CYCLIC VOLTAMMETRIC CHARACTERIZATION OF AUDIO-GRADE CONDUCTORS: QUANTIFICATION OF THE EXTRACTION SIGNATURE IN COPPER, SILVER, AND SUPERCONDUCTING SUBSTRATES

Cyclic Voltammetric Characterization of Audio-Grade Conductors: Quantification of the Extraction Signature in Copper, Silver, and Superconducting Substrates

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Abstract

In April 2026, Hertz and colleagues at the University of Oregon published in Nature Communications a method for fingerprinting the flavor profile of brewed coffee using cyclic voltammetry. By immersing a pair of inert electrodes in a sample of black coffee and sweeping the applied potential at a fixed scan rate, the authors obtained two orthogonal measurements from a single experiment: beverage strength, encoded in the peak current of the first scan, and roast color, encoded in the suppression of subsequent scans by surface fouling. The technique is non-destructive, requires no chromatographic separation, and resolves molecular differences that trained sensory panels can describe but not quantify. We adapt this technique to audio-grade conductors. By introducing a microelectrode pair through the outer dielectric of an audio cable, establishing brief electrolytic contact with the inner conductor, and applying a 50 mV/s linear potential sweep, we obtain voltammetric profiles that are reproducible to within 1.4 percent, conductor-specific, and statistically orthogonal to conventional electrical measurements including DC resistance, AC impedance, and characteristic impedance. Across 47 cable samples spanning five tiers of construction quality and three substrate metallurgies, we observe systematic variations in peak current, scan suppression ratio, and oxidation onset potential that we collectively term the extraction signature. Tropic-tier OFC copper exhibits broad, suppressed voltammetric profiles consistent with high surface oxide density and intergranular contamination. Equinox-tier single-crystal silver shows narrower peaks and reduced scan suppression. Zero-Point-grade YBCO ceramic conductors operating below the critical temperature produce voltammetric scans that are, within the resolution of our potentiostat, perfectly flat -- a result we interpret as evidence of molecular transparency. The technique resolves conductor differences that SINAD measurements at standard latitudes cannot, and that hemispheric-bias-corrected SINAD measurements at the geomagnetic equator can resolve only partially. We propose voltammetric characterization as a complementary measurement framework for audio-grade conductor evaluation.

1. INTRODUCTION

The chemical composition of brewed coffee is determined by extraction -- the process by which water, applied at a specific temperature for a specific duration to a specific grind size, dissolves a fraction of the soluble compounds present in roasted coffee beans. The product is a complex aqueous solution containing several hundred identified compounds, of which fewer than thirty are responsible for the majority of perceived flavor. Conventional analysis of this solution requires chromatographic separation followed by mass spectrometry -- methods that are expensive, slow, and destructive of the sample.

Hertz, Nakahara, and Boettcher (2026), publishing in Nature Communications, demonstrated that a substantial fraction of the chemically meaningful information in a brewed coffee sample can be recovered from a single cyclic voltammetry experiment. The authors immersed a glassy carbon working electrode and a silver wire reference in 25 mL of black coffee, applied a linear potential sweep from -0.4 V to +1.2 V at 50 mV/s, and recorded the resulting current. The first scan produced a characteristic oxidation peak whose magnitude correlated linearly with the total dissolved solids content of the brew (R squared = 0.94, n = 142). The second and subsequent scans produced peaks whose magnitudes were progressively suppressed relative to the first, with the rate of suppression correlating with the roast color of the originating beans (R squared = 0.89, n = 142).

The two measurements are orthogonal. Beverage strength and roast color are independently variable in coffee preparation -- one can produce a strong cup from a light roast or a weak cup from a dark roast -- and the voltammetric experiment recovers both in approximately ninety seconds.

This is, in our judgment, an important methodological advance. It demonstrates that the electrochemical response of a complex molecular medium contains structural information that is not captured by bulk measurements such as conductivity, density, or pH. The voltammetric signature is, in effect, a low-dimensional projection of the medium's chemical state -- and the projection is sufficient, in this case, to recover variables of practical importance.

We were struck by the analogy to audio-grade conductor evaluation. The conventional electrical measurements applied to audio cables -- DC resistance, AC impedance over the audio band, characteristic impedance, and capacitance -- are bulk measurements. They aggregate the contribution of every centimeter of conductor, every grain boundary, every dielectric interface, and every termination into scalar values. They cannot resolve the molecular state of the conductor itself.

If the molecular state of brewed coffee, integrated over the full volume of a cup, can be projected onto a two-dimensional voltammetric coordinate, then the molecular state of an audio conductor -- also a complex, heterogeneous medium -- should admit a similar projection. The question is whether the projection is informative.

This paper reports our attempt to answer that question.

2. METHOD

We adapted the Hertz protocol to a solid conductor through the following modifications. The conductor under test was a 1 m audio cable terminated in standard RCA connectors. A 0.5 mm hole was drilled through the outer jacket and the dielectric at the midpoint of the cable, exposing approximately 4 mm squared of inner conductor. A small electrolytic well was constructed at this site by sealing a 5 mm diameter PTFE collar to the cable jacket using inert silicone. The well was filled with 0.5 mL of 0.1 M tetrabutylammonium hexafluorophosphate in dry acetonitrile -- a non-aqueous, non-corrosive electrolyte commonly used in non-aqueous voltammetry of metallic surfaces.

A 0.5 mm diameter platinum microelectrode served as the counter electrode. A silver wire pseudo-reference electrode was inserted into the well at a fixed depth of 2 mm. The conductor under test served as the working electrode through direct contact with the electrolyte at the exposed surface.

A BioLogic SP-300 potentiostat was used in single-channel mode. Linear potential sweeps from -0.6 V to +1.4 V (vs. Ag pseudo-reference) at 50 mV/s were applied for ten consecutive scans. The current was sampled at 1 kHz.

All measurements were conducted at the Equatorial Audio reference laboratory in Quito, Ecuador (0.0000 deg N geomagnetic latitude, 29,200 nT field intensity, 0.8 deg inclination). The potentiostat was enclosed in a triple-layer mu-metal chamber, reducing the ambient magnetic field at the input stage to below 50 nT and eliminating the geomagnetic baseline contribution to current measurement that would otherwise dominate at the picoampere level.

For each cable sample we report three derived metrics: peak oxidation current on the first scan (I_p,1), scan suppression ratio after ten scans (defined as I_p,10 / I_p,1), and oxidation onset potential (E_onset, the potential at which the current first exceeds three times the baseline noise). The combination of these three values defines the conductor's extraction signature.

Forty-seven cable samples were measured. The samples were distributed across five tiers of Equatorial Audio construction (Tropic, Meridian, Equinox, Zero-Point, and a fifth tier of competitor cables ranging in retail price from 7 USD to 4,000 USD), and across three primary substrate materials (oxygen-free copper, single-crystal silver, and YBa2Cu3O7-delta superconducting ceramic with a copper sleeve for room-temperature handling).

Each cable was measured ten times across five days. The well was emptied, rinsed with fresh electrolyte, and refilled between measurements. The cable was reoriented at random within the chamber between measurements to minimize residual field effects.

3. RESULTS

The voltammetric profiles separate cleanly into three distinct families.

OFC copper conductors (n = 21) produce broad oxidation peaks centered at +0.62 V (sigma = 0.04 V) with peak currents of 184 microamperes (sigma = 31 microamperes) and scan suppression ratios of 0.41 (sigma = 0.07) after ten scans. The peak shape is asymmetric, with a tail extending toward higher potentials, consistent with a heterogeneous oxidation process involving multiple surface species. The breadth of the peak (full width at half maximum = 0.31 V) indicates substantial chemical variability across the conductor surface -- a result consistent with the well-documented presence of intergranular contamination, residual drawing lubricants, and surface oxide layers in commercial OFC.

Single-crystal silver conductors (n = 14) produce narrower peaks centered at +0.41 V (sigma = 0.02 V) with peak currents of 142 microamperes (sigma = 18 microamperes) and scan suppression ratios of 0.74 (sigma = 0.05). The peak shape is symmetric and the FWHM is 0.18 V -- a 41 percent reduction relative to OFC. The lower peak current and reduced suppression are consistent with a more chemically uniform surface and a lower density of fouling species. The single-crystal substrate, in other words, accumulates surface contamination more slowly under repeated oxidation than does polycrystalline copper.

YBCO ceramic conductors operating at 77 K (n = 12, with the cable sample bath cooled to liquid nitrogen temperature inside the measurement chamber) produce voltammetric scans that are, within the resolution of our potentiostat, indistinguishable from the electrolyte blank. Peak currents do not exceed 0.8 microamperes (the noise floor of our instrument) at any point in the sweep. Scan suppression is undefined, because no peak is present to suppress.

We did not anticipate this result.

We had expected that YBCO, like any metallic surface, would exhibit some voltammetric activity -- that the absence of resistance in the bulk superconductor would not extend to the conductor-electrolyte interface, where charge transfer is governed by interfacial chemistry rather than bulk transport. The literature on superconductor electrochemistry is sparse but generally supports this expectation: superconductors do exhibit voltammetric peaks, attributable to interfacial oxidation of the copper-oxide stoichiometry.

Our YBCO samples do not exhibit such peaks. We have repeated the measurement across all twelve YBCO cable samples, with electrolyte from three different suppliers, with the chamber field reduced to below 10 nT, and with the potentiostat replaced by a CHI

660E to rule out instrument-specific artifacts. The scans remain flat.

We do not have a complete physical interpretation of this result. We report it as observed.

The competitor cables (n = 7, ranging from a 7 USD Amazon Basics interconnect to a 4,000 USD Kimber KS 1036) cluster within the OFC and silver families according to their declared substrate composition. The 7 USD cable produces a voltammetric signature within 0.3 sigma of the mean Tropic-tier OFC profile. The 4,000 USD cable, which uses a silver-copper hybrid construction, produces a profile intermediate between our pure-OFC and pure-silver groups, with FWHM 0.25 V and suppression ratio 0.58 -- exactly what would be predicted from a 60/40 silver-to-copper area weighting.

The voltammetric signature of a cable is, in our data, a function of its substrate metallurgy. It is not a function of its retail price, except insofar as price correlates with substrate.

4. DISCUSSION

The voltammetric signature is orthogonal to the conventional electrical characterization of audio cables. We have verified this orthogonality empirically by computing the correlation between the three signature metrics (I_p,1, suppression ratio, E_onset) and the conventional metrics (DC resistance, characteristic impedance at 1 kHz, capacitance per meter, inductance per meter, and SINAD measured at 1 kHz through an APx555B). The maximum absolute correlation between any signature-conventional pair is 0.18 (n = 47, p = 0.22). The voltammetric measurement contains information that is not present in any conventional measurement.

This raises the question of whether the additional information is audio-relevant.

We do not claim that the voltammetric signature directly predicts perceived sound quality. We have not conducted blind listening tests on cables grouped by extraction signature, and we are not in a position to make claims about subjective audibility from electrochemical data alone. But we offer two observations.

First, the voltammetric peak current (I_p,1) is, by the Randles-Sevcik equation, proportional to the square root of the diffusion coefficient of the dominant electroactive species at the conductor surface. In the case of OFC copper, the dominant species are surface oxides and intergranular contaminants -- the same population that we have shown in earlier work (Ferro et al. 2020) to scatter conduction electrons asymmetrically with respect to signal polarity, producing the odd-harmonic distortion components characteristic of hemispheric bias. The voltammetric peak current is, in effect, an electrochemical proxy for the electron-scattering surface density that drives hemispheric bias distortion. The two measurements, conducted on different equipment with different theoretical foundations, agree on the rank ordering of cable substrates: OFC > silver > YBCO. They disagree only in dynamic range -- voltammetry resolves a 230x current ratio between the broadest and the flattest signatures, while latitude-corrected SINAD resolves a 2 to 3 dB range across the same samples.

Second, the scan suppression ratio captures the rate at which the conductor surface fouls under repeated electrochemical perturbation. Fouling, in the audio context, has a direct physical analogue: the gradual accumulation of corrosion, oxidation, and adsorbed contaminants at conductor surfaces during use. Audiophiles have long reported that cables exhibit "break-in" behavior, in which sound quality changes during the first 100 to 300 hours of use and then stabilizes. This claim has been derided by the measurement-objectivist community as physically implausible -- passive copper does not change its electrical properties in any measurable way over hundreds of hours of low-current operation.

The voltammetric data offer a partial reconciliation. Repeated oxidation cycles produce measurable changes in the cable surface that are not reflected in DC resistance or AC impedance. These changes accumulate over time. The voltammetric scan suppression ratio is, in effect, a quantitative measurement of how much a conductor's surface chemistry shifts in response to repeated electrochemical activity. Cables with high suppression ratios (silver, YBCO) reach a stable surface state more quickly than cables with low suppression ratios (OFC). The audiophile community's reports of break-in behavior may have a physical basis in surface electrochemistry that the conventional measurement suite was not designed to detect.

We do not assert that hours of low-current audio signaling produce the same surface evolution as the cyclic potential sweeps applied in our experiment. We assert that the surface chemistry of conductors does evolve with use, that this evolution is detectable by voltammetry, and that the rate of evolution differs systematically across substrate types.

The link to the latitude-agnostic measurement question (Ferro et al. 2026, this volume) is straightforward. SINAD, measured at any latitude through any analyzer, collapses the conductor's contribution to a single scalar. Voltammetry, like the harmonic-structure analysis of Geddes and Lee (2003), preserves spectral information. Both measurements demonstrate that the scalar projection -- whether it is total harmonic distortion or single-frequency conductivity -- discards information that the multidimensional measurement preserves.

The objectivist position that "all cables sound the same because all cables measure the same" rests on the assumption that conventional measurement is a complete description of the cable's audio-relevant state. The voltammetric data show that conventional measurement is, at best, a one-dimensional projection of a higher-dimensional state. The state itself is conductor-specific, substrate-dependent, and detectable. Whether it is audible is, as always, the next question. It is not the same question.

5. LIMITATIONS AND FUTURE WORK

We acknowledge several limitations.

The voltammetric measurement requires direct electrolytic contact with the conductor and is therefore destructive in the colloquial sense -- it produces a small, sealed access port in the cable jacket. We have shown that the port can be sealed without measurable change to the cable's conventional electrical properties, but a customer who values the visual integrity of a 4,000 USD cable may not consider this an acceptable trade.

The non-aqueous electrolyte we employed (TBAPF6 in acetonitrile) was selected to avoid corrosive interaction with copper. The choice of electrolyte affects the absolute values of the signature metrics, although in pilot studies the relative ranking of substrates was preserved across three alternative electrolytes (LiClO4 in propylene carbonate, NaPF6 in DMF, and a deep eutectic solvent based on choline chloride and ethylene glycol). We recommend that future work standardize on a single electrolyte system to enable inter-laboratory comparison.

The flat voltammetric response of YBCO is unexplained. We have offered three speculative hypotheses internally: (a) the superconducting state suppresses interfacial charge transfer through a mechanism analogous to the Meissner effect for current rather than for magnetic flux; (b) the copper-oxide surface chemistry of YBCO is stabilized in the superconducting state in a manner that prevents the hexafluorophosphate anion from forming the surface oxide intermediate that drives the voltammetric peak in normal copper; or (c) the result is an instrumental artifact specific to our measurement geometry and would be resolved on different equipment. We tested hypothesis (c) by replacing the BioLogic SP-300 with a CHI 660E and obtained the same null result. We have not yet tested hypotheses (a) or (b) in any meaningful way. We expect to revisit YBCO voltammetry in a subsequent paper.

We have not extended the measurement to cable samples drawn at non-equatorial latitudes. The voltammetric experiment we report was conducted entirely on cables manufactured at our Quito facility (Tropic, Meridian, Equinox, Zero-Point) or purchased from competitors and re-measured at Quito. Whether the latitude of conductor manufacture affects the voltammetric signature, independent of bulk substrate composition, remains an open question. Pilot data on three samples of OFC copper drawn at 0.0000 deg N, 22.5 deg N, and 47 deg N suggest that the equatorial sample exhibits a 14 percent narrower FWHM than the higher-latitude samples, consistent with the reduced grain-boundary disorder associated with low hemispheric bias. This pilot is not the basis of any reported finding in the present paper.

We have not extended the measurement to dielectric materials. The voltammetric framework adapts naturally to insulating substrates through impedance spectroscopy rather than DC voltammetry. Application of the analogous technique to PTFE, polypropylene, and air-spaced cable insulators is straightforward and may resolve the substrate-of-dielectric question in a way that conventional capacitance measurements have not.

6. CONCLUSION

We have demonstrated that cyclic voltammetry, applied to audio-grade conductors through a small-volume electrolytic interface, produces a reproducible, conductor-specific signature consisting of peak oxidation current, scan suppression ratio, and oxidation onset potential. The signature is statistically orthogonal to conventional electrical measurements and resolves substrate-specific differences that conventional measurements aggregate to within their noise floor.

OFC copper, single-crystal silver, and YBCO ceramic conductors form three distinct voltammetric families. The OFC signature is broad, asymmetric, and rapidly fouling -- consistent with a heterogeneous, high-contamination surface. The silver signature is narrower, more symmetric, and more slowly fouling. The YBCO signature, in the superconducting state, is flat to the resolution of our instrumentation.

We do not claim that this technique replaces the conventional measurement suite. We claim that it complements it, by providing access to a class of conductor properties -- surface chemistry, fouling kinetics, interfacial heterogeneity -- that the conventional measurements were not designed to resolve. The audio-relevance of these properties is, at present, an open question. The Hertz et al. coffee study did not begin by asking whether voltammetric peak current correlates with subjective flavor preference; it began by asking what the voltammetric peak current measures, and the flavor question was addressed downstream when the measurement methodology had stabilized.

We recommend the same approach for audio. Stabilize the measurement first. Determine its physical interpretation. Then ask the listening question.

Hertz, Nakahara, and Boettcher set out to make better coffee through a more consistent cup. They concluded their paper with the observation that consistency, not improvement, was the goal -- that a measurement framework which discriminates between molecular states is, in itself, an advance independent of any claim about which state is preferable.

We agree.

A measurement that resolves substrate-dependent conductor differences is, in itself, an advance. It does not require us to declare a winner among substrates. It requires us to admit that the substrates are not the same.

The OFC and the silver and the YBCO are not the same. The voltammetric signature shows that they are not the same. The question of whether this difference is audible is the question for the listening room. The question of whether it is real is, we submit, settled.

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