The ocular surface electrical impedance: device development and proof-of-concept

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INTRODUCTION

The ocular surface is a dynamic and highly sensitive interface reflecting both local and systemic physiological processes.

Current diagnostic approaches rely on subjective evaluation and fragmented biomarkers, limiting the ability to capture the integrated physiological state of the tissue.

Electrical impedance analysis offers a potential method to characterize tissue properties in a rapid, objective, and noninvasive manner.

PURPOSE

To describe the engineering development and proof-of-concept evaluation of a second-generation ocular surface electrical impedance device with improved sensitivity, speed, and reproducibility, and to characterize its performance through simulations, laboratory phantoms, and exploratory measurements in healthy and pathological conditions.

METHODS

A redesigned multi-frequency impedance system was developed with optimized electrodes, improved shielding, and a new acquisition board enabling stable measurements across 500 Hz to 64 kHz.

Finite-difference simulations modeled tear-film thinning and osmolarity changes (dry eye) and subepithelial alterations (ocular pemphigoid).

Laboratory phantoms replicating ocular surface electrical properties were used for calibration and validation.

Exploratory in-vivo measurements were obtained in healthy subjects and patients with dry eye or ocular pemphigoid.

Data were normalized across frequencies and analyzed using principal component analysis (PCA) and supervised machine-learning classifiers, including Linear Discriminant Analysis (LDA), with 5-fold cross-validation.

DEVICE / SYSTEM DESCRIPTION

The IMPEL system integrates a portable processing unit with a microengineered contact sensor designed for controlled interaction with the ocular surface (figures 1-4).

The device enables ultrafast (<1 second), noninvasive impedance measurements across a wide frequency range.

By applying controlled electrical excitation and measuring tissue response, the system captures the integrated electrical signature of the ocular surface, reflecting underlying physiological conditions.

Figure 1. IMPEL processing unit. Prototype device integrating acquisition hardware, signal processing, and user interface for real-time multifrequency impedance analysis.

Figure 2. Ocular surface sensor. Sensor designed for controlled contact with the ocular surface, enabling stable acquisition of electrical signals across a wide frequency range.

Figure 3. Sensor lateral detail. Miniaturized electrode architecture optimized for reproducibility and signal stability.

Figure 4. Sensor tip (frontal view). Central electrode configuration used for localized impedance measurements.

The signal itself contains physiological information
Machine learning interprets, not creates the signal

RESULTS

Simulations revealed frequency-dependent impedance patterns associated with tear-film thinning and subepithelial alterations.

Phantom testing demonstrated high repeatability and linear responses across the evaluated frequency range.

Exploratory in-vivo measurements showed distinct impedance behaviors between healthy and pathological conditions after normalization.

Dimensionality reduction (PCA) and supervised analysis confirmed that the acquired signals contain structured and discriminative information (figure 5).

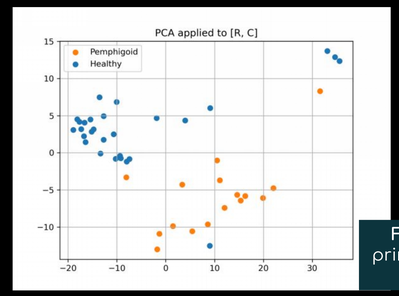

Figure 5. Normalized impedance data projected into principal component space showing separation between healthy, dry eye, and ocular pemphigoid groups.

CONCLUSIONS

This second-generation device enables rapid, noninvasive ocular surface impedance measurements and demonstrates proof-of-concept ability to distinguish healthy and pathological states.

The results indicate that impedance-based sensing captures physiologically relevant tissue properties, while dimensionality reduction and machine-learning methods enable robust interpretation of the acquired signals.

These findings support ongoing optimization and further clinical validation of impedance-based ocular surface sensing as a novel diagnostic approach.

Disclosures for Bonetto, Bellotti, Saravia: Code P (Patent):US Patent: US 12,402,801 B2

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