

# Electronic Contact Lenses as a 3P Medicine Tool: the Electrode Lead System Modeling

Dmitry M. Shamaev<sup>1,2\*</sup>, Elena N. Iomdina<sup>3</sup>, and Petr V. Luzhnov<sup>1</sup>

<sup>1</sup> Bauman Moscow State Technical University, 5 2nd Baumanskaya str., p.1, Moscow 105005, Russia

<sup>2</sup> Saint Petersburg Federal Research Center of the Russian Academy of Sciences, 39 14th Line V.O., Saint Petersburg 199178, Russia

<sup>3</sup> Helmholtz National Medical Research Center of Eye Diseases, 14/19 Sadovaya-Chernogryazskaya str., Moscow 105062, Russia

\*e-mail: [shamaev.dmitry@yandex.ru](mailto:shamaev.dmitry@yandex.ru)

**Abstract.** Electronic contact lenses (ECL) are a high-tech solution for diagnosing, including early, both ophthalmic and systemic diseases. The authors of the article propose the implementation of 3P medicine approaches by integrating electrodes and circuits into the ECL to realize bioelectrical impedance spectroscopy (BIS) of the anterior eye. This helps to analyze the blood circulation parameters of this part of the eye. Electrode lead system modeling integrated into the contact lens was carried out by using the finite element method. It was obtained for the correct operation, the presence of an electrically insulating layer between the biological tissues of the eye and the main material of the contact lens is necessary. The electrode diameter is 0.8 mm, and the optimal distance between the current electrodes should be 6 mm, between the potential – 4 mm. Assessment of the power level required for BIS shows the possibility of technical implementation of this methodology from an energy point of view. © 2023 Journal of Biomedical Photonics & Engineering.

**Keywords:** electronic contact lenses; ECL; biomarker; 3P medicine; bioimpedance; electrodes; lead system.

Paper #8974 received 12 May 2023; accepted for publication 6 Sep 2023; published online 13 Nov 2023. doi: [10.18287/JBPE23.09.040306](https://doi.org/10.18287/JBPE23.09.040306).

## 1 Introduction

The modern level of science and technology makes it possible to manufacture miniature devices for solving a wide range of medical problems. For example, electronic contact lens (ECL) is one of the high-tech solutions that significantly expand diagnostic and therapeutic possibilities in ophthalmology. The main advantage of ECL is the possibility of patient long-term wear. This allows us to analyze changes in a particular parameter over a long period, and not at separate moments when the patient is in a medical institution. The work [1] describes ECLs used for daily monitoring of intraocular pressure (IOP). Other developments show that it is possible to control systemic parameters, for example, the level of glucose in the blood that the corresponding level of glucose in the tear. This relationship was proved only in 2020 [2].

Many laboratories around the world develop miniature devices underway aimed at integrating classical or innovative sensors and circuits, including implementing wireless technologies for transmitting energy and information, into contact lenses

## 2 3P-Medicine, Tear Biomarkers, and Functional Indicators of the Anterior Part of the Eye

In the example of glucose control, it can be seen that the use of ECL allows the realization of personalized treatment. This means that you can find the required amount of medication for a particular person in a particular situation by focusing on the current concentration of glucose in his tear. Analysis of the dynamics of glucose levels makes it possible to determine objective criteria for predictive diagnosis, i.e.

predicting the nature of the development of the disease in a particular patient and choosing preventive treatment tactics on this basis. Thus, the 3P principle is realized: predictive, personalized, preventive medicine.

As known these principles began in the early 2000s, but they only became widespread a decade later, when it became obvious that the reactive approach in medicine was not effective [3].

As a result, the European Association for Predictive, Preventive, and Personalized Medicine (EPMA) was formed in Europe in 2008 [4]. The above principles are enshrined in law in the Russian Federation by the Order of the Ministry of Health of the Russian Federation No. 186 dated April 24, 2018 “On Approval of the Concept of Predictive, Preventive and Personalized Medicine” and included by Order of the Government of the Russian Federation dated December 28, 2012 No. 2580-r in the Strategy for the Development of Medical Science in the Russian Federation for a period until 2025. It is worth noting that in some publications you can find such terms as 4P- and 5P-medicine [5, 6]. The fourth P means participation, i.e. the patient must be involved in the process of diagnosis and treatment. The fifth P is psycho-cognitiveness. That means that the provision of medical services should take place taking into account the psychophysical state of the patient during diagnostic studies, and therapeutic and surgical manipulations, and, accordingly, the involvement (fourth P) of the patient will be more effective.

Human tears as one of the biological fluids contain a wide set of biomarkers. It is known that there are certain correlations between the concentrations of various components in tears and blood. Some examples of these are given in Table 1 [7].

Table 1 Concentrations of different components in tears and blood [7].

| Component       | Tear concentration | Blood concentration |
|-----------------|--------------------|---------------------|
| Na <sup>+</sup> | 120–165 mM         | 130–145 mM          |
| K <sup>+</sup>  | 20–42 mM           | 3.5–5 mM            |
| Glucose         | 0.1–0.6 mM         | 4.0–6.0 mM          |
| Urea            | 3.0–6.0 mM         | 3.3–6.5 mM          |
| Lactate         | 2–5 mM             | 0.5–0.8 mM          |
| Pyruvate        | 0.05–0.35 mM       | 0.1–0.2 mM          |
| Ascorbate       | 0.008–0.04 mM      | 0.04–0.06 mM        |
| Total protein   | ~ 7 g/L            | ~ 70 g/L            |

It is worth noting that the measurement of the concentrations of certain biomarkers in a tear is associated with certain difficulties associated with the fact that the tear fence should not be unsimulated. So, as

noted above, the direct dependence of the concentration of glucose in a tear on the concentration of glucose in the blood was proved only in 2020 [2]. Previously, this could not be proved for few years, because, as it was found later, a small amount of blood fell into samples of tear fluid.

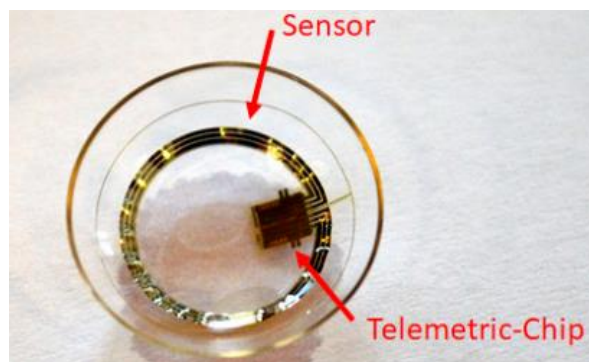
Contact lenses can help to solve the issue of the correct fence of tear fluid, as well as ensure the possibility of prolonged and continuous monitoring. Ordinary contact lenses are already widespread, can be worn for a long time, and do not cause significant discomfort to the patient. The modern level of microelectronics and technology allows to integration electronic circuits and sensors directly into contact lenses, thereby allowing to obtain high-tech minimally invasive diagnostic devices.

### 3 Electronic Contact Lenses

Each of these indicators, individually or in combination, can be used as a biomarker that is informative in the diagnosis and monitoring of some diseases. This correlation makes it possible to use tear fluid indicators as diagnostic and prognostic criteria not only for ophthalmic but also for systemic diseases, for example, in Alzheimer’s, Parkinson’s, thyroid gland, in some types of oncology, etc. [8]. In addition to chemicals in the tear, biomarkers can be physiological indicators, such as the IOP, the determination of which is necessary for the diagnosis and control of glaucoma. In modern ophthalmic practice, the analysis of lacrimal fluid is not very widespread, because it is to the complexity of accurate and unstimulated sampling of this biological fluid. This procedure can be made only by medical staff in a medical institution. This is especially related to measuring physiological parameters, for example, IOP.

As is said above electronic contact lenses can help solve the problem of long-term monitoring of biomarkers because the patient can wear them for a day or more. The modern level of microelectronics and technologies makes it possible to integrate biosensors and digital electronics with information and energy transmission channels into smart contact lenses.

The ECLs are the reality today because they have already been used in clinical practice since 2016 when the TriggerFish product (Switzerland) received approval from the US Food and Drug Administration (FDA) for clinical use in the US [9]. Fig. 1 shows a general view of such a product and its placement on the eye for measuring IOP during the day [10]. In the literature, one can find the results of laboratory studies aimed at integrating sensors of various types into ECLs [8]. The ECL measures the IOP during the day and is used to evaluate high-quality the minimum invasive surgery for the treatment of glaucoma or cataracts has been performed. It is known that the IOP has daily fluctuations. IOP is recorded before and after surgery by using ECL. In case of circus rhythms are not significantly disturbed, this means that the surgical operation was performed qualitatively and the patient has a favorable forecast for recovery after surgery.



(a)



(b)

Fig. 1 TriggerFish electronic contact lenses for measuring intraocular pressure [10], (a) ECL photo, (b) ECL on the eye.

Bauman Moscow State Technical University in cooperation with Helmholtz National Medical Research Center of Eye Diseases is developing ECL, in which it is planned to integrate a tetrapolar electrode lead system for the implementation of bioelectrical impedance spectroscopy (BIS) of the hemodynamics of the anterior eye. This technique appeared in the 60s, one should use double anesthetics and put on a suction cup on the open eye. Development is based on the experience of the above team on the of a transpalpebral research methodology development, i.e. through a closed eyelid, which makes it possible to refuse anesthesia [11]. The BIS makes it possible to study the parameters of blood circulation in the anterior eye, which are informative biomarkers of many ophthalmic diseases, for example, myopia, especially in the early stages of development, including in children. Work results on the development of a transpalpebral methodology were introduced into the work of the Helmholtz National Medical Research Center of Eye Diseases.

The logical development of the above technology is the integration of the electrode system in ECL. This makes it possible to implement the approaches of 3P medicine and control the dynamics of pulse blood filling of the anterior eye, which is impossible when using the transpalpebral technique or any other that is carried out

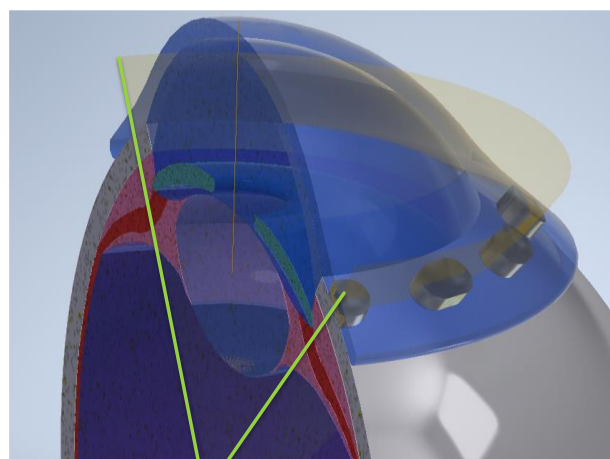
exclusively in a medical institution. Among the existing ECL developments that analyze various biomarkers of the eyes, most developments are aimed at the biochemical indicators of tears. A separate ECL class is aimed at analyzing intraocular pressure, or rather the dynamics of its physiological parameter. This is because the sensors are installed not inside the eye, but from the outside, and evaluation of intraocular pressure is based on some mathematical models according to indirect signs. The literary review did not reveal developments aimed at the implementation of bioelectrical impedance spectroscopy in the ECL. In this regard, there is no information about geometric and constructive parameters of electrode lead system in the literature.

We have simulated the BIS by the finite element method when the electrode lead system is integrated into the ECL. We can use a three-dimensional model developed in the work [12], which is shown in Fig. 2. It is an anatomically reliable three-dimensional model of the eyeball with located electrodes and, considering the blood supply system of the eye.

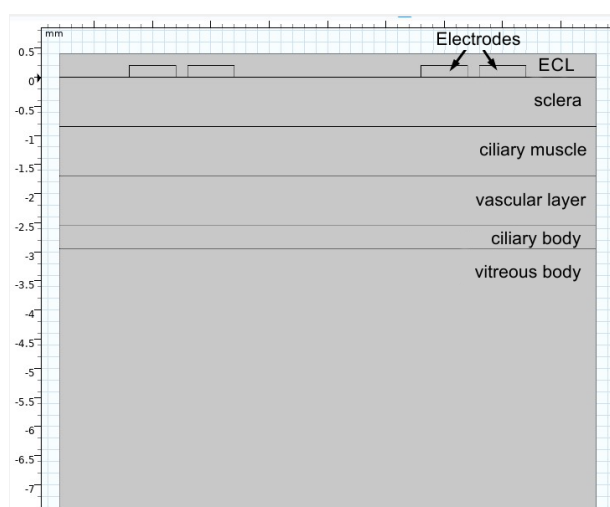
As a rule, the presence of blood circulation in the eyeball models is considered an artifact and neglect it. However, in this case, blood circulation is a central object of study and cannot be neglected. It is considered that the eyeball consists of about 40 different types of tissues, in the model geometry is 9 of the most pronounced tissues of the eye, one of which is the blood structures of the eye (shown in Fig. 2(a) in red color in the model). The geometry is based on an anatomical atlas having dimensional scales. The assumption is also made that the parameters of the blood supply layer are represented by blood parameters.

BIS is carried out at a frequency of 100 kHz and a current of 4 mA. It is possible to use a double-electrode or four-electrode research scheme. Because when using the four-electrode scheme, the resistance of the electrode-tissue does not fall into the measured value, such a measurement scheme is considered preferable. In such a study, two electrodes are used to skip high-frequency current through tissues and are located outside, and two other electrodes are located between them for measurement. Due to this, there are no significant restrictions on the placement of the electrodes, then the framework of this work investigates a 4-electrode connection scheme. All electrodes, as a rule, have the same geometry.

Since the object of the study is the most blood supply of the anterior eye, the electrodes for the ECL should be located as close to them as possible. During anatomy and on the three-dimensional model it is clear that the most optimal location will be the electrode's location near the eye limb. Because of this, the model of symmetry can be distinguished from the model, which looks in the form of a cone (shown in Fig. 2(a) in the form of an orange surface and green lines in a cross-sectional plane). This surface passes through all the electrodes. The angle between the forming and the axis of the cone is selected so that the surface passes through the widest part of the circulatory layer and the geometric center of the eyeball.



(a)



(b)

Fig. 1 Models of the eyeball. (a) A three-dimensional model of the eyeball with installed electrodes, (b) layers in a two-dimensional model of the eye.

Within the framework of this work, based on the above surface, a flat model was formed, which includes five layers of the eyeball, electrodes, and directly the material of the contact lens, which is shown in Fig. 2(b).

Table 2 shows the specific electrical conductivity and relative dielectric permeability of individual eye tissues at a frequency of 100 kHz used in the model [13]. The current source is set on the right electrode, the left electrode was used as grounded. Because the ECL is installed on the open eye, the system is moistened with tear liquid, and the conjunctiva, presumably, does not have any electrical insulating properties, it is assumed that there is no resistance between electrode and tissue.

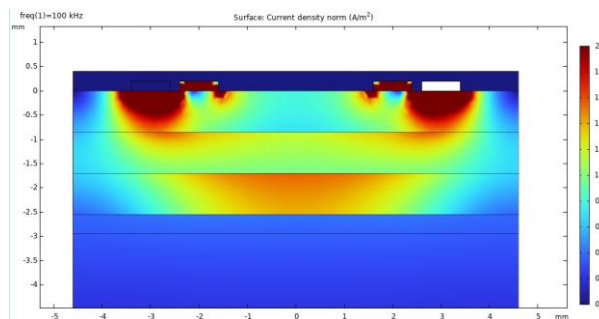
It was obtained that for correct BIS, it is necessary that an electrically insulating layer is necessary between the eye tissues and the material. Only the surface of the electrodes should be in contact with the surface of the sclera. Otherwise, if the electrical conductivity of the ECL material is comparable to the electrical conductivity of the eye tissue, then almost the entire current passes through the ECL, which makes the BIS study of the

vascular layer of the anterior eye extremely unfortunate to changes in the pulse blood supply.

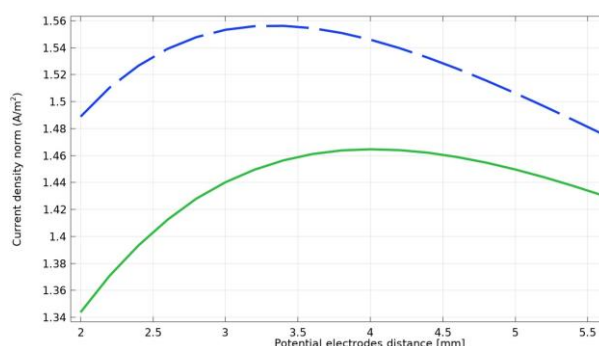
If we use an electrical insulating layer between the tissue and the ECL, the voltage on potential electrodes is 7.9 mV. Fig. 3(a) shows the resulting distribution of current density in the eye tissues. Pulse blood supply was modeled by a change in the conductivity of the vascular layer. The level of blood supply to the eye is about 1 ml per minute, and on average 0.018 ml of blood flows in the eye. That is why, the increment of the conduction of the vascular layer in one heart blow will be about 0.3%. The amendment to the model showed that the amplitude of the recorded pulse blood supply should be 5.6  $\mu$ V. This is comparable to the real voltage levels recorded in BIS studies of other areas of the body, and can be measured by ordinary electronics.

Table 2 Eye tissue properties used in the model (100 kHz) [13].

| Eye tissue     | Conductivity, S/m | Relative permittivity |
|----------------|-------------------|-----------------------|
| Sclera         | 0.5               | 37.5                  |
| Ciliary body   | 0.40              | 66.1                  |
| Vascular layer | 1.35              | 64.2                  |
| Ciliary muscle | 0.84              | 58.8                  |
| Vitreous body  | 0.40              | 66.2                  |



(a)



(b)

Fig. 3 Simulation results. (a) Current density distribution [A/m<sup>2</sup>] in the eye tissues of the anterior eye. (b) Current density in the vascular layer: the dotted line is the maximum, and the solid line is the average.

The voltage on the current electrodes was 15 mV, so the necessary power for the study is about 60  $\mu$ W. Compared to ECL, which is developed by other teams, this value is small, even considering that when implementing the methodology, it will be necessary to implement other electronic components from measuring cascades to the wireless transmission and energy transmission schemes [14]. This confirms the potential for the integration of electrodes for EI in electronic contact lenses.

The optimal electrodes location was studied during the simulation. Fig. 3(b) shows graphs of the current density as a function of the interelectrode distance. The distance between the potential electrodes was changed by step 0.1 mm, the center of current electrodes was located at a distance of 1 mm from the center of potential ones. The size of the electrodes was 0.8 mm in diameter. The results showed that the maximum current density at a single point of the vascular layer can be achieved with an interelectrode distance of 3.4 mm. However, it is not correct to use the maximum value of the current density in a separate layer for BIS; it is more correct to use the average value, which reflects the total amount of current passing through the vascular layer. In this case, the optimal location of potential electrodes is at a distance of 4 mm, and current electrodes are at a distance of 6 mm. This will give the greatest sensitivity to pulse fluctuations in the blood filling of the anterior eye at the depth of the ciliary body. Moreover, with such an arrangement of the electrodes, there is no such significant difference in current densities within the boundaries of one vascular layer, as in the presence of the maximum found value, i.e. with a wider arrangement of electrodes, the current density is distributed more evenly, which will contribute to the fact that the integral estimate of the density while in the desired layer will be more correct.

## 4 Conclusion

The ECL alloys wide opportunities allow you to realize modern concepts in the organization of healthcare – 3P-medicine. The main advantage of the ECL is the possibility of prolonged non-invasive monitoring of biomarkers of both ophthalmic and systemic indicators

of the body. Most of the existing works of large scientific groups are aimed at developing ECL for the analysis of biochemical markers contained in a tear. For this, innovative sensory systems are developed, but there are almost no sensors for the analysis of physiological indicators of the eye, except for systems for analyzing intraocular pressure. The electrode lead system in an electronic contact lens proposed in the work will implement the methodology of electroimpedance research. This will analyze the level of blood supply of the anterior eye. At the same time, no other method, widespread in ophthalmology, does not allow analyzing the level of blood supply to the front part of the eye. Based on the proposed two-dimensional model, modeling the distribution of currents in the fabrics of the front department of the eye was carried out during BIS in case the electrodes are located decently, i.e. on the sclera along the iris of the eye. Modeling made it possible to determine the optimal location of the electrodes in the electrode lead system, which is supposed to integrate into the ECL. It is 4 mm between potential electrodes and 6 mm between current ones with an electrode size of 0.8 mm. In this case, the presence of an electrically insulating layer between the tissues of the eye and the main material of the contact lens is necessary. In addition to the development of the diving system directly, it is necessary to develop schematic solutions for the implementation of the BIS methodology, power schemes, and information transmitting through wireless communication channels, while they should be integrated into contact lenses and have the properties of bioadexcence and biocompatibility. This is material for subsequent research and development.

## 5 Acknowledgment

The work was supported by the RF Presidential Grant for State Support of Leading Scientific Schools № HIII-122.2022.1.6.

## Disclosures

The authors declare no conflict of interest.

## References

1. K. Gillmann, G. E. Bravetti, L. J. Niegowski, and K. Mansouri, “[Using sensors to estimate intraocular pressure: a review of intraocular pressure telemetry in clinical practice](#),” *Expert Review of Ophthalmology* 14(6), 263–276 (2019).
2. M. Aihara, N. Kubota, T. Minami, R. Shirakawa, Y. Sakurai, T. Hayashi, M. Iwamoto, I. Takamoto, T. Kubota, R. Suzuki, S. Usami, H. Jinnouchi, M. Aihara, T. Yamauchi, T. Sakata, and T. Kadowaki, “[Association between tear and blood glucose concentrations: Random intercept model adjusted with confounders in tear samples negative for occult blood](#),” *Journal of Diabetes Investigation* 12(2), 266–276 (2021).
3. M. Flores, G. Glusman, K. Brogaard, N. D. Price, and L. Hood, “[P4 medicine: how systems medicine will transform the healthcare sector and society](#),” *Personalized Medicine* 10(6), 565–576 (2013).
4. O. Golubnitschaja, B. Baban, G. Boniolo, W. Wang, R. Bubnov, M. Kapalla, K. Krapfenbauer, M. S. Mozaffari, and V. Costigliola, “[Medicine in the early twenty-first century: paradigm and anticipation - EPMA position paper 2016](#),” *EPMA Journal* 7(1), 23 (2016).

5. S. G. Alonso, I. de la T. Díez, and B. G. Zapirain, “[Predictive, Personalized, Preventive and Participatory \(4P\) Medicine Applied to Telemedicine and eHealth in the Literature](#),” *Journal of Medical Systems* 43, 140 (2019).
6. B. Blobel, P. Ruotsalainen, and M. Giacomini, “[Standards and Principles to Enable Interoperability and Integration of 5P Medicine Ecosystems](#),” in *pHealth 2022: Proceedings of the 19<sup>th</sup> International Conference on Wearable Micro and Nano Technologies for Personalized Health*, B. Blobel, B. Yang, and M. Giacomini (Eds.), IOS Press, 3–19 (2022).
7. S. Tinku, C. Collini, L. Lorenzelli, and R. S. Dahiya, “[Smart Contact Lens Using Passive Structures](#),” *Sensors*, 2014 IEEE 2(5), 2107–2110 (2014).
8. L. Jones, A. Hui, C.-M. Phan, M. L. Read, D. Azar, J. Buch, J. B. Ciolino, S. A. Naroo, B. Pall, K. Romond, P. Sankaridurg, C. M. Schnider, L. Terry, and M. Willcox, “[BCLA CLEAR - Contact lens technologies of the future. Contact lens and anterior eye](#),” *Contact Lens and Anterior Eye* 44(2), 398–430 (2021).
9. “FDA permits marketing of device that senses optimal time to check patient’s eye pressure,” U.S. Food and Drug, 4 March 2016 (accessed 20 December 2022). [<https://www.fda.gov/news-events/press-announcements/fda-permits-marketing-device-senses-optimal-time-check-patients-eye-pressure>].
10. B. Pajic, M. Resan, B. Pajic-Eggspuehler, H. Massa, and Z. Cvejic, “[Triggerfish Recording of IOP Patterns in Combined HFDS Minimally Invasive Glaucoma and Cataract Surgery: A Prospective Study](#),” *Journal of Clinical Medicine* 10(16), 3472 (2021).
11. D. M. Shamaev, P. V. Luzhnov, T. O. Pika, E. N. Iomdina, A. P. Kleyman, and A. A. Sianosyan, “[Applying Transpalpebral Rheophthalmography to Monitor Effectiveness of the Treatment of Patients with Glaucoma](#),” *International Journal of Biomedicine* 6(4), 287–289 (2016).
12. D. Shamaev, P. Luzhnov, and E. Iomdina, “[Mathematical Modeling of Ocular Pulse Blood Filling in Rheophthalmography](#),” in *World Congress on Medical Physics and Biomedical Engineering 2018*, Springer Singapore, 495–498 (2019).
13. C. Gabriel, S. Gabriel, “[Compilation of the dielectric properties of body tissues at RF and microwave frequencies](#),” Final Report for the Period 15 December 1994–14 December 1995, King’s College London, UK (1996).
14. C. Jeon, J. Koo, K. Lee, M. Lee, S. K. Kim, S. Shin, S. K. Hahn, and J. Y. Sim, “[Smart Contact Lens Controller IC Supporting Dual-Mode Telemetry with Wireless-Powered Backscattering LSK and EM-Radiated RF Transmission Using a Single-Loop Antenna](#),” *IEEE Journal of Solid-State Circuits* 55(4), 856–867 (2020).