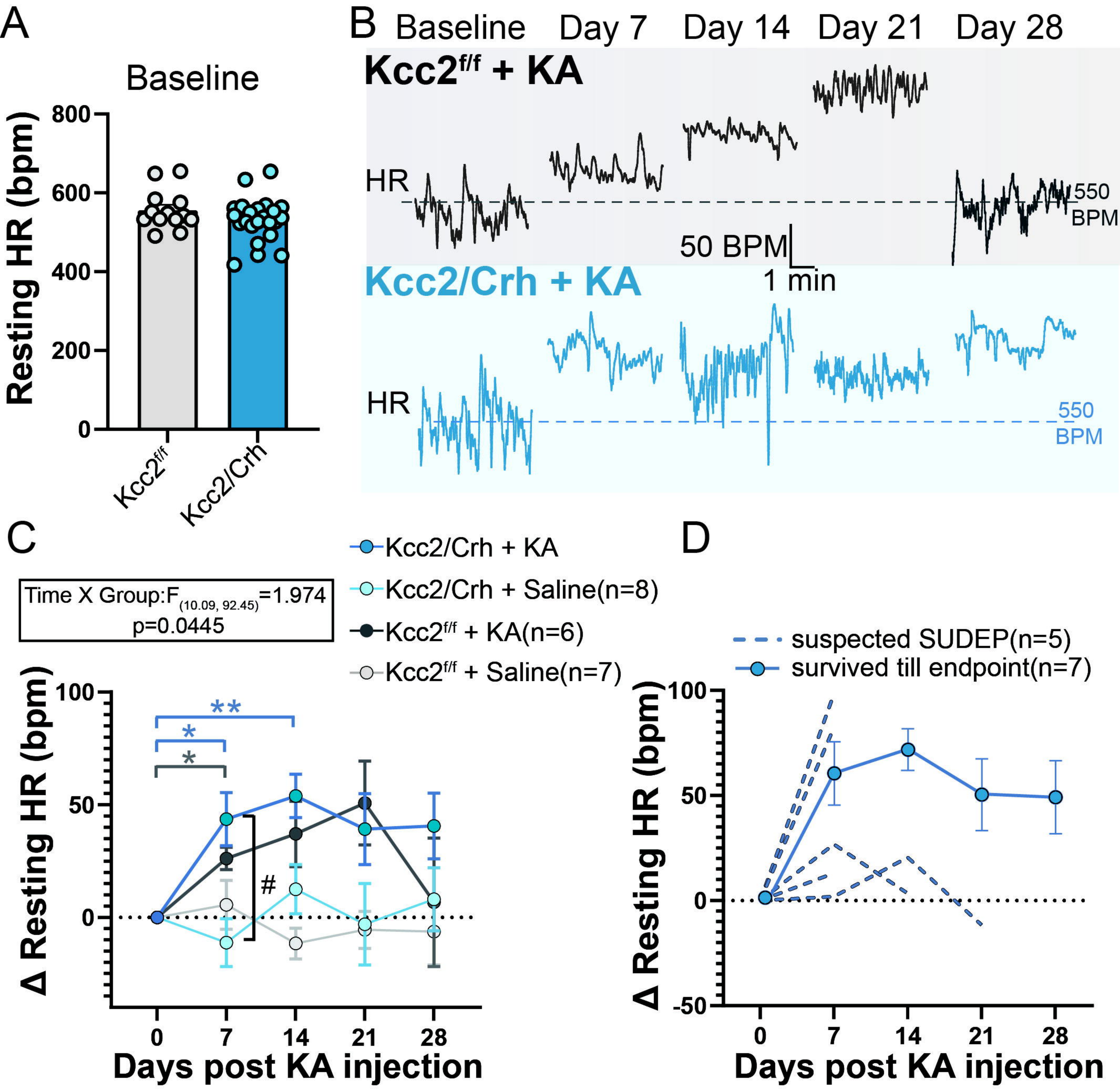
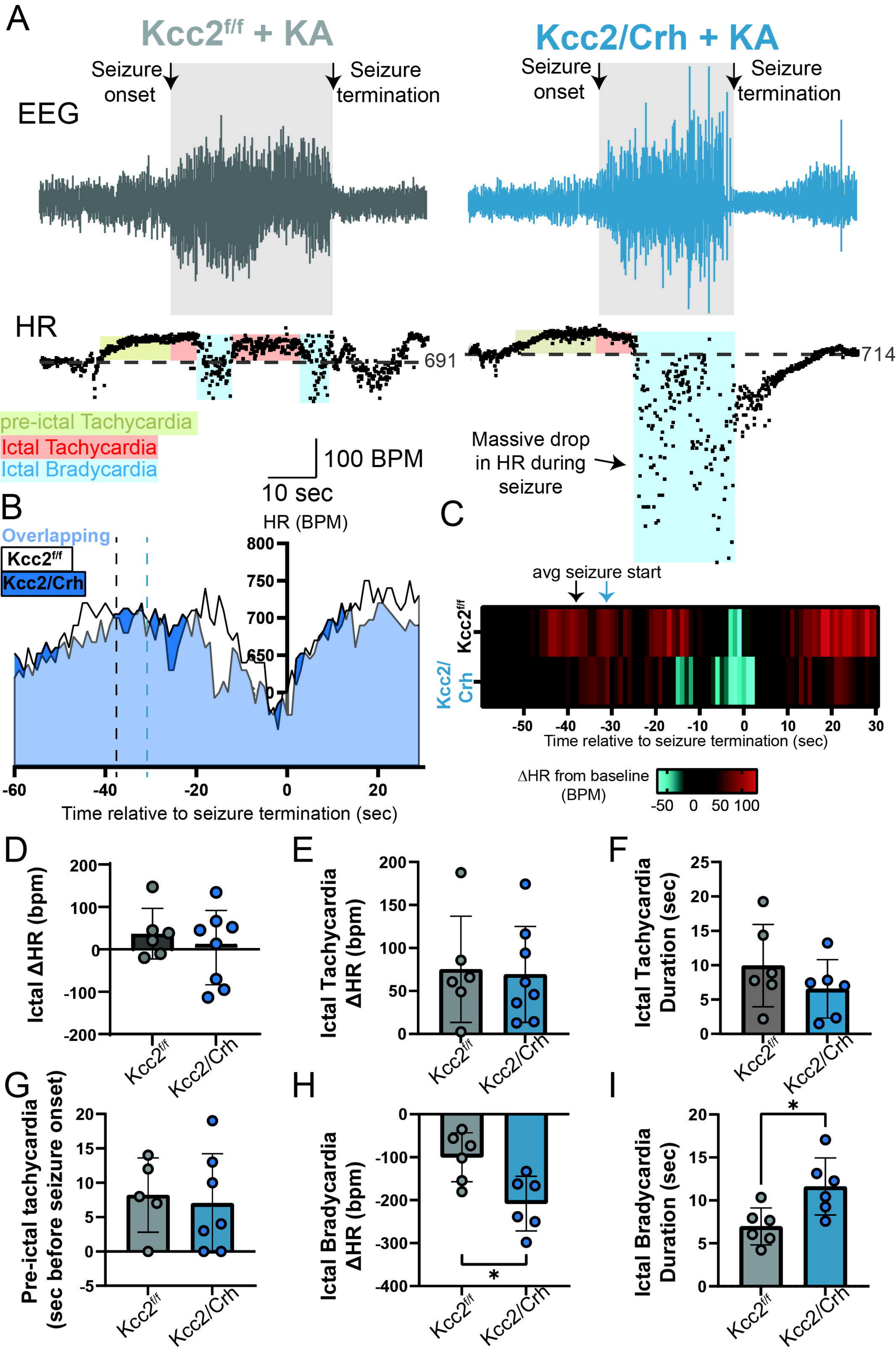
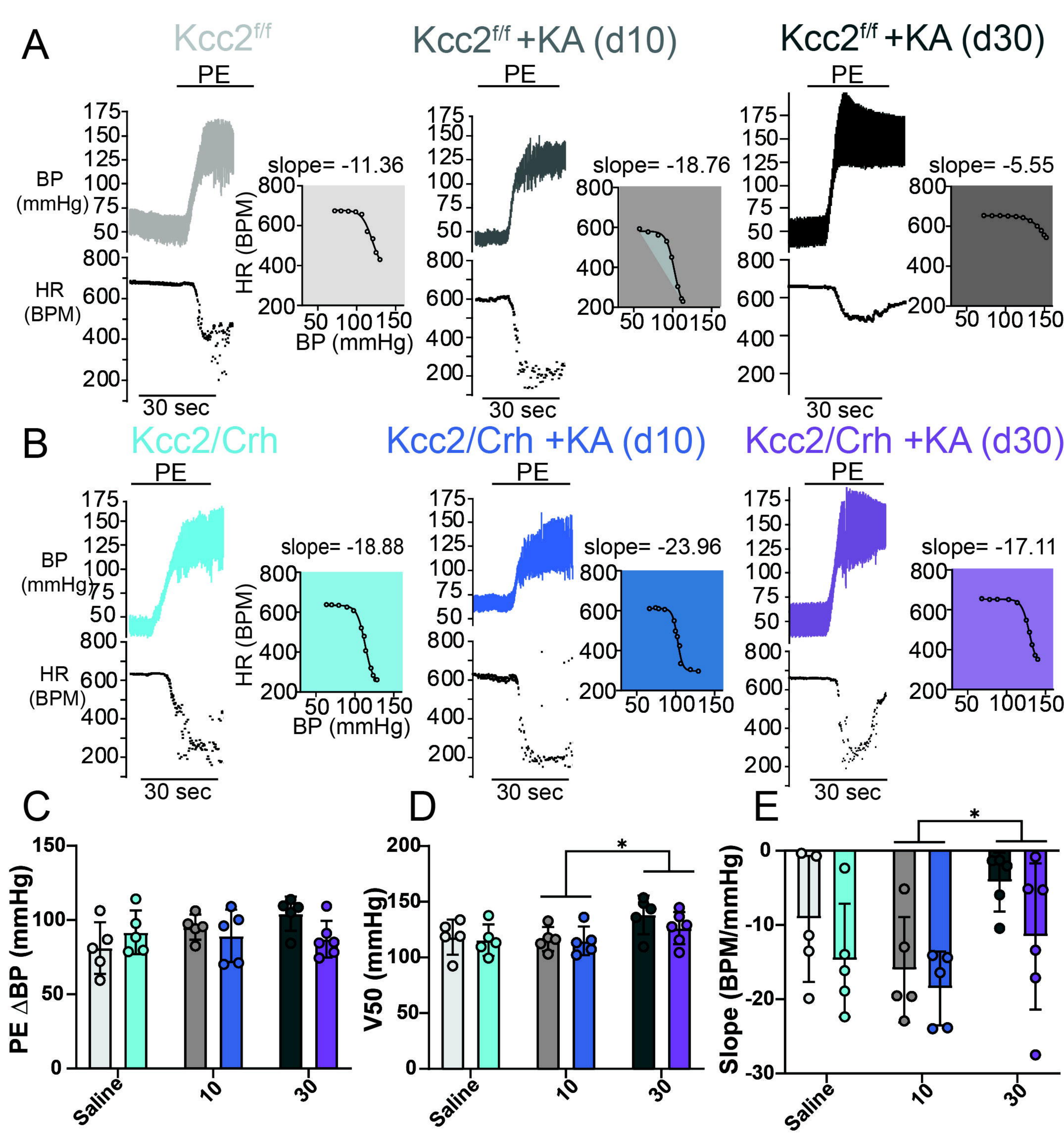
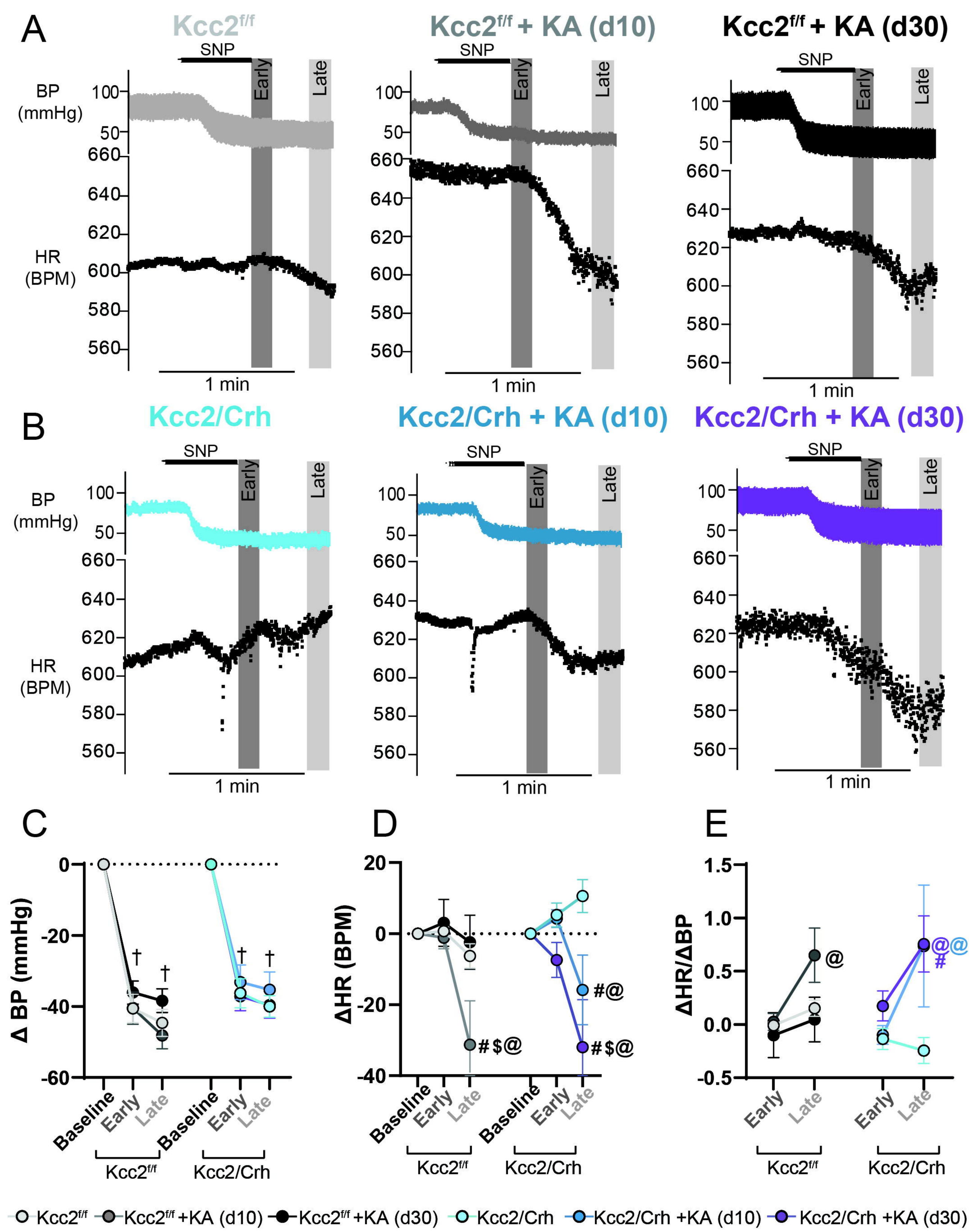
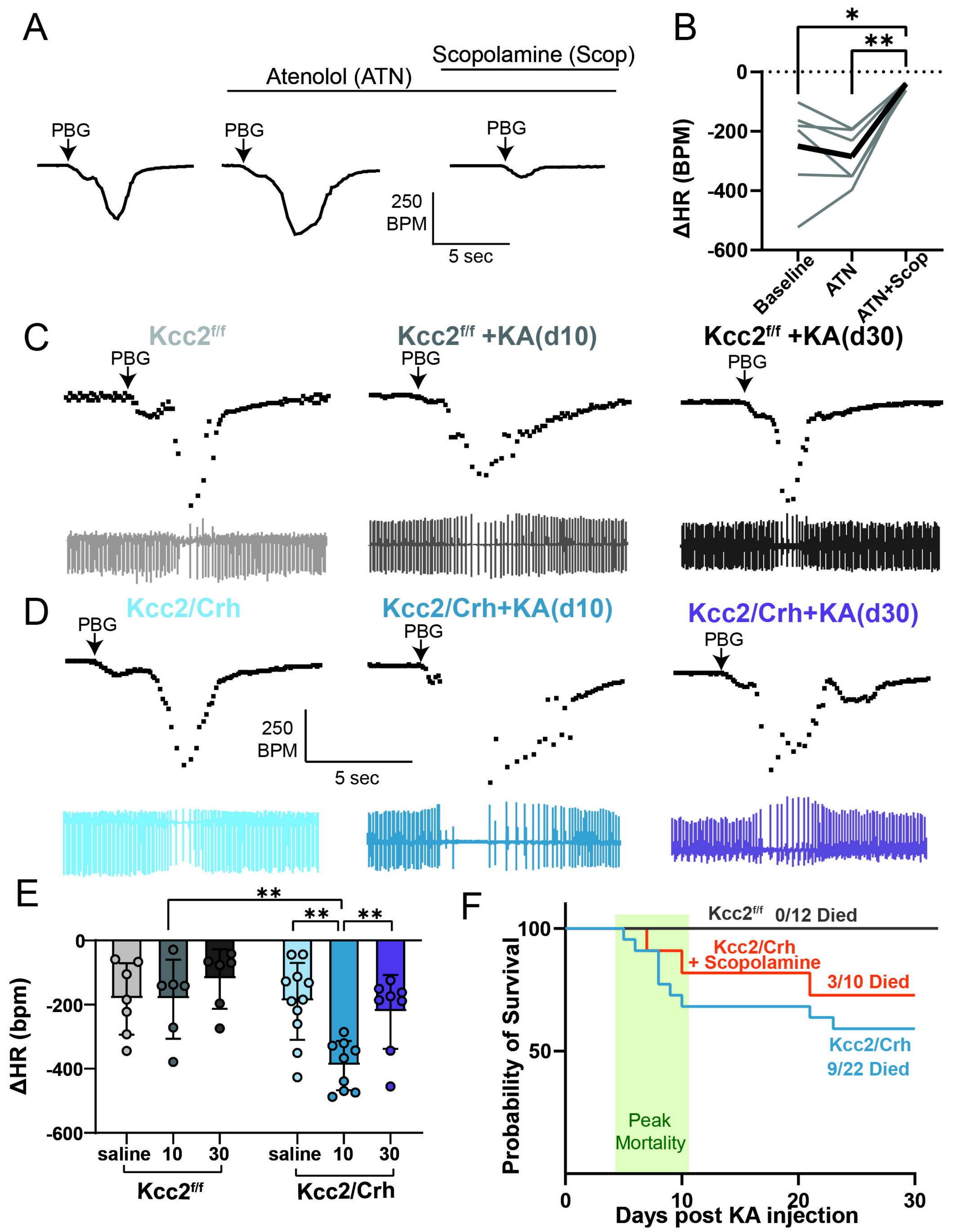
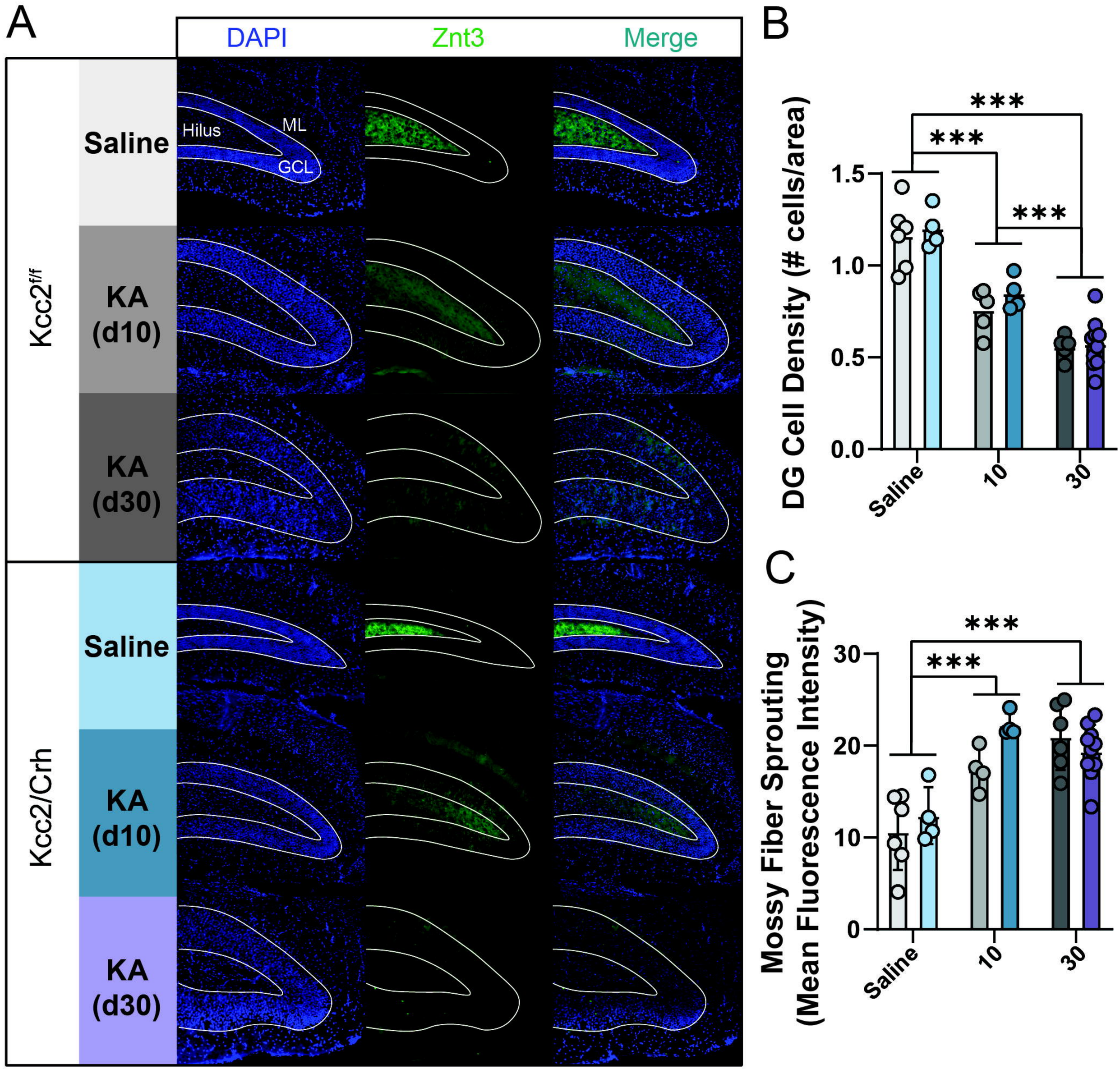

A
Baseline
Resting HR (bpm)
800
600
400
200
0
Kcc2f/f
Kcc2/Crh
B
Baseline
Day 7
Day 14
Day 21
Day 28
Kcc2f/f + KA
HR
550 BPM
50 BPM
1 min
Kcc2/Crh + KA
HR
550 BPM
C
Time X Group:F(10.09, 92.45)=1.974
p=0.0445
Kcc2/Crh + KA
Kcc2/Crh + Saline(n=8)
Kcc2f/f + KA(n=6)
Kcc2f/f + Saline(n=7)
Δ Resting HR (bpm)
100
50
0
**
*
*
#
0
7
14
21
28
Days post KA injection
D
suspected SUDEP(n=5)
survived till endpoint(n=7)
Δ Resting HR (bpm)
100
50
0
-50
0
7
14
21
28
Days post KA injection


A
Kcc2f/f + KA
Kcc2/Crh + KA
Seizure onset
Seizure termination
EEG
HR
691
714
pre-ictal Tachycardia
Ictal Tachycardia
Ictal Bradycardia
100 BPM
10 sec
Massive drop in HR during seizure
B
HR (BPM)
Overlapping
Kcc2f/f
Kcc2/Crh
800
750
700
650
-60
-40
-20
0
20
Time relative to seizure termination (sec)
C
avg seizure start
Kcc2f/f
Kcc2/Crh
-50
-40
-30
-20
-10
0
10
20
30
Time relative to seizure termination (sec)
ΔHR from baseline (BPM)
-50 0 50 100
D
Ictal ΔHR (bpm)
200
100
0
-100
-200
Kcc2f/f
Kcc2/Crh
E
Ictal Tachycardia ΔHR (bpm)
200
150
100
50
0
Kcc2f/f
Kcc2/Crh
F
Ictal Tachycardia Duration (sec)
25
20
15
10
5
0
Kcc2f/f
Kcc2/Crh
G
Pre-ictal tachycardia (sec before seizure onset)
20
15
10
5
0
-5
Kcc2f/f
Kcc2/Crh
H
Ictal Bradycardia ΔHR (bpm)
0
-100
-200
-300
-400
*
Kcc2f/f
Kcc2/Crh
I
Ictal Bradycardia Duration (sec)
20
15
10
5
0
*
Kcc2f/f
Kcc2/Crh


A
Kcc2f/f
Kcc2f/f +KA (d10)
Kcc2f/f +KA (d30)
PE
BP (mmHg)
HR (BPM)
30 sec
slope= -11.36
slope= -18.76
slope= -5.55
HR (BPM)
BP (mmHg)
B
Kcc2/Crh
Kcc2/Crh +KA (d10)
Kcc2/Crh +KA (d30)
slope= -18.88
slope= -23.96
slope= -17.11
C
PE ΔBP (mmHg)
Saline
10
30
D
V50 (mmHg)
*
E
Slope (BPM/mmHg)


A
Kcc2f/f
Kcc2f/f + KA (d10)
Kcc2f/f + KA (d30)
SNP
Early
Late
BP (mmHg)
HR (BPM)
1 min
B
Kcc2/Crh
Kcc2/Crh + KA (d10)
Kcc2/Crh + KA (d30)
C
Δ BP (mmHg)
Baseline
Early
Late
Kcc2f/f
Kcc2/Crh
D
ΔHR (BPM)
#$@
#@
E
ΔHR/ΔBP
@
@@
#
Kcc2f/f
Kcc2f/f +KA (d10)
Kcc2f/f +KA (d30)
Kcc2/Crh
Kcc2/Crh +KA (d10)
Kcc2/Crh +KA (d30)


A
Scopolamine (Scop)
Atenolol (ATN)
PBG
PBG
PBG
250
BPM
5 sec
B
*
**
0
-200
-400
-600
ΔHR (BPM)
Baseline
ATN
ATN+Scop
C
Kcc2f/f
Kcc2f/f +KA(d10)
Kcc2f/f +KA(d30)
PBG
PBG
PBG
D
Kcc2/Crh
Kcc2/Crh+KA(d10)
Kcc2/Crh+KA(d30)
PBG
PBG
PBG
250
BPM
5 sec
E
**
**
**
0
-200
-400
-600
ΔHR (bpm)
saline
10
30
saline
10
30
Kcc2f/f
Kcc2/Crh
F
Kcc2f/f 0/12 Died
Kcc2/Crh
+ Scopolamine
3/10 Died
Kcc2/Crh
9/22 Died
Peak
Mortality
100
50
Probability of Survival
0
10
20
30
Days post KA injection


A
DAPI
Znt3
Merge
Hilus
ML
GCL
Kcc2f/f
Saline
KA (d10)
KA (d30)
Kcc2/Crh
Saline
KA (d10)
KA (d30)
B
DG Cell Density (# cells/area)
***
***
***
1.5
1.0
0.5
0.0
Saline
10
30
C
Mossy Fiber Sprouting (Mean Fluorescence Intensity)
***
***
30
20
10
0
Saline
10
30