



HAL
open science

Anesthetic action on extra-synaptic receptors: effects in neural population models of EEG activity

Meysam Hashemi, Axel Hutt, Jamie Sleight

► To cite this version:

Meysam Hashemi, Axel Hutt, Jamie Sleight. Anesthetic action on extra-synaptic receptors: effects in neural population models of EEG activity. *Frontiers in Systems Neuroscience*, 2014, pp.1-19. hal-01088062

HAL Id: hal-01088062

<https://inria.hal.science/hal-01088062>

Submitted on 27 Nov 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



1

Anesthetic action on extra-synaptic receptors: effects in neural population models of EEG activity.

Meysam Hashemi¹, Axel Hutt^{1,*} and Jamie Sleigh²

¹INRIA CR Nancy - Grand Est, Team Neurosys, Villers-les-Nancy, France

²Department of Anaesthesiology, Waikato Clinical School, University of Auckland, Hamilton, New Zealand

Correspondence*:

Axel Hutt
INRIA CR Nancy - Grand Est, Team Neurosys, Villers-les-Nancy, France,
axel.hutt@inria.fr

General anesthesia: from theory to experiments

2 ABSTRACT

3 The role of extra-synaptic receptors in the regulation of excitation and inhibition in the brain
4 has attracted increasing attention. Because activity in the extra-synaptic receptors plays a role in
5 regulating the level of excitation and inhibition in the brain, they may be important in determining
6 the level of consciousness. This paper reviews briefly the literature on extra-synaptic GABA
7 and NMDA receptors and their affinity to anesthetic drugs. We propose a neural population
8 model that illustrates how the effect of the anesthetic drug propofol on GABAergic extra-
9 synaptic receptors results in changes in neural population activity and the electroencephalogram
10 (EEG). Our results show that increased tonic inhibition in inhibitory cortical neurons cause a
11 dramatic increase in the power of both δ and α bands. Conversely, the effects of increased tonic
12 inhibition in cortical excitatory neurons and thalamic relay neurons have the opposite effect and
13 decrease the power in these bands. The increased δ -activity is in accord with observed data
14 for deepening propofol anesthesia; but is absolutely dependent on the inclusion of extrasynaptic
15 (tonic) GABA action in the model.

16 **Keywords:** GABA receptor, neural mass, propofol, power spectrum, general anesthesia

1 INTRODUCTION

17 General anesthesia is used daily to enable surgery, but its underlying mechanisms of action are still
18 largely a mystery. In recent decades there have been successful efforts to reveal the drug action on
19 single receptors (1, 2, 3), however their effect on neural populations, networks of neural populations,
20 and brain areas, still remains unsolved. To explain the underlying neural mechanism during the loss
21 of consciousness, two prominent hypotheses are the loss of integration information, developed by
22 Tononi (4, 5, 6), and a sharp phase transition of the brain activity involving a drop of neural activity,
23 put forward by Steyn-Ross et al. (7, 8). These hypotheses are not mutually exclusive. For instance,
24 a recent experimental study on the effects of propofol on neural activity measured at various spatial
25 scales (9) has revealed both decreased functional connectivity between brain areas and a dramatic
26 drop of neuron firing rates after loss of consciousness. A large amount of experimental literature
27 has revealed characteristic spectral signal changes in electroencephalographic data (EEG) and Local

28 Field Potentials (LFPs) during general anesthesia (10, 11, 9, 12, 13). Moreover, several previous
29 theoretical studies have proposed neural models to explain certain EEG signal features observed during
30 anesthesia (14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25). Although these studies may incorporate realistic
31 neurobiological details of the brains' network topology and neuronal function, they have simplified
32 dramatically the anesthetic action by considering only synaptic excitatory and inhibitory receptors. There
33 is a growing amount of experimental research that has revealed the importance of extra-synaptic receptors
34 (ESR) for neural interactions in general (3, 26), and for anesthesia especially, see (27, 2) and references
35 therein.

36 To elucidate the role of ESR in the context of anesthesia, one approach might be to do a theoretical study
37 of a realistic neural population model which reproduces the characteristic signal features observed in EEG.
38 To perform such a theoretical study, it is necessary to incorporate physiological properties of extrasynaptic
39 receptors into neural population models.

40

41 Gamma-aminobutyric acid (GABA) receptors are a large and important class of ionotropic receptors.
42 These receptors are located in the neuron's membrane and respond to the neurotransmitter GABA by
43 opening Cl^- channels and inducing an inward hyperpolarising membrane current. This response may
44 either be: phasic at synaptic receptors or, tonic at ESR which lie distant from synaptic terminals (28, 29,
45 30, 31, 32, 33). The phasic response evolves on a time scale of 10–200 ms whereas tonic response evolves
46 on a much longer time scale (34, 35).

47 The precise biochemical origin of tonic inhibition is still heavily debated (36, 37). A rather simple and
48 intuitive model explains the tonic current as a spillover of excess neurotransmitter from synapses. This is
49 due to incomplete GABA uptake by nearby synaptic GABA_A -receptors. The remaining neurotransmitter
50 is thus able to diffuse to more distant GABA_A -receptors via extracellular space (36, 31, 38, 39). This
51 spillover may explain the longer time scale of tonic responses found experimentally. In addition, this
52 explanation implies that even small concentrations of neurotransmitters are sufficient to generate tonic
53 activity because of the high sensitivity of ESRs.

54 The effect of extra-synaptic receptors on the dendritic activity has not attracted much attention. This may
55 because there are only a relatively small number of such receptors as compared to synaptic receptors (40,
56 36). Moreover, only recently have experimental studies been able to classify and localize different sub-
57 types of GABA_A receptors (31, 36). GABA_A receptors are pentameric ligand-gated ion channels and it
58 has been found that δ -sub units of GABA_A receptors occur exclusively at ESRs (32, 36, 41, 42, 43). This
59 indicates a specific role of these receptors for the neural information processing in general with specific
60 implications in diseases (3) and consciousness (40).

61 Tonic inhibition induced by extra-synaptic GABA_A -receptors represents a persistent increase in the
62 cell membrane's conductance. On the single neuron level, this diminishes the membrane time constant
63 and, consequently, reduces the size and duration of excitatory post-synaptic potentials propagating on
64 the dendrite. Hence tonic inhibition reduces the excitability of the membrane and increases the effective
65 firing threshold (36). At the neural population level, extra-synaptic receptors affect the excitability of
66 interneuron-pyramidal cell networks and thus modify network oscillations (30). Kopanitsa (40) argues
67 that the sustained spatially widespread tonic inhibition is energetically more effective for the system to
68 diminish neural population activity than short-lasting local phasic inhibition, since lower neurotransmitter
69 concentrations are sufficient. The critical factor in this mechanism is the the relatively high sensitivity of
70 ESRs to modulations by anesthetic agents (36, 44, 28, 45). The brain areas that have been shown to be
71 affected by anesthetic-induced tonic inhibition are the hippocampus (46), brain stem (47), cerebellum (45)
72 and the thalamus (32). Since these areas are supposed to play a role in general anesthesia (2), extra-
73 synaptic receptors may mediate clinical anesthetic effects, such as hypnosis and amnesia (48). Thus it is
74 reasonable to argue that GABA_A ESRs set the background inhibition of neural populations and the brain
75 network and mediate slow consciousness phenomena, such as loss of consciousness, sleep or arousal (40).

76

77 Converse to GABAergic receptors, N-methyl-D-aspartate (NMDA) receptors respond to the
78 neurotransmitter glutamate by excitatory inward Na^+ and Ca^{2+} currents and K^+ outward currents. The

79 response of NMDA receptors to glutamate depends on their spatial location with respect to synaptic
80 terminals and the presence of co-agonists. A recent experimental study has revealed that the population
81 of NMDA receptors, which are close to synaptic terminals, are primarily activated by the co-agonist d-
82 serine in the presence of glutamate; while extra-synaptic NMDA receptors (more distant from the synaptic
83 terminals) respond primarily to glutamate and the co-agonist glycine (49, 50). D-serine and glycine are
84 endogenous amino acids found naturally in the brain (d-serine is a derivative of glycine). Similar to
85 GABAergic ESRs, it has been shown that there exists a significant ambient glutamate concentration which
86 induces a tonic excitatory current (51, 52). This current is evoked primarily at extra-synaptic NMDA
87 receptors (53) and may be regulated by other cells, such as neighbouring astrocytes (52, 54) which control
88 glutamate uptake and also synthesize d-serine (55).

89 Commonly-used GABAergic anesthetic drugs directly modify the corresponding receptors. However
90 various anesthetics are also known to affect the endogenous co-agonists of NMDA receptors (56, 49, 57).
91 Hence, the possible anesthetic effect on NMDA receptors is more complex and indirect than for
92 GABAergic ESRs. There is a large class of NMDA receptor antagonists, that inhibit the excitatory action
93 of NMDA receptors. These anesthetics induce so-called dissociative anesthesia (58) leading to amnesia
94 and analgesia without depressing respiration, but also characterised by distorted perceptions of sight and
95 sound and feelings of dissociation from the environment. An example of a dissociative anesthetic drug
96 is the inhalational anesthetic xenon which - amongst other actions - binds primarily to the extra-synaptic
97 glycine site of NMDA receptors (59) and attenuates long term potentiation present in the hippocampus by
98 reducing extrasynaptic receptor currents (60).

99

100 To understand how the anesthetic effect of extra-synaptic receptor activity on the microscopic single
101 neuron scale could lead to changes in EEG and behavior that can be observed at macroscopic scales, it
102 is necessary to establish a bridge between the two scales. This bridge may be formulated as a dynamical
103 theoretical model. Neural population models represent a good candidate for a dynamic description of
104 neural activity at an intermediate mesoscopic scale (61, 62, 63). These models describe properties of
105 ensembles of neurons, such as the mean firing rate and the mean dendritic current (64), whilst their output
106 variables can be strongly linked to macroscopic experimental quantities such as Local Field Potentials
107 (LFPs) and EEG (63, 65). An increasing number of theoretical studies have used neural population
108 models to describe signal features in LFPs and EEG observed during anesthesia (21, 17). Most of these
109 studies take into account anesthetic action on excitatory and/or inhibitory synapses (14, 66, 7, 67, 68)
110 while few consider extra-synaptic receptors (69). This link between the synaptic receptor properties in
111 an ensemble of neurons and the average population dynamics is straight-forward, since classical neural
112 population models already involve the average synaptic response function. The situation is different for
113 extra-synaptic receptors, since their action is not incorporated into the classical models. A very recent
114 work has filled this gap (24). This theoretical work demonstrated a method to include mathematically
115 extra-synaptic GABA_A receptor action in neural population models; which enables researchers to study
116 how changing anesthetic extra-synaptic receptor action modifies spectral features in the EEG, which might
117 then be observed experimentally.

118

119 The current work uses a cortico-thalamic neural population model involving anesthetic synaptic
120 inhibition with a well-established connection topology; and then extends this model by including the
121 effects of extra-synaptic GABAergic receptor action in the presence of the anesthetic drug propofol.
122 With the help of this model, we demonstrate the role of extra-synaptic GABAergic inhibition, and the
123 importance of tonic inhibition in the cortical inhibitory neuronal population, in explaining experimental
124 EEG power spectra.

2 MATERIAL & METHODS

EEG DATA

125 We re-analysed previously-obtained experimental data from subjects that had been given a short propofol
 126 anesthetic. The details of the methods can be found in (70). In brief, after obtaining regional ethical
 127 committee approval and written informed consent, five healthy subjects (mean age 27.7 yrs, four males)
 128 were studied. They were on no psychoactive drugs and had been starved for at least 6 hours prior to
 129 the study. They were monitored and managed as per clinical anesthesia, according to the Australia and
 130 New Zealand College of Anaesthetists best practice guidelines. The induction consisted of an intravenous
 131 infusion of propofol at 1500 mg/hr until the subject no longer responded to verbal command. Typically
 132 this occurred about 5 minutes into the infusion. The estimated effect-site concentrations of propofol were
 133 calculated using standard population-based pharmacokinetic models.

134 The EEG was acquired using the Electrical Geodesics 128 channel Ag/AgCl electrode system (Eugene,
 135 CO, USA) referenced to Cz. Electrode impedances were below 30 KOhm (100 MOhm input impedance
 136 amplifier). The sampling frequency was 250 Hz, with a 0.1 – 100 Hz analogue band pass filter, and A-D
 137 conversion was at 12 bits precision. The EEG data were re-referenced to a grand mean, and band-pass
 138 filtered using 3-rd order Butterworth filters 0.2 – 45 Hz to eliminate line-noise. An additional Whittaker
 139 filter was applied to reduce movement and blink artifacts. The power in each frequency was obtained
 140 applying a short-time Fourier transform with a moving window of 60 sec and 54 sec overlap. The power
 141 spectra have been computed 1 min before infusion start ($t = 1$ min) and 4 min after infusion ($t = 5$
 142 min). For visualization reasons, these power spectra at different time instances have been smoothed by a
 143 running average over frequencies with a 1 Hz window and a 0.017 Hz frequency step.

THALAMO-CORTICAL MODEL

144 The body of the model (71, 72) is based on a population-level description of a single thalamo-cortical
 145 module comprising four populations of neurons, namely excitatory (E) and inhibitory (I) cortical
 146 population, a population built of thalamo-cortical relay neurons (S) and of thalamic reticular neurons
 147 (R). The details of the model and the nominal parameter values are taken from a previous work (72, 73).
 148 This model is based on the original idea of Lopes da Silva et al., stating that the α -rhythm represents
 149 the noisy thalamic input signal band-pass filtered by feedback-connected cortical and thalamic neural
 150 populations (74). Here we just briefly describe the key concepts of the model. The average soma
 151 membrane potential denoted by V_a , for $a = E, I, S, R$ is modeled by

$$V_a(t) = \sum_{b=E,I,R,S} h_b(t) \otimes \nu_{ab} \phi_b(t - \tau_{ab}), \quad (1)$$

152 where \otimes represents the temporal convolution, $h_b(t) = H_b \bar{h}_b(t)$ where $\bar{h}_b(t)$ denotes the mean synaptic
 153 response function defined by

$$\bar{h}_b(t) = \frac{\alpha \beta_b}{\alpha - \beta_b} \left(e^{-\beta_b t} - e^{-\alpha t} \right), \quad (2)$$

154 and α and β_b (with units Hz) are the synaptic rise and decay rates of the synaptic response, respectively.
 155 The synaptic decay rates and synaptic response functions depend on the source neurons of type b only
 156 and are independent of the target neurons. The constant prefactor H_b defines the response function
 157 amplitude subject to the anesthetic concentration. Here, we assume identical excitatory synaptic receptors
 158 with constant rise and decay rate. Inhibitory synaptic receptors are also assumed to exhibit identical
 159 constant rise and decay rates while their decay rates depend on the anesthetic concentration. This strong
 160 approximation is taken from a previous study (68) to be able to compare our results, while preliminary

161 studies with more realistic parameters show similar results (not shown).
 162 The constants ν_{ab} are the strengths of the connections from population of type b to population of type a
 163 (in mVs), and ϕ_b is the average firing rate of the population b (in Hz). The connections between cortex
 164 and thalamus are associated with a same nonzero time delay, $\tau_{ab} = \tau$, while the delay term is assumed to
 165 be zero within the cortex and within the thalamus (75).

166 By virtue of long-range axonal projections of excitatory cortical neurons and by assuming the spatially-
 167 homogeneous dynamics on the cortex, the average firing rate ϕ_E obeys the damped oscillator equation

$$D\phi_E = S(V_E), \quad (3)$$

168 where the operator D is defined as

$$D = \left(\frac{1}{\gamma} \frac{\partial}{\partial t} + 1 \right)^2 \quad (4)$$

169 and γ is the cortical damping rate. It is assumed that the spatial spread of activity is very fast in other
 170 populations and the activity variable can be approximated by a sigmoidal function as $\phi_b = S(V_b)$, for
 171 $b = I, S, R$. Conversely to the original model (72, 73, 75) we use a more realistic transfer function
 172 derived from properties of type I-neurons given by (24)

$$S(V_a) = \text{Sig}(V_a, 0) - \text{Sig}(V_a, \rho), \quad (5)$$

173 with

$$\text{Sig}(V_a, \rho) = \frac{S_a^{max}}{2} \left(1 + \text{erf} \left(\frac{V_a - \theta_a - \rho\sigma^2}{\sqrt{2}\sigma} \right) \right) e^{-\rho(V_a - \theta_a) + \rho^2\sigma^2/2}, \quad (6)$$

174 with $\sigma = 10$ mV and $\rho = 0.08$ mV⁻¹, where σ is related to the standard deviation of firing thresholds, the
 175 parameter $\rho < \infty$ reflects the properties of type I-neurons, S_a^{max} is the maximum population firing rate,
 176 and θ_a is the mean firing threshold of neurons in population a . In contrast to the standard transfer function
 177 given in (72), the transfer function in Eq. (6) is not anti-symmetric to its inflection point anymore (27) and
 178 exhibits a larger nonlinear gain (slope) for large potentials $V_a > \theta_a$ compared to small potentials $V_a < \theta_a$.
 179 This asymmetry results from the firing properties of type-I neurons, see (24, 27) for more details. For
 180 $\rho \rightarrow \infty$, the sigmoid function becomes the conventional symmetric transfer function.

181 The external input to the system is considered as a non-specific input to thalamo-cortical relay neurons
 182 as

$$\phi_N = \langle \phi_N \rangle + \sqrt{2\kappa}\xi(t), \quad (7)$$

183 where $\langle \phi_N \rangle$ indicates its mean value and $\xi(t)$ is a zero average Gaussian white noise and κ is the noise
 184 intensity.

185 The power spectrum characterises small fluctuations about the resting state of the system defined by
 186 $dV_a(t)/dt = 0$. Following (63, 72), it is assumed that the activity of excitatory cortical neurons generates
 187 the EEG, and due to the specific choice of external input to thalamo-cortical relay neurons, the power
 188 spectrum of the EEG is related to the Greens function of linear deviations about the resting state by (25)

$$P_E(\omega) = 2\kappa\sqrt{2\pi} \left| \tilde{G}_{1,3}(\omega) \right|^2, \quad (8)$$

189 in which $P_E(\omega)$ depends just on one matrix component of the matrix Greens function $\tilde{G}(\omega)$, see the
 190 Appendix for its definition. We point out that the subsequent power spectrum analysis is based on
 191 Eq. (8) and changing a system parameter, such as the factor p , changes the resting state, the corresponding
 192 nonlinear gains and consequently the power spectrum. In addition, the power spectrum analysis is valid
 193 only if the resting state is stable and hence the fluctuations do not diverge. We have taken care of this
 194 additional condition and all given parameters guarantee the existence and stability of the resting state.

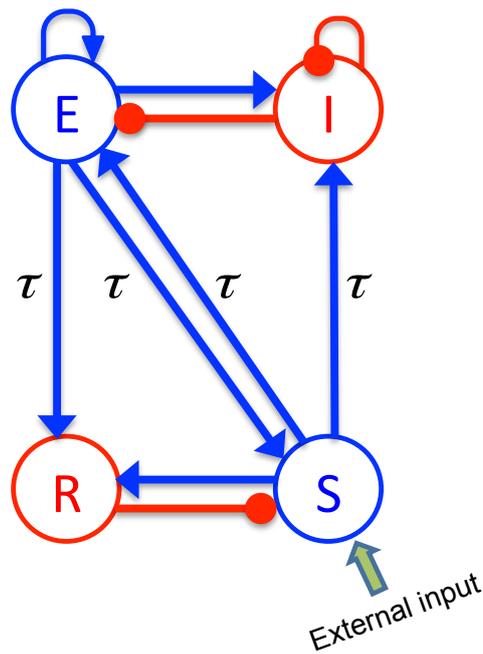


Figure 1. The schematic of a thalamo-cortical module. The blue arrows indicate excitatory connections while the red connections with filled circle ends denote inhibitory connections. The symbols E , I , S , and R denote the excitatory and inhibitory cortical neurons, thalamo-cortical relay, and thalamic reticular neurons respectively. In addition thalamocortical and corticothalamic connections exhibit the same nonzero time delay τ .

EFFECT OF PROPOFOL ON NEURAL POPULATIONS

195 In order to mimic anesthetic action, we consider the general anesthetic propofol which affects synaptic
 196 and extra-synaptic GABAergic receptors. We assume that the decay rate of inhibitory synapses is identical
 197 in all neural populations under study, and decreases with increasing propofol concentration in accordance
 198 with experimental findings (76, 67). Mathematically, such a dependence on the anesthetic concentration
 199 can be taken into account by a concentration factor $p \geq 1$ and $\beta_b = \beta_0/p$ while increasing p reflects an
 200 increase of the on-site concentration of propofol (21, 17, 68).

201 Since propofol has been shown to retain the amplitude of inhibitory synaptic response functions (76),
 202 one can define $H_b = \Gamma(\alpha, \beta_0)/\Gamma(\alpha, \beta_b)$ for $b = I, R$, where

$$\Gamma(\alpha, \beta) = \frac{\alpha\beta}{\alpha - \beta} \left[(\alpha/\beta)^{\frac{-\beta}{\alpha-\beta}} - (\alpha/\beta)^{\frac{-\alpha}{\alpha-\beta}} \right],$$

203 i.e., $\Gamma(\alpha, \beta_b) = \bar{h}_b(t_0)$ is the peak amplitude of $\bar{h}_b(t)$ at time $t_0 = \ln(\alpha/\beta_b)/(\alpha - \beta_b)$. Thereby the
 204 maximum height of $h_b(t)$ is $h_{max} = \Gamma(\alpha, \beta_0)$ which is independent of the action of propofol (68).
 205 Moreover, since it is assumed that propofol does not act on excitatory synaptic transmission, $H_b = 1$
 206 and $h_b(t) = \bar{h}_b(t)$ for $b = E, S$.

207 The GABAergic ESR tonic inhibition can be represented in the model as a constant shift of the firing
 208 threshold in neural population models (24). For simplicity, we assume a linear relationship between the
 209 anesthetic concentration parameter p and the extra-synaptic threshold shift

$$\theta_a = \theta_0 + (p - 1)k_a \quad (9)$$

210 with the unique firing threshold $\theta_0 = 15$ mV identical for all populations in the absence of propofol
 211 and the extra-synaptic anesthetic sensitivity $k_a > 0$. Here, $(p - 1)k_a$ is the tonic inhibition induced by

212 extra-synaptic action which depends linearly on the propofol concentration. Future experimental studies
 213 may motivate a more realistic relationship of threshold shift and the anesthetic concentration parameter.
 214 Summarizing, synaptic and extra-synaptic inhibition, and hence anesthetic action, is present in the cortical
 215 populations E and I and in the thalamic population of relay neurons S .

POWER SPECTRUM

216 The present study examines the effect of tonic inhibition in various populations E , I , S on the power
 217 spectrum of neural activity in cortical excitatory neurons, i.e., population E . We will focus on the power
 218 in the δ - and α - frequency ranges in the interval $[0.5\text{Hz}-4\text{Hz}]$ and $[8\text{Hz}-12\text{Hz}]$, respectively.
 219

220 The subsequent analysis reveals power peaks in these frequency ranges, whose magnitude changes with
 221 the level of tonic inhibition. These power peaks exhibit a maximum of power, expressed mathematically as
 222 a local maximum of the function $P_E(f)$ where P_E is taken from Eq. (8). The local maximum at frequency
 223 f_0 is defined as $dP_E/df = 0$, $d^2P_E/df^2 < 0$ computed at f_0 . If there is a local maximum of power in the
 224 δ - frequency range, then δ -activity is present, whereas a missing local maximum in the δ -frequency
 225 range indicates missing δ -activity. Since the magnitude and frequency of power peaks change with the
 226 propofol concentration and extra-synaptic threshold, the concentration factor p and the extra-synaptic
 227 anesthetic sensitivity k_a are the parameters of the power spectrum, i.e. $P_E = P_E(p, k_a, f)$.
 228

229 To illustrate the usefulness of this parametrization, let us assume a factor k_{a0} for which no δ -power
 230 peak exists in the power spectrum $P_E(p, k_{a0}, f)$, and k_{a1} , $k_{a1} > k_{a0}$ is the extra-synaptic anesthetic
 231 sensitivity leading to a spectral δ -power peak in $P_E(p, k_{a1}, f)$ with $dP_E(p, k_{a1}, f_{max})/df_{max} = 0$ where
 232 f_{max} is a frequency in the δ -frequency range. Mathematically, then the continuity of all model functions
 233 and variables guarantee that there is a threshold for the emergence of δ -activity at a certain extra-
 234 synaptic anesthetic sensitivity $k_{a,thr}$ with $k_{a0} \leq k_{a,thr} \leq k_{a1}$. Consequently, if a threshold extra-synaptic
 235 anesthetic sensitivity for δ -activity exists, then the variation of model variables about this critical point
 236 guarantees the emergence of δ -activity. This mathematical reasoning allows us to investigate conditions
 237 under which δ -activity may emerge.

3 RESULTS

238 Figure 2 illustrates how the EEG power spectrum depends on the concentration of propofol for a single
 239 subject. After starting the infusion at $t = 0$ min, the estimated propofol effect-site concentration
 240 increases gradually with time (Fig. 2(A)); resulting in increased power in the δ - and α -frequency ranges
 241 (Fig. 2(B)). Over the period of the spectrogram the subject has become progressively more sedated; until
 242 a $t = 5$ min the subject no longer responds to verbal command but would still be responsive to nociceptive
 243 stimuli. Figure 2(C) shows the power spectra in the awake and sedation conditions. We observe a power
 244 enhancement primarily in the δ - and α -frequency ranges.
 245

246 To understand how propofol might enhance δ - and α -power, we study the power spectrum of our
 247 theoretical model for different anesthetic concentration levels and examine the impact of adding tonic
 248 inhibition via extra-synaptic GABA_A receptors. Figure 3(A) shows the interaction between propofol and
 249 tonic inhibition in the cortical inhibitory neuronal population. If we set the tonic inhibition to zero ($k_I =$
 250 0mV), we observe a decrease in spectral power as propofol concentrations increase (i.e. the power moves
 251 from the black line to the blue line in the figure). If we set the tonic inhibition to $(p - 1) \cdot 15$ mV we
 252 see the opposite effect - there is an increase of δ - and α -power (black line to red line), with increasing
 253 propofol concentration.

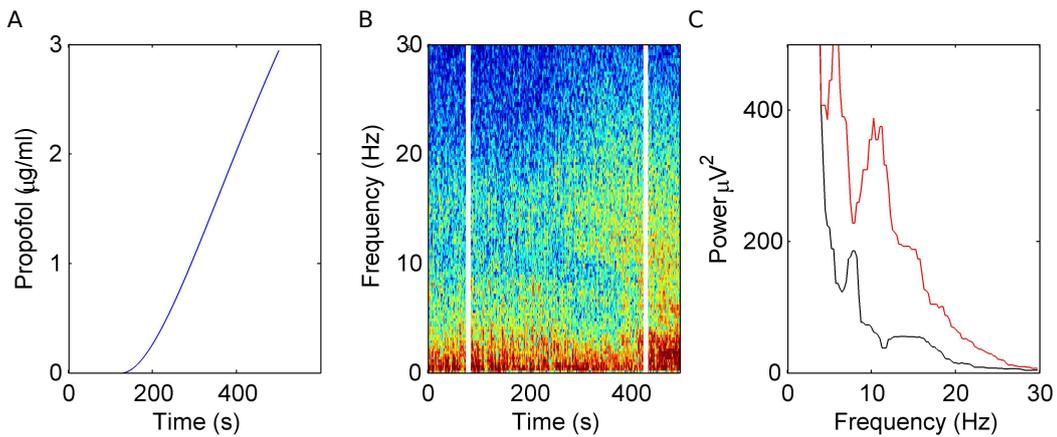


Figure 2. Electroencephalographic data observed under anesthesia sedation in a single subject while increasing the propofol concentration. (A) Blood plasma concentration of propofol with respect to administration time. (B) Spectrogram of frontal EEG power. The vertical lines denote time windows well before the administration (left line) and at about 5min after the start of propofol infusion (right side); (C) Power spectra computed before the infusion of propofol (black) and 5 min after the start of infusion (red).

254 Previous studies have indicated that extra-synaptic inhibition in thalamic relay neurons may control the
 255 level of inhibition in the brain (3). However Fig. 3(B) reveals that adding a non-zero tonic inhibition in
 256 the thalamic relay neurons causes a decrease in the spectral power, similar to the previous case of absent
 257 tonic inhibition in the inhibitory cortical neurons.

258 It is well-known that GABAergic anesthetics change the EEG from high frequency-low amplitude
 259 signals to low frequency-high amplitude signals (77, 78). Figure 3(C,D) show simulated time series in
 260 the absence and presence of tonic inhibition in cortical inhibitory cells reproducing this experimental
 261 finding.
 262

263 Our results elucidates that tonic inhibition in cortical interneurons and thalamic relay neurons affect
 264 the cortical power spectrum differently. This finding is similar to results of a previous computational
 265 neural population study of a cortico-thalamic feedback single-neuron model (69). Figure 4 shows how
 266 the resting membrane potential (Fig. 4(A)) and the nonlinear gain (Fig. 4(B)) in the cortical excitatory
 267 population change with differing extra-synaptic anesthetic sensitivity in cortical inhibitory neurons (k_I)
 268 and in the thalamic relay neurons (k_S). We observe that both the resting potential and the nonlinear gain
 269 of cortical excitatory neurons increase when the cortical inhibitory extra-synaptic anesthetic sensitivity
 270 k_I increases, whereas resting potential and nonlinear gain of cortical excitatory neurons decrease when
 271 the extra-synaptic anesthetic sensitivity in thalamic relay neuron k_S increases. Since the nonlinear gain
 272 is proportional to the systems responsiveness to external stimuli, the power enhancement in population I
 273 may be explained by the augmented responsiveness of the cortical excitatory neurons. This responsiveness
 274 depends on the sub-circuit in which the neurons are involved. Since relay neurons are part of the thalamo-
 275 cortical feedback loop, while cortical inhibitory neurons contribute to the cortical loop, the cell types
 276 respond differently to the thalamic input. Essentially assuming tonic inhibition in the population of
 277 cortical excitatory neurons E , the study reveals a similar propofol concentration dependence of the power
 278 spectrum, the resting state potential and the nonlinear gain as for the thalamic tonic inhibition S . This
 279 shows the unique tonic inhibition effect in the cortical inhibitory neurons.
 280

281 Figure 3(A) shows the power spectrum for single values of the extra-synaptic sensitivity k_I , for single
 282 values of the concentration factor p and fixed strength of self cortical inhibition ν_{ii} , while Fig. 4 gives more
 283 details on the role of extra-synaptic sensitivity for fixed values of the concentration factor p and fixed
 284 cortical self-inhibition. To understand better the interplay between tonic inhibition, synaptic inhibition

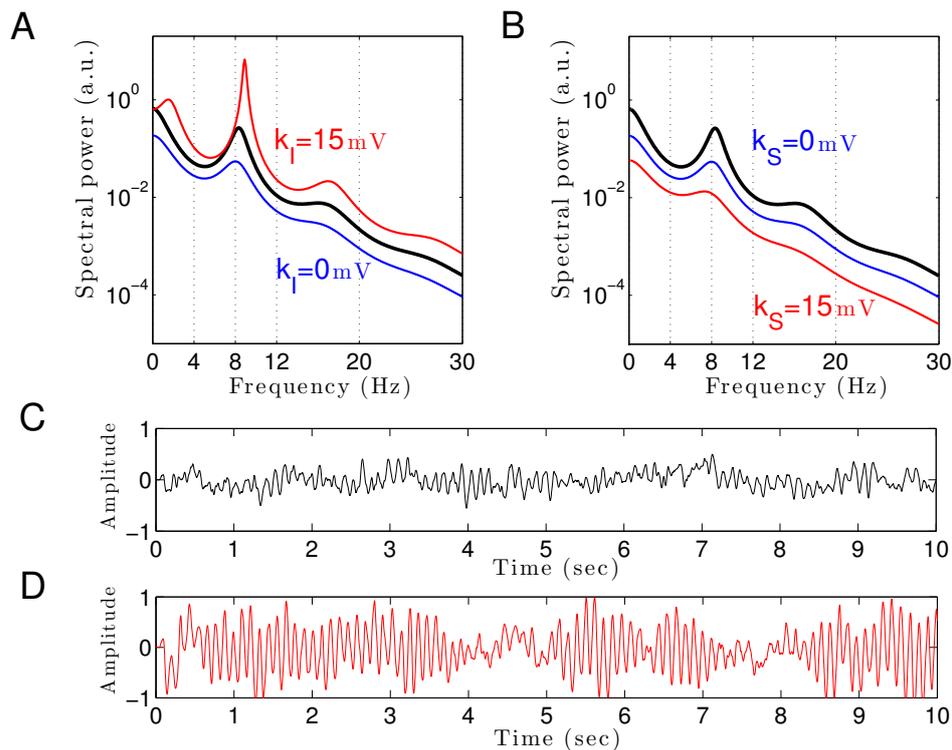


Figure 3. The theoretical EEG power spectrum in the baseline and in the sedation condition with and without tonic inhibition in the cortical inhibitory neurons I in (A) and the thalamic relay neurons S in (B) and corresponding simulated EEG time-series. In (A) the administration of propofol without tonic inhibition (blue line) attenuates the power spectrum compared to the baseline condition (black line) while the tonic inhibition (red line) increases the global power and generates oscillatory activity in the δ -frequency range. In (B) increasing the anesthetic concentration yields a global power decrease in the sedation condition without tonic inhibition (blue line) and a further power decrease in the presence of tonic inhibition (red line). In (A) and (B), the black lines indicate the EEG-spectral power in the baseline condition ($p = 1$), and the blue and red lines show the power spectrum in anesthesia condition ($p = 1.125$) in the absence ($k_a = 0$) and in the presence ($k_a = 15$ mV) of tonic inhibition, respectively. (C) The simulated EEG time-series ($\phi_E(t)$ defined in Eq. (3)) in the absence of extra-synaptic effects, i.e. $k_E = k_I = k_S = 0$ mV. (D) The EEG time-series in the presence of extra-synaptic action in cortical inhibitory neurons with $k_I = 15$ mV, $k_E = k_S = 0$ mV. The tonic inhibition changes the EEGs from low-amplitude, high-frequency pattern to high-amplitude, low-frequency pattern. In addition, the strength of self cortical inhibition is $\nu_{ii} = -1.8$ mVs.

285 and the strength of cortical self-inhibition, Figure 5 shows the parameter pairs of synaptic inhibition p
 286 and the threshold of extra-synaptic sensitivity $k_{I,thr}$ at different self-inhibition levels, for which a peak
 287 in the δ -frequency range emerges. Recall that the $k_{I,thr}$ is the critical (smallest) value of extra-synaptic
 288 sensitivity in cortical inhibitory neurons k_I , that lead to $dP_E/df = 0$, $d^2P_E/df^2 < 0$ computed at $f_{max} \in$
 289 δ -range, cf. the subsection on the power spectrum in section 2. Parameter values beyond the respective
 290 curves lead to δ -activity power peaks. We observe that δ -activity always emerges for sufficiently strong
 291 tonic inhibition (large extra-synaptic sensitivity k_I) and sufficiently strong self-inhibition ν_{ii} , while the
 292 weaker the self inhibition is the larger is the necessary extra-synaptic sensitivity or the synaptic inhibition
 293 to generate δ -activity. Even for vanishing self cortical inhibition ($\nu_{ii} = 0$), mathematical analysis (not
 294 shown) reveals that there is still a δ -peak in the power spectrum for large enough synaptic or tonic
 295 inhibition (for p or k_I large enough).

296 Moreover, Fig. 5 reveals a minimum tonic inhibition level (minimum value of k_I) beneath which no
 297 δ -power peak emerges, irrespective of the level of synaptic inhibition (p). This result indicates a major
 298 role of tonic inhibition in the generation of δ -activity, since it may support δ -activity even if the synaptic
 299 inhibition level is not sufficient to support it.

300

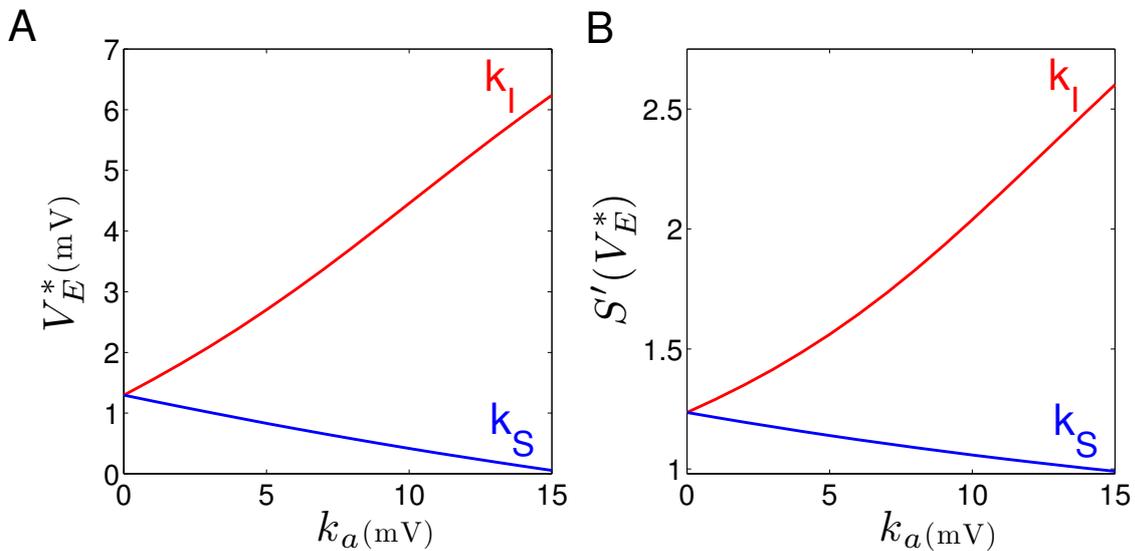


Figure 4. Increasing the tonic inhibition (factor k_a for $a = I$ and S) affects the resting state of excitatory cortical neurons V_E^* (A) and the corresponding nonlinear cortical gain function (B). Here the anesthetic concentration factor is identical in the populations $a = E, I$ and S to ($p = 1.125$). In addition, the strength of self cortical inhibition is $\nu_{ii} = -1.8$ mVs.

4 DISCUSSION

301 In the sedation phase, for modest concentrations of propofol, the EEG power spectrum exhibits an
 302 increase in the δ - and α -frequency ranges (Fig. 2) as found experimentally in the induction phase
 303 of propofol anesthesia (79). One possible explanation for these phenomena is by postulating stronger
 304 GABAergic potentiation within cortical inhibitory neurons than within cortical pyramidal neurons (68).
 305 We hypothesize, that cortical GABAergic self inhibition plays a decisive role. Figure 3 reveals that
 306 the power surge in these frequency ranges might also result from extra-synaptic tonic inhibition active
 307 in cortical inhibitory neurons. Tonic inhibition increases the firing threshold and hence diminishes the
 308 output of inhibitory neurons to excitatory cortical neurons, which then allows increased excitation in
 309 the excitatory population and a power surge in the EEG. Conversely tonic inhibition in the thalamic
 310 relay cells does not induce power surge in EEG since augmented inhibition in the thalamic relay cells
 311 yields diminished excitation in cortical excitatory neurons, leading to a decrease in EEG power. This
 312 interpretation is corroborated by Fig. 4 which demonstrates augmented and diminished nonlinear gain
 313 in cortical excitatory neurons assuming tonic inhibition in inhibitory and thalamic relay population,
 314 respectively. This reflects enhanced and weakened response to the noisy thalamic external input, see
 315 previous theoretical studies (68, 25) for a similar line of argument.

316 Figure 3 clearly reveals the emergence of δ -activity caused by extra-synaptic tonic inhibition which is
 317 affirmed by the existence of a minimum level of extra-synaptic inhibition shown in Fig. 5. Conversely,
 318 α -activity appears to be much less sensitive to tonic inhibition since it is present for all tonic inhibition
 319 levels. One interpretation may be the generation of α -activity by the cortico-thalamic feedback as
 320 hypothesized theoretically (80) while δ -activity results from the cortical interaction of excitatory
 321 and inhibitory neurons. The exact origins of propofol-induced α - and δ -activity are not known for
 322 certain. We find that the α oscillations arise from thalamocortical resonances. These oscillations are

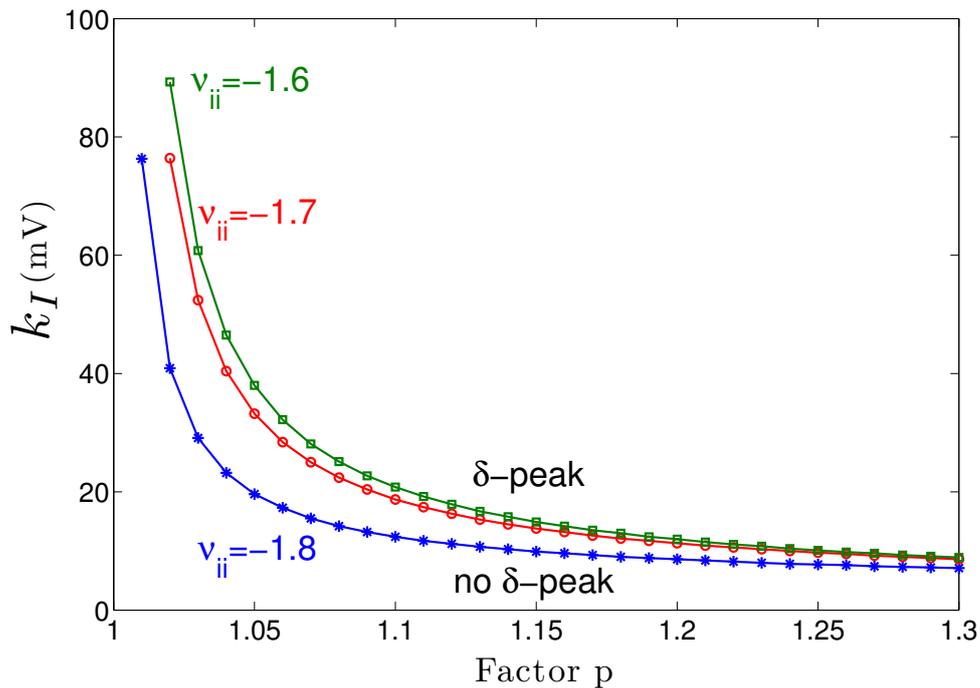


Figure 5. Parameter space for δ -power peak. The lines give the smallest (threshold) value of the extra-synaptic sensitivity $k_{I,thr}$ that induces δ -oscillations in the sedation condition with respect to the concentration factor p for different values of self-inhibitory connections ν_{ii} . The weaker the self cortical inhibition (the smaller $|\nu_{ii}|$), the higher the necessary level of propofol concentration (larger p) and the tonic inhibition (larger $(p-1) \cdot k_I$) to induce δ -activity.

323 commonly synchronous across widespread cortical regions and are not easily generated in isolated cortical
 324 tissue (81, 82). This affirms the original model of Lopes da Silva et al. (74). However, our model results
 325 are equivalent to results of other models describing α -activity by purely cortical interactions. We are
 326 not aware of a methodology ruling out one or the other model and this is not the aim of the present
 327 work. Our work just reveals the additional possibility that the thalamus serves as a possible (indirect)
 328 source of α -activity. Similarly, the origin of δ -activity is not clear, but slow activity does increase
 329 at higher concentrations of propofol - which may be associated with decreasing α -waves as observed
 330 during desflurane general anesthesia (83). This is in keeping with δ -waves becoming more pronounced
 331 as the cortico-thalamic systems becomes increasingly hyperpolarized. However there is a lot of variability
 332 between patients as regards the relative power of α - and δ -activity during general anesthesia; which
 333 would suggest that the true explanation is more complex, and requires recognition of other factors such as
 334 the one presented in this paper - the influence of the propofol on extra-synaptic inhibition.

335 Although anesthetic action on synaptic and extra-synaptic GABAergic receptors is different, both
 336 actions diminish neural activity and hence increase inhibition. Figure 5 elucidates that strong enough
 337 extra-synaptic or synaptic inhibition induce δ -activity. Hence, one may argue that the level of inhibition
 338 plays an important role while its origin, i.e. synaptic or extra-synaptic, plays a secondary role. This
 339 interpretation corroborates the idea of the balance of excitation and inhibition as the major mechanism
 340 in general anesthesia. This interpretation is in good accordance to previous experimental findings on the
 341 important role of the balance of excitation and inhibition in brain network under anesthesia (84, 85).
 342 Such global concepts as excitation-inhibition balance are attractive to describe complex processes in
 343 general anesthesia. For instance, anesthetics alter arousal in several pathways, such as the cholinergic
 344 pathway (86) and the orexinergic pathway which has been identified to activate a complex functional
 345 network controlling, inter alia, the emergence from unconsciousness (87).

346

347 Our theoretical study considers the anesthetic propofol and its corresponding action at synaptic and
 348 extra-synaptic GABAergic receptors only, whereas it is known that propofol induces inhibition at various
 349 other receptors as well (2, 88) including minor effects on NMDA-receptors and voltage-gated potassium
 350 channels (2). Propofol also potentiates glycine receptors which are found all over the central nervous
 351 system and have a major role in regulating inhibition, e.g., in the brain stem (89).

352 Similar to extra-synaptic inhibition resulting from ambient GABA concentrations, the presence of
 353 ambient concentrations of glycine close to NMDA-receptors entails tonic depolarization. This tonic
 354 excitation diminishes the firing threshold of neurons and hence may counteract inhibition. The present
 355 work considers tonic inhibition only and neglects tonic excitation effect. Although it would be important
 356 to study tonic excitation effects, this additional study would exceed the major aim of the manuscript,
 357 namely demonstrating the fundamental effect of tonic anesthetic action.

358 In addition, by virtue of the focus on extra-synaptic action, the model proposed neglects known
 359 anesthetic effects on different receptors and ion channels, although they have been shown experimentally,
 360 e.g. (2, 90) and references therein, and theoretically (91) to affect EEG activity. Specifically, the latter
 361 work of Bojak et al. (91) considers anesthetic effects on hyperpolarization-activated cyclic nucleotide-
 362 gated potassium channel 1 (HCN1) subunits which, effectively, increase the mean firing threshold in
 363 neural populations and strongly resembles the tonic inhibition induced by extra-synaptic GABA-receptors.

364 The model network topology includes a single module of a closed thalamo-cortical feedback loop (92)
 365 comprising two thalamic nuclei and cortical excitatory and inhibitory neurons. This model represents a
 366 first approximation of brain networks since it neglects brain stem activity including the reticular activating
 367 system (RAS) (93) which has significant modulating effects on attention, arousal and consciousness.
 368 Future work will include structures of the brain stem, propofol action on glycine receptors, and will take
 369 into account the RAS - since its neural structures involved exhibit strong extra-synaptic inhibition (94, 95,
 370 96). The model also neglects the cholinergic pathway originating from the basal forebrain (97) which is
 371 known to co-regulate the level of consciousness (86).

372 Essentially, our theoretical model assumes population coding implying rate-coding response activity
 373 of neuron populations subjected to external thalamic noise. The model does not consider specific single
 374 neuron dynamics found experimentally under anesthetic conditions. For instance, it has been hypothesized
 375 that, at certain levels of anesthetic concentration, thalamic neurons switch their activity from tonic firing
 376 to bursting and induce loss of consciousness (98).
 377

378 In spite of these limitations, our model reproduces qualitatively the action of propofol on EEG and
 379 reveals the possible impact of extra-synaptic GABAergic receptors on the EEG power. To our knowledge,
 380 the present work is the first to link extra-synaptic GABAergic action and experimental EEG. Future work
 381 will refine the model involving additional receptor action, e.g., tonic excitation caused by ambient glycine
 382 concentrations, and sub-cortical brain structures.

APPENDIX A. POWER SPECTRUM

383 The resting state (stationary state) of Eqs. (1) defined by $dV_a(t)/dt = 0$ obeys

$$\begin{aligned} V_E^* &= \nu_{ee}S(V_E^*) + H_b\nu_{ei}S(V_I^*) + \nu_{es}S(V_S^*), \\ V_I^* &= \nu_{ie}S(V_E^*) + H_b\nu_{ii}S(V_I^*) + \nu_{is}S(V_S^*), \\ V_S^* &= \nu_{se}S(V_E^*) + H_b\nu_{sr}S(V_R^*) + \langle\phi_N\rangle, \\ V_R^* &= \nu_{re}S(V_E^*) + \nu_{rs}S(V_S^*), \end{aligned} \quad (10)$$

384 where V_a^* denotes the resting state value of V_a for $a = E, I, S, R$. Moreover Eq. (3) gives $\phi_E^* = S(V_E^*)$.
 385 Then we linearize Eqs. (1) about the obtained resting state and write them in a general matrix form of a

386 linear DDE as

$$\hat{\mathbf{L}} \left(\frac{\partial}{\partial t} \right) \mathbf{X}(t) = \mathbf{A}\mathbf{X}(t) + \mathbf{B}\mathbf{X}(t - \tau) + \boldsymbol{\xi}(t), \quad (11)$$

where

$$\mathbf{X}(t) = \begin{pmatrix} \phi_E(t) - \phi_E^* \\ V_I(t) - V_I^* \\ V_S(t) - V_S^* \\ V_R(t) - V_R^* \end{pmatrix}, \quad \hat{\mathbf{L}} = \begin{pmatrix} \tilde{L} \frac{\tilde{D}}{K_{11}} & 0 & 0 & 0 \\ 0 & \tilde{L} & 0 & 0 \\ 0 & 0 & \tilde{L} & 0 \\ 0 & 0 & 0 & \tilde{L} \end{pmatrix},$$

$$\mathbf{A} = \begin{pmatrix} K_1 & K_2 & 0 & 0 \\ K_4 & K_5 & 0 & 0 \\ 0 & 0 & 0 & K_8 \\ 0 & 0 & K_{10} & 0 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 0 & 0 & K_3 & 0 \\ 0 & 0 & K_6 & 0 \\ K_7 & 0 & 0 & 0 \\ K_9 & 0 & 0 & 0 \end{pmatrix}, \quad \boldsymbol{\xi}(t) = \begin{pmatrix} 0 \\ 0 \\ \sqrt{2\kappa}\xi(t) \\ 0 \end{pmatrix}, \quad (12)$$

387 with $\tilde{L} = (1 + i\omega/\alpha)(1 + i\omega/\beta_0)$, $\tilde{D} = (1 + i\omega/\gamma)^2$, and

$$K_1 = \nu_{ee}, K_2 = H_b \nu_{ei} \frac{\partial S_I[V]}{\partial V} \Big|_{V=V_I^*}, K_3 = \nu_{es} \frac{\partial S_S[V]}{\partial V} \Big|_{V=V_S^*},$$

$$K_4 = \nu_{ie}, K_5 = H_b \nu_{ii} \frac{\partial S_I[V]}{\partial V} \Big|_{V=V_I^*}, K_6 = \nu_{is} \frac{\partial S_S[V]}{\partial V} \Big|_{V=V_S^*},$$

$$K_7 = \nu_{se}, K_8 = H_b \nu_{sr} \frac{\partial S_R[V]}{\partial V} \Big|_{V=V_R^*}, K_9 = \nu_{re},$$

$$K_{10} = \nu_{rs} \frac{\partial S_S[V]}{\partial V} \Big|_{V=V_S^*}, K_{11} = \frac{\partial S[V]}{\partial V} \Big|_{V=V_E^*}.$$

388 The power spectral density matrix $\mathbf{P}(\omega)$ of $\mathbf{X}(t)$ is the Fourier transform of the auto-correlation function
389 matrix $\langle \mathbf{X}(t)^t \mathbf{X}(t - T) \rangle$ (Wiener-Khinchine Theorem) leading to

$$\mathbf{P}(\omega) = 2\kappa \sqrt{2\pi} \tilde{\mathbf{G}}(\omega) \tilde{\mathbf{G}}^t(-\omega),$$

390 where $\tilde{\mathbf{G}}(\omega)$ is the Fourier transform of the matrix Greens function and the high index t denotes the
391 transposed matrix (25).

392 At the end, the model assumes that excitatory activity generates the EEG and by virtue of the specific
393 choice of external input to relay neurons, the power spectrum of the EEG depends just on one matrix
394 component of the Greens function by

$$P_E(\omega) = 2\kappa \sqrt{2\pi} \tilde{G}_{1,3}(\omega) \tilde{G}_{1,3}(-\omega) = 2\kappa \sqrt{2\pi} \left| \tilde{G}_{1,3}(\omega) \right|^2, \quad (13)$$

395 cf. Eq. (8), where

$$\tilde{\mathbf{G}}(\omega) = \frac{1}{\sqrt{2\pi}} [\hat{\mathbf{L}} - \mathbf{A} - \mathbf{B}e^{-i\omega\tau}]^{-1} = \frac{1}{\sqrt{2\pi}} \begin{bmatrix} \tilde{L} \frac{\tilde{D}}{K_{11}} - K_1 & -K_2 & -K_3 e^{-i\omega\tau} & 0 \\ -K_4 & \tilde{L} - K_5 & -K_6 & 0 \\ -K_7 e^{-i\omega\tau} & 0 & \tilde{L} & -K_8 \\ -K_9 e^{-i\omega\tau} & 0 & -K_{10} & \tilde{L} \end{bmatrix}^{-1}. \quad (14)$$

APPENDIX B. PARAMETER VALUES

The subsequent table gives the nominal values of model parameters.

Parameter	Symbol	Nominal value
Maximum firing-rate of all populations	S^{max}	250 Hz
Mean firing threshold of all populations	θ	15 mV
Firing rate variance of all populations	σ	10 mV
Type-I population effect constant of all populations	ρ	0.08 mV ⁻¹
Synaptic rise rate	α	200 s ⁻¹
Synaptic decay rate	β_0	50 s ⁻¹
Synaptic strength from E to E neurons	ν_{ee}	1.2 mVs
Synaptic strength from E to I neurons	ν_{ie}	1.2 mVs
Synaptic strength from E to S neurons	ν_{se}	1.2 mVs
Synaptic strength from E to R neurons	ν_{re}	0.4 mVs
Synaptic strength from I to I neurons	ν_{ii}	-1.8 mVs
Synaptic strength from I to E neurons	ν_{ei}	-1.8 mVs
Synaptic strength from S to E neurons	ν_{es}	1.2 mVs
Synaptic strength from S to I neurons	ν_{is}	1.2 mVs
Synaptic strength from S to R neurons	ν_{rs}	0.2 mVs
Synaptic strength from R to S neurons	ν_{sr}	-0.8 mVs
Mean value of external input	$\langle \phi_N \rangle$	1 mV
Intensity of external noise	κ	0.1 mV
Cortical damping rate	γ	150 s ⁻¹
Transmission delay between cortex and thalamus	τ	40 ms

396

DISCLOSURE/CONFLICT-OF-INTEREST STATEMENT

397 The authors declare that the research was conducted in the absence of any commercial or financial
398 relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

399 MH has chosen the model and performed the model analysis, AH has conceived the study and JS has
400 acquired and analyzed the experimental data. The authors have written the manuscript to equal parts and
401 have approved the final version.

ACKNOWLEDGEMENT

402 *Funding:* The research resulting to the presented work has received funding from the European Research
403 Council under the European Unions Seventh Framework Programme (FP7/2007-2013) / ERC grant
404 agreement no. 257253.

REFERENCES

- 405 1. Franks N, Lieb W. Molecular and cellular mechanisms of general anesthesia. *Nature* **367** (1994)
406 607–614.
- 407 2. Alkire M, Hudetz A, Tononi G. Consciousness and anesthesia. *Science* **322** (2008) 876–880. doi:10.
408 1126/science.1149213.
- 409 3. Brickley SG, Mody S. Extrasynaptic GABA_A receptors: Their function in the CNS and implications
410 for disease. *Neuron* **73** (2012) 23–34.
- 411 4. Murphy M, Bruno MA, Riedner BA, Boveroux P, Noirhomme Q, Landsness EC, et al. Propofol
412 anesthesia and sleep: A high-density EEG study. *Sleep* **34** (2011) 283–291.
- 413 5. Boly M, Moran R, Murphy M, Boveroux P, Bruno MA, Noirhomme Q, et al. Connectivity changes
414 underlying spectral EEG changes during propofol-induced loss of consciousness. *J. Neurosci.* **32**
415 (2012) 7082–7090.
- 416 6. Tononi G. An information integration theory of consciousness. *BMC Neurosci.* **5** (2004) 42.
- 417 7. Steyn-Ross M, Steyn-Ross D, Sleight J. Modelling general anaesthesia as a first-order phase transition
418 in the cortex. *Prog. Biophys. Molec. Biol.* **85** (2004) 369–385.
- 419 8. Friedman EB, Sun Y, Moore JT, Hung HT, Meng QC, Perera P, et al. A conserved behavioral state
420 barrier impedes transitions between anesthetic-induced unconsciousness and wakefulness: Evidence
421 for neural inertia. *PLoS ONE* **5** (2010) e11903.
- 422 9. Lewis L, Weiner V, Mukamel E, Donoghue J, Eskandar E, Madsen J, et al. Rapid fragmentation of
423 neuronal networks at the onset of propofol-induced unconsciousness. *Proc Natl Acad Sci USA* **109**
424 (2012) E3377–3386.
- 425 10. Cimenser A, Purdon PL, Pierce ET, Walsh JL, Salazar-Gomez AF, Harrell PG, et al. Tracking brain
426 states under general anesthesia by using global coherence analysis. *Proc. Natl. Acad. Sci. USA* **108**
427 (2011) 8832–8837.
- 428 11. Purdon PL, Pierce ET, Mukamel EA, Prerau MJ, Walsh JL, Wong KF, et al. Electroencephalogram
429 signatures of loss and recovery of consciousness from propofol. *Proc. Natl. Acad. Sci. USA* **110**
430 (2012) E1142–1150.
- 431 12. Sellers KK, Bennett DV, Hutt A, Frohlich F. Anesthesia differentially modulates spontaneous network
432 dynamics by cortical area and layer. *J. Neurophysiol.* **in press** (2013).
- 433 13. Vizuete J, Pillay S, Ropella K, Hudetz A. Graded defragmentation of cortical neuronal firing during
434 recovery of consciousness in rats. *Neuroscience* **275** (2014) 340–351.
- 435 14. Ching S, Cimenser A, Purdon PL, Brown EN, Kopell NJ. Thalamocortical model for a propofol-
436 induced-rhythm associated with loss of consciousness. *Proc. Natl. Acad. Sci. USA* **107** (2010) 22665–
437 22670.
- 438 15. Ching S, Purdon PL, Vijayand S, Kopell NJ, Brown EN. A neurophysiological/metabolic model for
439 burst suppression. *Proc. Natl. Acad. Sci. USA* **109** (2012) 3095–3100.
- 440 16. McCarthy MM, Brown EN, Kopell N. Potential network mechanisms mediating
441 electroencephalographic beta rhythm changes during propofol-induced paradoxical excitation.
442 *J. Neurosci.* **28** (2008) 13488–13504.
- 443 17. Hutt A, Sleight J, Steyn-Ross A, Steyn-Ross ML. General anaesthesia. *Scholarpedia* **8** (2013) 30485.
- 444 18. Steyn-Ross M, Steyn-Ross D, Sleight JW, Liley DTJ. Theoretical electroencephalogram stationary
445 spectrum for a white-noise-driven cortex: Evidence for a general anesthetic-induced phase transition.
446 *Phys. Rev. E* **60** (1999) 7299–7311.
- 447 19. Wilson M, Sleight J, Steyn-Ross A, Steyn-Ross M. General anesthetic-induced seizures can be
448 explained by a mean-field model of cortical dynamics. *Anesthesiol.* **104** (2006) 588–593.
- 449 20. Steyn-Ross M, Steyn-Ross D, Sleight J. Interacting Turing-Hopf instabilities drive symmetry-breaking
450 transitions in a mean-field model of the cortex: A mechanism for the slow oscillation. *Phys. Rev. X* **3**
451 (2013) 021005.
- 452 21. Foster B, Bojak I, Liley DJ. Population based models of cortical drug response: insights from
453 anaesthesia. *Cogn. Neurodyn.* **2** (2008) 283–296.
- 454 22. Liley D, Walsh M. The mesoscopic modeling of burst suppression during anesthesia. *Front. Comput.*
455 *Neurosci.* **7** (2013) 46.

- 456 **23** .Bojak I, Liley D. Modeling the effects of anesthesia on the electroencephalogram. *Phys. Rev. E* **71**
457 (2005) 041902.
- 458 **24** .Hutt A, Buhry L. Study of GABAergic extra-synaptic tonic inhibition in single neurons and neural
459 populations by traversing neural scales: application to propofol-induced anaesthesia. *J. Comput.*
460 *Neurosci.* **37** (2014) 417–437.
- 461 **25** .Hutt A. The anaesthetic propofol shifts the frequency of maximum spectral power in EEG during
462 general anaesthesia: analytical insights from a linear model. *Front. Comp. Neurosci.* **7** (2013) 2.
- 463 **26** .Hardingham GE, Bading H. Synaptic versus extrasynaptic nmda receptor signalling: implications for
464 neurodegenerative disorders. *Nature Rev. Neurosci.* **11** (2012) 682–696.
- 465 **27** .Hutt A. The population firing rate in the presence of GABAergic tonic inhibition in single neurons
466 and application to general anaesthesia. *Cogn. Neurodyn.* **6** (2012) 227–237.
- 467 **28** .Yeung JYT, Canning KJ, Zhu G, Pennefather P, Macdonald JF, Orser BA. Tonicly activated GABAA
468 receptors in hippocampal neurons are high-affinity, low-conductance sensors for extracellular gaba.
469 *Molec. Pharmacol.* **63** (2003) 2–8.
- 470 **29** .Brickley SG, Cull-Candy SG, Farrant M. Development of a tonic form of synaptic inhibition in rat
471 cerebellar granule cells resulting from persistent activation of GABAA receptors. *J. Physiol.* **497**
472 (1996) 753–759.
- 473 **30** .Semyanov A, Walker MC, Kullmann DM. Gaba uptake regulates cortical excitability via cell-type
474 specific tonic inhibition. *Nat. Neurosci.* **6** (2003) 484–490.
- 475 **31** .Semyanov A, Walker MC, Kullmann DM, Silver RA. Tonicly active GABAA receptors: modulating
476 gain and maintaining the tone. *Trends Neurosci.* **27** (2004) 262–269.
- 477 **32** .Belelli D, Harrison NL, Maguire J, Macdonald RL, Walker MC, Cope DW. Extra-synaptic GABAA
478 receptors: form, pharmacology, and function. *J. Neurosci.* **29** (2009) 12757–12763.
- 479 **33** .Kaneda M, Farrant M, Cull-Candy SG. Whole-cell and single-channel currents activated by GABA
480 and glycine in granule cells of the rat cerebellum. *J. Physiol.* **485** (1995) 419–435.
- 481 **34** .Cavalier P, Hamann M, Rossi D, Mobbs P, Attwell D. Tonic excitation and inhibition of neurons:
482 ambient transmitter sources and computational consequences. *Prog. Biophys. Mol. Biol.* **87** (2005)
483 3–16.
- 484 **35** .Hamann M, Rossi D, Attwell D. Tonic and spillover inhibition of grnule cells control information
485 flow through cerebellar cortex. *Neuron* **33** (2002) 625–633.
- 486 **36** .Farrant M, Nusser Z. Variations on an inhibitory theme: phasic and tonic activation of GABAA
487 receptors. *Nature Rev. Neurosci.* **6** (2005) 215–229.
- 488 **37** .Bright DP, Renzi M, Bartram J, McGee TP, MacKenzie G, Hosie AM, et al. Profound desensitization
489 by ambient GABA limits activation of delta-containing GABAA receptors during spillover. *J.*
490 *Neurosci.* **31** (2011) 753–763.
- 491 **38** .Nusser Z, Cull-Candy S, Farrant M. Differences in synaptic GABAA receptor number underlie
492 variation in GABA mini amplitude. *Neuron* **19** (1997) 697–709.
- 493 **39** .Bright DP, Aller M, Brickley S. Synaptic release generates a tonic GABA_A receptor-mediated
494 conductance that modulates burst precision in thalamic relay neurons. *J. Neurosci.* **27** (2007)
495 2560–2569.
- 496 **40** .Kopanitsa MV. Extrasynaptic receptors of neurotransmitters: Distribution, mechanisms of activation,
497 and physiological role. *Neurophysiology* **29** (1997) 448–458.
- 498 **41** .Nusser Z, Sieghart W, Somogyi P. Segregation of different GABAA receptors to synaptic and
499 extrasynaptic membranes of cerebellar granule cells. *J. Neurosci.* **18** (1998) 1693–1703.
- 500 **42** .Wei W, Zhang N, Peng Z, Houser CR, Mody I. Perisynaptic localization of subunit-containing
501 GABAA receptors and their activation by GABA spillover in the mouse dentate gyrus. *J. Neurosci.*
502 **23** (2003) 10650–10661.
- 503 **43** .Ye Z, McGee T, Houston C, Brickley S. The contribution of δ subunit-containing gaba_a receptors to
504 phasic and tonic conductance changes in cerebellum, thalamus and neocortex. *Front. Neural Circ.* **7**
505 (2013) 1–8.
- 506 **44** .Orser B. Extrasynaptic GABAA receptors are critical targets for sedative-hypnotic drugs. *J. Clin.*
507 *Sleep Med.* **2** (2006) S12–8.

- 508 45 .Houston C, McGee T, MacKenzie G, Troyano-Cuturi K, Mateos Rodriguez P, Kutsarova E, et al. Are
509 extrasynaptic gaba_a receptors important targets for sedative/hypnotic drugs ? *J. Neurosci.* **32** (2012)
510 3887–3897.
- 511 46 .Bai D, Zhu G, Pennefather P, Jackson MF, MacDonald JF, Orser B. Distinct functional and
512 pharmacological properties of tonic and quantal inhibitory postsynaptic currents mediated by
513 γ -aminobutyric acid a receptors in hippocampal neurons. *Molec. Pharmacol.* **59** (2001) 814–824.
- 514 47 .McDougall SJ, Bailey TW, Mendelowitz D, Andresen MC. Propofol enhances both tonic and phasic
515 inhibitory currents in second-order neurons of the solitary tract nucleus (nts). *Neuropharmacol.* **54**
516 (2008) 552–563.
- 517 48 .Kretschmannova K, Hines RM, Revilla-Sanchez R, Terunuma M, Tretter V, Jurd R, et al. Enhanced
518 tonic inhibition influences the hypnotic and amnesic actions of the intravenous anesthetics etomidate
519 and propofol. *J. Neurosci.* **33** (2013) 7264–7273.
- 520 49 .Papouin T, Ladépêche L, Ruel J, Sacchi S, Labasque M, Hanini M, et al. Synaptic and extrasynaptic
521 nmda receptors are gated by different endogenous coagonists. *Cell* **150** (2012) 633–646.
- 522 50 .Mothet J, Parent A, Wolosker H, Brady Jr R, Linden D, Ferris C, et al. d-serine is an endogenous
523 ligand for the glycine site of the n-methyl-d-aspartate receptor. *Proc. Natl. Acad. Sci. USA* **97** (2000)
524 4926–4931.
- 525 51 .Sah P, Hestrin S, Nicoli R. Tonic activation of nmda receptors by ambient glutamate enhances
526 excitability on neurons. *Science* **246** (1989) 815–818.
- 527 52 .Fleming T, Scott V, Naskar K, J N, Brown C, Stern J. State-dependent changes in astrocyte regulation
528 of extrasynaptic nmda receptor signalling in neurosecretory neurons. *J. Physiol.* **589** (2011) 3929–
529 3941.
- 530 53 .Le Meur K, Galante M, Angulo MC, Audinat E. Tonic activation of nmda receptors by ambient
531 glutamate of non-synaptic origin in the rat hippocampus. *J. Physiol.* **580** (2007) 373–383.
- 532 54 .Panatier A, Theodosis D, Mothet JP, Touquet B, Pollegioni L, Poulain D, et al. Glia-derived d-serine
533 controls nmda receptor activity and synaptic memory. *Cell* **125** (2006) 775–784.
- 534 55 .Wolosker H, Blackshaw S, Snyder S. Serine racemase: a glial enzyme synthesizing d-serine to regulate
535 glutamate-n-methyl-d-aspartate neurotransmission. *Proc. Natl. Acad. Sci. USA* **96** (1999) 13409–
536 13414.
- 537 56 .Martin D, Plagenhoef M, Abraham J, Dennison R, Aronstam R. Volatile anesthetics and glutamate
538 activation of n-methyl-d-aspartate receptors. *Biochem Pharmacol.* **49** (1995) 809–817.
- 539 57 .Daniels S, Roberts R. Post-synaptic inhibitory mechanisms of anaesthesia: glycine receptors. *Toxicol.*
540 *Lett.* **100-101** (1998) 71–76.
- 541 58 .Pender J. Dissociative anesthesia. *Calif. Med.* **113** (1970) 73.
- 542 59 .Dickinson R, Peterson B, Banks P, Simillis C, Martin J, Valenzuela C, et al. Competitive inhibition at
543 the glycine site of the n-methyl-d-aspartate receptor by the anesthetics xenon and isoflurane: evidence
544 from molecular modeling and electrophysiology. *Anesthesiology* **107** (2007) 756–767.
- 545 60 .Kratzer S, Mattusch C, Köchs E, Eder M, Haseneder R, Rammes G. Xenon attenuates hippocampal
546 long-term potentiation by diminishing synaptic and extrasynaptic n-methyl-d- aspartate receptor
547 currents. *Anesth.* **116** (2012) 673–682.
- 548 61 .Bressloff P. Spatiotemporal dynamics of continuum neural fields. *J. Phys. A* **45** (2012) 033001.
- 549 62 .Coombes S. Neural Fields. *Scholarpedia* **1** (2006) 1373.
- 550 63 .Nunez P, Srinivasan R. *Electric Fields of the Brain: The Neurophysics of EEG* (Oxford University
551 Press, New York - Oxford) (2006).
- 552 64 .Hutt A. Oscillatory activity in excitable neural systems. *Contemp. Phys.* **51** (2009) 3–16.
- 553 65 .Wright J, Kydd R. The electroencephalogram and cortical neural networks. *Network* **3** (1992)
554 341–362.
- 555 66 .Liley D, Bojak I. Understanding the transition to seizure by modeling the epileptiform activity of
556 general anaesthetic agents. *J. Clin. Neurophysiol.* **22** (2005) 300–313.
- 557 67 .Hutt A, Longtin A. Effects of the anesthetic agent propofol on neural populations. *Cogn. Neurodyn.*
558 **4** (2009) 37–59.
- 559 68 .Hindriks R, van Putten MJAM. Meanfield modeling of propofol-induced changes in spontaneous EEG
560 rhythms. *Neuroimage* **60** (2012) 2323–2344.

- 561 69 .Talavera J, Esser S, Amzica F, Antognini J. Modeling the GABAergic action of etomidate on the
562 thalamocortical system. *Anesth Analg.* **108** (2009).
- 563 70 .Johnson B, Sleigh J, Kirk I, Williams M. High-density EEG mapping during general anaesthesia with
564 xenon and propofol: a pilot study. *Anaesth Intensive Care.* **31** (2003) 155–163.
- 565 71 .Rennie C, Robinson P, Wright J. Unified neurophysical model of EEG spectra and evoked potentials.
566 *Biol. Cybern.* **86** (2002) 457–471.
- 567 72 .Robinson P, Loxley P, O'Connor S, Rennie C. Modal analysis of corticothalamic dynamics,
568 electroencephalographic spectra and evoked potentials. *Phys. Rev. E* **63** (2001) 041909.
- 569 73 .Robinson P, Rennie C, Rowe D. Dynamics of large-scale brain activity in normal arousal states and
570 epileptic seizures. *Phys. Rev. E* **65** (2002) 041924.
- 571 74 .Lopes da Silva F, Hoeks A, Smits H, Zetterberg L. Model of brain rhythmic activity. *Kybernetik* **15**
572 (1974) 27–37.
- 573 75 .Victor J, Drover J, Conte M, Schiff N. Mean-field modeling of thalamocortical dynamics and a model-
574 driven approach to EEG analysis. *Proceed. Natl. Acad. Science USA* **118** (2011) 15631–15638.
- 575 76 .Kitamura A, Marszalec W, Yeh J, Narahashi T. Effects of halothane and propofol on excitatory and
576 inhibitory synaptic transmission in rat cortical neurons. *J. Pharmacol.* **304** (2002) 162–171.
- 577 77 .Feshchenko VA, Veselis RA, Reinsel RA. Propofol-induced alpha rhythm. *Neuropsychobiology* **50**
578 (2004) 257–266.
- 579 78 .Gugino LD, Chabot RJ, Prichep LS, John ER, Formanek V, Aglio LS. Quantitative EEG changes
580 associated with loss and return of consciousness in healthy adult volunteers anaesthetized with
581 propofol or sevoflurane. *Br. J. Anaesth.* **87** (2001) 421–428.
- 582 79 .San-Juan D, Chiappa K, Cole A. Propofol and the electroencephalogram. *Clin. Neurophysiol.* **121**
583 (2010) 998–1006.
- 584 80 .Robinson P, CJRennie, DLRowe, SCO'Connor. Estimation of multiscale neurophysiologic parameters
585 by electroencephalographic means. *Human Brain Mapping* **23** (2004) 53–72.
- 586 81 .Destexhe A, Contreras D, Steriade M. Mechanisms underlying the synchronizing action of
587 corticothalamic feedback through inhibition of thalamic relay cells. *J. Neurophysiol.* **79** (1999)
588 999–1016.
- 589 82 .Contreras D, Destexhe A, Sejnowski T, Steriade M. Control of spatiotemporal coherence of a thalamic
590 oscillation by corticothalamic feedback. *Science* **274** (1996) 771–774.
- 591 83 .Mulholland C, Somogyi A, Barratt D, Coller J, Hutchinson M, Jacobson G, et al. Association of
592 innate immune single-nucleotide polymorphisms with the electroencephalogram during desflurane
593 general anaesthesia. *J. Mol. Neurosci.* **52** (2014) 497–506.
- 594 84 .Taub A, Katz Y, Lampl I. Cortical balance of excitation and inhibition is regulated by the rate of
595 synaptic activity. *J. Neurosci.* **33** (2013) 14359–14368.
- 596 85 .Okun M, Lampl I. Instantaneous correlation of excitation and inhibition during ongoing and sensory-
597 evoked activities. *Nat. Neurosci.* **11** (2008) 535–537.
- 598 86 .Brown E, Lydic R, Schiff N. General anesthesia, sleep, and coma. *N Engl J Med* **363** (2010) 2638–
599 2650.
- 600 87 .Kelz M, Sun Y, Chen J, Cheng Meng Q, Moore J, Veasey S, et al. An essential role for orexins in
601 emergence from general anesthesia. *Proc. Natl. Acad. Sci. U S A* **105** (2008) 1309–1314.
- 602 88 .Nguyen H, Li K, da Graca R, Delphin E, Xiong M, Ye J. Behavior and cellular evidence for propofol-
603 induced hypnosis involving brain glycine receptors. *Anesthesiology* **110** (2009) 326–332.
- 604 89 .Lynch J. Molecular structure and function of the glycine receptor chloride channel. *Physiol. Rev.* **84**
605 (2004) 1051–1095.
- 606 90 .Grasshoff C, Drexler B, Rudolph U, Antkowiak B. Anaesthetic drugs: linking molecular actions to
607 clinical effects. *Curr. Pharm. Des.* **12** (2006) 3665–3679.
- 608 91 .Bojak I, Day H, Liley D. Ketamine, propofol, and the eeg: a neural field analysis of hcn1-mediated
609 interactions. *Front. Comput. Neurosci.* **7** (2013) 22.
- 610 92 .Granger R, Hearn R. Models of thalamocortical system. *Scholarpedia* **2** (2007) 1796.
- 611 93 .Magoun H. An ascending reticular activating system in the brain stem. *AMA Arch. Neurol. Psych.* **67**
612 (1952) 145–154.

- 613 **94** .Vanini G, Baghdoyan H. Extrasynaptic GABAA receptors in rat pontine reticular formation increase
614 wakefulness. *Sleep* **36** (2013) 337–343.
- 615 **95** .Fiset P, Paus T, Daloze T, Plourde G, Meuret P, Bonhomme V, et al. Brain mechanisms of propofol-
616 induced loss of consciousness in humans: a positron emission tomographic study. *J. Neurosci.* **19**
617 (1999) 5506–5513.
- 618 **96** .Franks N. General anesthesia: from molecular targets to neuronal pathways of sleep and arousal.
619 *Nat.Rev.Neurosc.* **9** (2008) 370–386. doi:10.1038/nrn2372.
- 620 **97** .Laalou F, de Vasconcelos A, Oberling P, Jeltsch H, Cassel J, Pain L. Involvement of the basal
621 cholinergic forebrain in the mediation of general (propofol) anesthesia. *Anesthesiology* **108** (2008)
622 888–896.
- 623 **98** .Alkire M, Haier RJ, Fallon JH. Toward a unified theory of narcosis: brain imaging evidence
624 for a thalamocortical switch as the neurophysiologic basis of anesthetic-induced unconsciousness.
625 *Conscious Cogn.* **9** (2000) 370–386.