One VCO as a Null Detector for the HEEPidermis Bioimpedance Chain

Two-page summary of a simulation study

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What I propose. Stop using the ring VCO of HEEPidermis [1] as a voltmeter and use it only to compare two nodes.

1. **P11, one-VCO null-balancing bridge.** A switch feeds the one VCO the tissue node and the reference node (R_{ref}) in turn every 1 ms. The firmware servos the reference current DAC until both phases give the same count, so $G = I_T/(I_R R_{ref})$. The VCO's nonlinear curve, gain error and temperature drift cancel: **no look-up table and no calibration interrupt**.
2. **P12, three tones and a Cole fit** for spectroscopy, with the excitation auto-ranged so the node stays in the VCO's range: **0.6 s instead of 1.6 s** for eight frequencies.
3. **P13, duty-cycled VCO** (the current DAC stays on): front end **11.3 to 1.22 µW** at the same accuracy.

Why. In the paper's chain the VCO turns the node voltage into a frequency and the firmware maps the count back to a voltage with a straight line. In my model, built from transistor-level SKY130 data, the VCO's $f(V)$ is curved and drifts by about 1.9 %/°C. The straight line only holds in a 0.55-0.65 V window (0.54 % error, 16 CPU wake-ups an hour), and a look-up table taken at power-up is 7.2 % off once the chip has warmed 8 °C on the skin.

Table 1: The paper's design against the proposal, in the same model. Simulation only, nothing is measured.

Metric	Paper's design (this model)	**Proposed**	By
Skin conductance, chip warming 8 °C [% RMS]	7.2 (calibrated at power-up)	**0.15** (5 more chips: 0.05 to 0.21)	P11
Calibration needed	VCO line or look-up table	**none: ratio of two currents**	P11
CPU wake-ups per hour	16	**8**	P11
Spectroscopy, 8 frequencies [% RMS $\|Z\|$]	0.89 in 1.6 s (stepped sine)	**0.11 in 0.6 s**	P12
Single-frequency $\|Z\|$, phase	4.7 %, 3.6° in 1.0 s	**0.66 %, 0.009° in 0.5 s**	P2
Front-end power (VCO + current DAC)	11.3 µW	**1.22 µW** at 4 % duty	P13

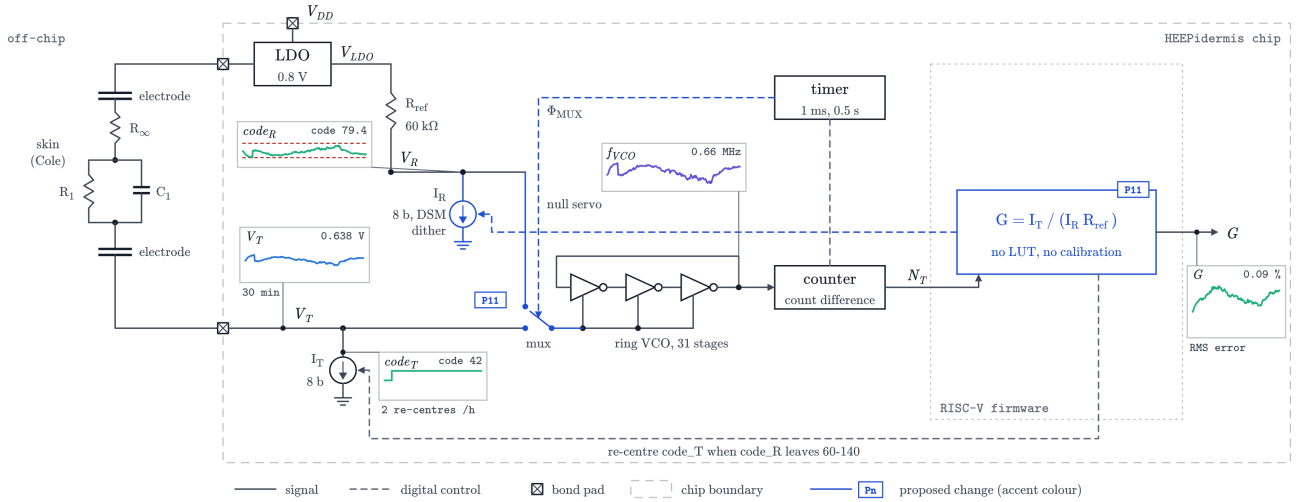
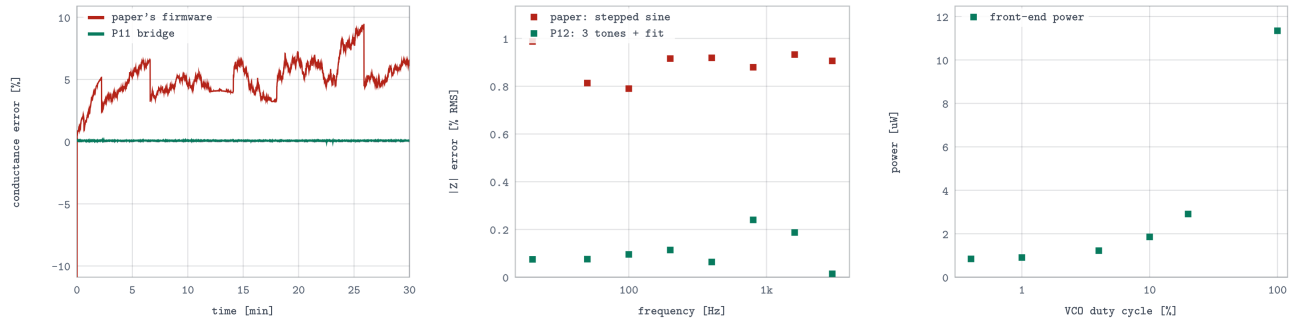


Figure 1: The proposed chain (P11), as drawn on the web page; changes in blue. The insets are a 30-minute run of this circuit while the chip warms onto skin: tissue node V_T, tissue and reference DAC codes, VCO frequency, and true against estimated conductance G.



(a) P11: conductance error over 30 min while the chip warms; paper's firmware (red) against the bridge (green).

(b) P12: $|Z|$ error at the eight sweep frequencies; stepped sine against three tones with a Cole fit.

(c) P13: front-end power against the VCO's duty cycle; GSR error stays at 0.083 %.

Figure 2: The evidence for the three core proposals.

How the model was built and checked. The chain is rebuilt at block level (LDO, Cole tissue, two 8-bit current DACs, 31-stage ring VCO-ADCs with non-reset counters, timer, firmware). The VCO's $f(V)$ and its temperature drift and the DAC's bit weights (Monte Carlo chips) come from SKY130 transistor-level simulation, mapped onto the paper's voltage and frequency range. The same model runs the paper's flows and every proposal; the browser version is checked against the Python model. Twelve proposals were simulated in total; one did not help (a multisine capture) and four helped only partly, all reported on the web page.

Limits. Simulation only. SKY130 is not the paper's TSMC 65 nm process, the tissue is a Cole model with assumed values, and the bridge assumes the DAC bit weights are known to 0.1 %. HEEPidermis results are post-layout simulation of a taped-out chip.

What I would do next. Build the bridge on the actual HEEPidermis firmware and measure it on the chip, then check P12 on real skin and electrode impedances.

References

[1] J. Sapriza *et al.*, "HEEPidermis: a versatile SoC for BioZ recording," in *Proc. IEEE LASCAS*, 2026, doi:10.1109/LASCAS67804.2026.11457136.