eNeuro, 2021, vol.8, N4

Full-band eeg recordings using hybrid ac/dc-divider filters

Nasretdinov A., Evstifeev A., Vinokurova D., Burkhanova-Zakirova G., Chernova K., Churina Z., Khazipov R.
Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

Full-band DC recordings enable recording of slow electrical brain signals that are severely compromised during con-ventional AC recordings. However, full-band DC recordings may be limited by the amplifier's dynamic input range and the loss of small amplitude high-frequency signals. Recently, Neuralynx has proposed full-band recordings with inverse filtering for signal reconstruction based on hybrid AC/DC-divider RRC filters that enable only partial suppres-sion of DC signals. However, the quality of signal reconstruction for biological signals has not yet been assessed. Here, we propose a novel digital inverse filter based on a mathematical model describing RRC filter properties, which provides high computational accuracy and versatility. Second, we propose procedures for the evaluation of the inverse filter coefficients, adapted for each recording channel to minimize the error caused by the deviation of the real values of the RRC filter elements from their nominal values. We demonstrate that this approach enables near 99% reconstruction quality of high-potassium-induced cortical spreading depolarizations (SDs), endothelin-induced ischemic negative ultraslow potentials (NUPs), and whole-cell recordings of membrane potential using RRC filters. The quality of the reconstruction was significantly higher than with the existing inverse filtering procedures. Thus, RRC filters with inverse filtering are optimal for full-band EEG recordings in various applications.

http://dx.doi.org/10.1523/ENEURO.0246-21.2021

Keywords

DC recordings, EEG, Inverse filter

References

[1] Abächerli R, Isaksen J, Schmid R, Leber R, Schmid HJ, Generali G (2016) Digital DC-reconstruction of AC-coupled electrophysiological signals with a single inverting filter. PLoS One 11:e0150207.

[2] Birbaumer N, Ellbert T, Canavan AGM, Rockstroh B (1990) Slow potentials of the cerebral cortex and behavior. Physiol Rev 70:1–28.

[3] Buzsáki G, Draguhn A (2004) Neuronal oscillations in cortical net-works. Science 304:1926–1929.

[4] Carlson AP, Shuttleworth CW, Major S, Lemale CL, Dreier JP, Hartings JA (2018) Terminal spreading depolarizations causing electrocortical silencing prior to clinical brain death: case report. J Neurosurg 131:1773–1779.

[5] Colonnese MT, Khazipov R (2010) "Slow activity transients" in infant rat visual cortex: a spreading synchronous oscillation patterned by retinal waves. J Neurosci 30:4325–4337.

[6] Cui RQ, Huter D, Egkher A, Lang W, Lindinger G, Deecke L (2000) High resolution DC-EEG mapping of the Bereitschaftspotential preceding simple or complex bimanual sequential finger move-ment. Exp Brain Res 134:49–57.

[7] Dreier JP (2011) The role of spreading depression, spreading depola-rization and spreading ischemia in neurological disease. NatMed 17:439–447.

[8] Dreier JP, Reiffurth C (2015) The stroke-migraine depolarization con-tinuum. Neuron 86:902–922.

[9] Dreier JP, Kleeberg J, Petzold G, Priller J, Windmüller O, Orzechowski HD, Lindauer U, Heinemann U, Einhäupl KM, Dirnagl U (2002) Endothelin-1 potently induces Leão's cortical spreading depression in vivo in the rat: a model for an endothelial trigger of migrainous aura? Brain 125:102–112.

[10] Dreier JP, Fabricius M, Ayata C, Sakowitz OW, Shuttleworth CW, Dohmen C, Graf R, Vajkoczy P, Helbok R, Suzuki M, Schiefecker AJ, Major S, Winkler MK, Kang EJ, Milakara D, Oliveira-Ferreira AI, Reiffurth C, Revankar GS, Sugimoto K, Dengler NF, et al. (2017) Recording, analysis, and interpretation of spreading depolariza-tions in neurointensive care: review and recommendations of the COSBID research group. J Cereb Blood Flow Metab 37:1595– 1625.

[11] Dreier JP, Major S, Foreman B, Winkler MKL, Kang EJ, Milakara D, Lemale CL, DiNapoli V, Hinzman JM, Woitzik J, Andaluz N, Carlson A, Hartings JA (2018) Terminal spreading depolarization and electrical silence in death of human cerebral cortex. Ann Neurol 83:295–310.

[12] Dreier JP, Major S, Lemale CL, Kola V, Reiffurth C, Schoknecht K, Hecht N, Hartings JA, Woitzik J (2019) Correlates of spreading de-polarization, spreading depression, and negative ultraslow potential in epidural versus subdural electrocorticography. Front Neurosci 13:373.

[13] Drenckhahn C, Winkler MK, Major S, Scheel M, Kang EJ, Pinczolits A, Grozea C, Hartings JA, Woitzik J, Dreier JP; COSBID study group (2012) Correlates of spreading depolarization in human scalp electroencephalography. Brain 135:853–868.

[14] Fox MD, Raichle ME (2007) Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging. Nat Rev Neurosci 8:700–711.

[15] Grooms JK, Thompson GJ, Pan WJ, Billings J, Schumacher EH, Epstein CM, Keilholz SD (2017) Infraslow electroencephalographic and dynamic resting state network activity. Brain Connect 7:265– 280.

[16] Hartings JA, Watanabe T, Dreier JP, Major S, Vendelbo L, Fabricius M (2009) Recovery of slow potentials in AC-coupled electrocorti-cography: application to spreading depolarizations in rat and human cerebral cortex. J Neurophysiol 102:2563–2575.

[17] Hartings JA, York J, Carroll CP, Hinzman JM, Mahoney E, Krueger B, Winkler MKL, Major S, Horst V, Jahnke P, Woitzik J, Kola V, Du Y, Hagen M, Jiang J, Dreier JP (2017) Subarachnoid blood acutely induces spreading depolarizations and early cortical infarction. Brain 140:2673–2690.

[18] Herreras O, Makarova J (2020) Mechanisms of the negative potential associated with Leão's spreading depolarization: a history of brain electrogenesis. J Cereb Blood Flow Metab 40:1934–1952.

[19] Kovac S, Speckmann EJ, Gorji A (2018) Uncensored EEG: the role of DC potentials in neurobiology of the brain. Prog Neurobiol 165– 167:51–65.

[20] Lecci S, Fernandez LMJ, Weber FD, Cardis R, Chatton JY, Born J, Lüthi A (2017) Coordinated infraslow neural and cardiac oscillations mark fragility and offline periods in mammalian sleep. Sci Adv 3:e1602026.

[21] Lückl J, Lemale CL, Kola V, Horst V, Khojasteh U, Oliveira-Ferreira AI, Major S, Winkler MKL, Kang EJ, Schoknecht K, Martus P, Hartings JA, Woitzik J, Dreier JP (2018) The negative ultraslow po-tential, electrophysiological correlate of infarction in the human cortex. Brain 141:1734–1752.

[22] Miyawaki H, Billeh YN, Diba K (2017) Low activity microstates during sleep. Sleep 40:zsx066.

[23] Nasretdinov A, Lotfullina N, Vinokurova D, Lebedeva J, Burkhanova G, Chernova K, Zakharov A, Khazipov R (2017) Direct current coupled recordings of cortical spreading depression using silicone probes. Front Cell Neurosci 11:1–11.

[24] Oliveira-Ferreira AI, Milakara D, Alam M, Jorks D, Major S, Hartings JA, Lückl J, Martus P, Graf R, Dohmen C, Bohner G, Woitzik J, Dreier JP; COSBID study group (2010) Experimental and prelimi-nary clinical evidence of an ischemic zone with prolonged negative DC shifts surrounded by a normally perfused tissue belt with per-sistent electrocorticographic depression. J Cereb Blood Flow Metab 30:1504–1519.

[25] Onton JA, Kang DY, Coleman TP (2016) Visualization of whole-night sleep EEG from 2-channel mobile recording device reveals distinct deep sleep stages with differential electrodermal activity. Front Hum Neurosci 10:605–612.

[26] Pietrobon D, Moskowitz MA (2014) Chaos and commotion in the wake of cortical spreading depression and spreading depolariza-tions. Nat Rev Neurosci 15:379–393.

[27] Rodin E, Constantino T, Bigelow J (2014) Interictal infraslow activity in patients with epilepsy. Clin Neurophysiol 125:919–929.

[28] Vanhatalo S, Palva JM, Holmes MD, Miller JW, Voipio J, Kaila K (2004) Infraslow oscillations modulate excitability and interictal epileptic activity in the human cortex during sleep. Proc Natl Acad Sci USA 101:5053–5057.

[29] Vanhatalo S, Palva JM, Andersson S, Rivera C, Voipio J, Kaila K (2005a) Slow endogenous activity transients and developmental expression of K+-Cl-cotransporter 2 in the immature human cor-tex. EurJ Neurosci 22:2799–2804.

[30] Vanhatalo S, Voipio J, Kaila K (2005b) Full-band EEG (FbEEG): an emerging standard in electroencephalography. Clin Neurophysiol 116:1–8.

[31] Voipio J, Tallgren P, Heinonen E, Vanhatalo S, Kaila K (2003) Millivolt-scale DC shifts in the human scalp EEG: evidence for a nonneuronal generator. J Neurophysiol 89:2208–2214.

[32] Zakharov A, Chernova K, Burkhanova G, Holmes GL, Khazipov R (2019) Segregation of seizures and spreading depolarization across cortical layers. Epilepsia 60:2386–2397.