

# BIOIMPEDANCE TECHNOLOGY IN OUTPATIENT ESTHETIC PRACTICE: ENGINEERING PRINCIPLES, MEASUREMENT PROTOCOL, AND CLINICAL VALIDATION AGAINST VISUAL AGING ASSESSMENT

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## Abstract:

**Background:** Bioimpedance analysis (BIA) is an engineering measurement technique that quantifies tissue electrical properties by passing a low-amplitude alternating current through biological tissue. Applied to skin, BIA measures stratum corneum water content through changes in electrical capacitance. Despite wide use of BIA devices in dermatological research, their application and validation in outpatient esthetic practice settings remain limited.

**Objective:** To describe the engineering principles underlying bioimpedance skin measurement, to present a standardized seven-zone facial measurement protocol applicable in esthetic practice, and to validate the technology against independently rated visual aging scores in a pilot clinical sample.

**Methods:** A cross-sectional observational pilot study (ClinicalTrials.gov: NCT07564869; n = 30 women, ages 30–60, Florida) measured skin hydration using the BT-Analyze bioimpedance device [1] at seven facial zones under standardized environmental conditions (20–22°C, 40–60% relative humidity). Three readings per zone were taken after 20 min acclimatization; zone scores were averaged to compute BT-mean. Visual aging was independently rated using a modified Glogau scale (0–18 points) [2] by a blinded expert cosmetologist from standardized photographs.

**Results:** BT-mean correlated negatively with Glogau visual aging score ( $r_s = -0.796$ ,  $p < 0.001$ ). In multiple linear regression, BT-mean was the sole significant predictor ( $\beta = -0.250$ ,  $p < 0.001$ ; adj.  $R^2 = 0.64$ ) after adjustment for age, Fitzpatrick skin type, moisturizer use, and menopausal status. Partial Spearman correlation controlling for age:  $r_s = -0.745$  ( $p < 0.001$ ). All seven facial zones reached significance ( $p \leq 0.004$ ).

**Conclusions:** Bioimpedance skin measurement under standardized conditions produces data that correlate strongly with visual aging outcomes, independent of chronological age. The seven-zone facial protocol described here is feasible in outpatient settings and provides quantifiable, trackable data for clinical monitoring. Engineering standardization of measurement conditions is essential for reproducible results.

**Keywords:** bioimpedance analysis; skin hydration measurement; electrical capacitance; esthetic practice; facial aging; BT-Analyze; measurement protocol; non-invasive assessment; clinical validation.

## 1. Introduction

### 1.1 Engineering basis of bioimpedance analysis

Bioimpedance analysis (BIA) measures the opposition of biological tissue to the flow of an alternating electrical current. When a low-amplitude current (typically 0.1–1 mA) at a defined frequency is applied to tissue, the impedance response depends on the tissue's capacitive and resistive properties [3]. In skin, the stratum corneum acts as a dielectric capacitor: its water content determines capacitance, and higher water content reduces impedance. Devices designed specifically for stratum corneum assessment, such as the BT-Analyze, operate on the capacitance principle, measuring changes in electrical permittivity at the skin surface rather than bulk tissue impedance [1].

The physics of the measurement are well characterized. Dry stratum corneum has a low dielectric constant because water molecules — which have a high dielectric constant of approximately 80 — are absent. As hydration increases, the dielectric constant rises proportionally, and the device registers a higher capacitance reading. The BT-Analyze outputs a dimensionless hydration index on a 0–65

scale, where  $\leq 25$  indicates dry skin, 35–45 is the manufacturer's optimal range, and  $\geq 55$  indicates high hydration [1].

### 1.2 Sources of measurement variability

Bioimpedance readings at the skin surface are sensitive to several environmental and physiological factors that must be controlled to obtain reproducible results. Temperature affects stratum corneum water distribution: higher ambient temperature increases transepidermal water loss, temporarily altering surface readings. Relative humidity determines the hydration equilibrium of the outer stratum corneum layers. Physical activity immediately before measurement elevates skin temperature and sweat output, both of which confound readings. Topical products applied within four hours of measurement leave a residual film that artificially elevates capacitance [4].

Time of day also matters. Skin hydration follows a diurnal rhythm, with peak values typically in the early afternoon and lower values in the morning and evening. Standardizing measurement time to a defined window — in this study, 10:00–14:00 — removes this source of within-subject variability. Probe pressure and contact angle affect the sensor–skin interface; standardized perpendicular application with consistent pressure is required.

### 1.3 Multi-zone facial measurement

The face is not a uniform tissue. Sebaceous gland density, epidermal thickness, vascular supply, and chronic UV exposure history differ substantially across anatomical sites. The forehead has high sebaceous density; the periorbital zone has the thinnest epidermis; the cheeks receive differential sun exposure depending on occupational and behavioral factors. A single-site measurement therefore does not represent the face as a whole. A seven-zone protocol — forehead center, nose tip, chin, bilateral cheeks, and bilateral periorbital zones — captures this topographic variability and allows zone-specific analysis alongside a composite BT-mean [1, 4].

Zone-specific data are particularly valuable when asymmetry is suspected. Factors such as chronic UVA exposure through automotive side glass, habitual sleeping position, or unilateral wind exposure can produce lateralized hydration differences that would be invisible in a single-point measurement. The seven-zone protocol makes these patterns detectable.

## 2. Methods

### 2.1 Study design

A cross-sectional observational pilot study was conducted at a licensed esthetic practice in Winter Garden, Florida (ClinicalTrials.gov: NCT07564869; Protocol ID: IAS-SKIN-2026-001). The study followed STROBE reporting guidelines [5]. Written informed consent was obtained from all 30 participants. The study involved only non-invasive bioimpedance measurements and standardized photography.

### 2.2 Participants

Thirty women aged 30–60 years (three age groups,  $n = 10$  each) were enrolled by convenience sampling. Inclusion: attendance without makeup or cosmetic products for  $\geq 4$  hours. Exclusion: active dermatological disease, injectable procedures within 6 months, systemic skin-affecting medications, pregnancy, or lactation.

### 2.3 Measurement protocol

The BT-Analyze sensor was applied to seven facial zones in standardized sequence: forehead center, nose tip, chin, right cheek, left cheek, right periorbital, left periorbital. Each zone was measured three times consecutively. Measurements were taken after 20 min acclimatization in a controlled room (20–22°C, 40–60% relative humidity) between 10:00 and 14:00. The probe was disinfected with 70% isopropyl alcohol between participants. Zone score was the mean of three readings; BT-mean was the mean of all seven zone scores.

### 2.4 Visual aging assessment

A blinded expert cosmetologist ( $\geq 7$  years clinical experience) rated all 30 photographs using a six-criterion modified Glogau scale (0–18 points) [2]. Photographs were standardized (50-cm distance, dual softboxes at 45°, neutral gray background, manual camera mode). The assessor received images labeled with anonymous codes in randomized order, without access to hydration data or participant age.

## 2.5 Statistical analysis

Primary: Spearman rank correlation ( $r_s$ ) between BT-mean and Glogau score. Secondary: multiple linear regression with BT-mean, age, Fitzpatrick type, moisturizer use, and menopausal status as predictors; partial Spearman correlation controlling for age; zone-specific Spearman correlations. All analyses: Python (SciPy v1.11, NumPy v1.24). Significance threshold:  $\alpha = .05$ , two-tailed.

## 3. Results

### 3.1 Descriptive statistics

All 30 participants completed the visit. Mean age:  $44.7 \pm 8.1$  years (range 33–60). Overall BT-mean:  $33.91 \pm 10.24$  units. Mean Glogau score:  $8.13 \pm 3.32$ . Kruskal-Wallis test across three age groups was not significant for BT-mean ( $H = 1.87$ ,  $p = 0.393$ ) or Glogau score ( $H = 1.64$ ,  $p = 0.439$ ).

### 3.2 Primary correlation

BT-mean correlated negatively with Glogau score ( $r_s = -0.796$ ,  $p < 0.001$ ,  $n = 30$ ). Multiple regression:  $R^2 = 0.703$ , adj.  $R^2 = 0.640$ ,  $F(5,24) = 11.33$ ,  $p < 0.001$ . BT-mean was the sole significant predictor ( $\beta = -0.250$ ,  $SE = 0.040$ ,  $p < 0.001$ ). Partial  $r_s$  controlling for age:  $-0.745$  ( $p < 0.001$ ).

### 3.3 Zone-specific results

All seven zones reached significance ( $p \leq 0.004$ ; Table 1). The left cheek produced the strongest association ( $r_s = -0.811$ ), followed by the right cheek ( $r_s = -0.759$ ) and forehead ( $r_s = -0.727$ ). The nose was weakest ( $r_s = -0.572$ ,  $p = 0.001$ ). The inter-zone variability (mean CV = 23.3%) reflects genuine anatomical differences in sebaceous density and UV exposure history rather than instrument imprecision.

**Table 1.** Zone-specific Spearman correlations with Glogau visual aging score ( $n = 30$ )

| Facial Zone       | $r_s$         | p-value | Significance |
|-------------------|---------------|---------|--------------|
| Left cheek        | <b>-0.811</b> | <0.001  | ***          |
| Right cheek       | -0.759        | <0.001  | ***          |
| Forehead          | -0.727        | <0.001  | ***          |
| Chin              | -0.723        | <0.001  | ***          |
| Left periorbital  | -0.635        | 0.0002  | ***          |
| Nose              | -0.572        | 0.001   | **           |
| Right periorbital | -0.507        | 0.004   | **           |

\*\*\* $p < 0.001$ ; \*\* $p < 0.01$ . Ranked by  $|r_s|$ .

## 4. Discussion

### 4.1 Engineering conditions as prerequisite for valid data

The correlation between BT-mean and visual aging ( $r_s = -0.796$ ) was obtained under carefully controlled measurement conditions. Temperature, humidity, measurement timing, product exclusion, and probe technique were all standardized. Without these controls, measurement-to-measurement variability would obscure the biological signal. Esthetic practices implementing bioimpedance assessment should treat these engineering conditions as mandatory protocol elements, not optional precautions.

The 20-minute acclimatization period is particularly important. Skin equilibrates with ambient temperature and humidity within this window; measurements taken before equilibration reflect transit conditions rather than resting skin state. The fixed measurement window (10:00–14:00) controls for diurnal hydration variation. The four-hour product exclusion removes the confounding effect of topical residue on capacitance readings.

### 4.2 Clinical value of zone-specific mapping

The finding that all seven zones reached significance, but with coefficients ranging from  $-0.507$  to  $-0.811$ , demonstrates that a composite BT-mean conceals meaningful topographic

variation. The left cheek–right cheek difference ( $r_s = -0.811$  vs.  $-0.759$ ) is small in absolute terms but directionally consistent with expected asymmetric UVA exposure in Florida drivers, where automotive side-door glass transmits UVA to the driver's left side [6]. Zone mapping makes this kind of asymmetry detectable in routine practice.

For practitioners, the zone-specific profile has direct clinical utility: it identifies which facial areas show the greatest hydration–aging association, informing both assessment focus and targeted treatment recommendations.

### 4.3 Limitations

The pilot sample ( $n = 30$ , single center, convenience sampling) limits statistical power and generalizability. Cross-sectional design does not permit causal conclusions. The BT-Analyze measures stratum corneum hydration only; dermal water content requires high-frequency ultrasound for direct assessment. A single blinded assessor was used for visual aging rating, precluding inter-rater reliability estimation. The Glogau scale used here is a modified version without independent validation data.

### 5. Conclusions

Bioimpedance skin assessment, when conducted under standardized engineering conditions, produces hydration data that correlate strongly with visual aging outcomes independently of age. The seven-zone facial protocol described here is feasible in outpatient esthetic settings, requires no biological samples, and generates numeric data suitable for longitudinal tracking. Zone-specific mapping adds information not available from single-site measurement. Engineering rigor in measurement conditions is the prerequisite for clinically meaningful data.

### Conflict of Interest

The author is the founder of the esthetic practice where data were collected. No commercial products were evaluated; no financial relationships with device manufacturers exist.

### Funding

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### References:

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