

**STOMATOLOGIYADA AQLLI INTRAORAL BIOSENSORLARDAN
FOYDALANISH: OG'IZ BO'SHLIG'I HOLATINI REAL VAQT REJIMIDA
MONITORING QILISH IMKONIYATLARI**

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ANNOTATSIYA

Maqolada stomatologiyada aqlli intraoral biosensorlardan foydalanish va og'iz bo'shlig'i holatini real vaqt rejimida monitoring qilishning zamonaviy imkoniyatlari tahlil qilindi. Tadqiqot birlamchi klinik tajriba emas, balki 2023–2026-yillardagi sistematik sharhlar, sensor-prototip tadqiqotlari, periodontal biomarker meta-tahlillari va O'zbekiston mualliflarining so'lak diagnostikasi hamda elektrokimyoviy sensorlarga oid ishlariga tayangan ikkilamchi dalillar sintezidir. 2024-yilgi sistematik sharhda 2384 topilmadan 11 tadqiqot kiritilib, 9 xil intraoral qurilma aniqlangan; 8 tadqiqot uzluksiz monitoring, 3 tadqiqot point-of-care formatida bo'lgan, 7 xil biomarker o'rganilgan va 6 ish so'lak glyukozasiga bag'ishlangan. Mouthguard-tipidagi glyukoza biosensori 5–1000 $\mu\text{mol/L}$ diapazonda ishlagan va telemetriya tizimi bilan 5 soatdan ortiq barqaror monitoring ko'rsatgan. Uric-acid mouthguard platformasi 2 Hz chastotada Bluetooth orqali real-time ma'lumot uzatgan. 2026-yilgi ikki nuqtali intraoral pH sensori standart eritmalarda $R^2 \geq 0,99$ va ICC 0,977–0,999 ishonchlilik ko'rsatgan. 2024-yilgi mouthguard-turbidlik sensori 1–4000 FTU dinamik diapazonda ishlagan; bitta saliva namunasida sensor 553 FTU, spektrofotometr esa 576 FTU qayd etgan. Periodontal monitoring uchun 2024-yilgi meta-tahlilda periodontit bemorlarida salivary MMP-8 sog'lomlarga nisbatan o'rtacha 273,26 ng/ml yuqori bo'lgan. Natijalar aqlli intraoral biosensorlar kariyes xavfi, xerostomia, og'iz gigiyenasi, periodontal faoliyat va ayrim tizimli biomarkerlarni uzluksiz kuzatish uchun katta potensialga ega ekanini ko'rsatadi. Biroq biofouling, kalibratsiya drift, sensorning og'izdagi biokompatibilligi, quvvat manbai, data privacy va klinik thresholdlar bo'yicha muammolar sabab ushbu texnologiyalar hozircha asosan proof-of-concept bosqichida.

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Kalit soʻzlar: intraoral biosensor, aqlli stomatologiya, soʻlak, real-time monitoring, pH sensor, glyukoza, laktat, MMP-8, wearable mouthguard, Bluetooth biosensor.

АННОТАЦИЯ

В статье рассматриваются современные возможности применения интеллектуальных внутриротовых биосенсоров для мониторинга состояния полости рта в режиме реального времени. Работа представляет собой синтез систематических обзоров, исследований прототипов сенсоров, метаанализов слюнных биомаркеров 2023–2026 гг. и публикаций авторов из Узбекистана. Систематический обзор 2024 года включил 11 исследований и девять различных внутриротовых устройств; восемь работ были посвящены непрерывному мониторингу, три — point-of-care приложениям, семь различных биомаркеров изучались, а глюкоза слюны была целью шести исследований. Mouthguard-биосенсор глюкозы работал в диапазоне 5–1000 мкмоль/л и обеспечивал стабильный телеметрический мониторинг более 5 часов. Новый двухканальный датчик pH 2026 года показал $R^2 \geq 0,99$ и ICC 0,977–0,999. Оптический mouthguard-сенсор мутности слюны работал в диапазоне 1–4000 FTU и показал 553 FTU против 576 FTU при спектрофотометрии. Для пародонтологического мониторинга метаанализ 2024 года выявил повышение MMP-8 в слюне при периодонтите в среднем на 273,26 нг/мл по сравнению со здоровыми лицами. Несмотря на высокий потенциал, большинство технологий остаются на стадии proof-of-concept и требуют клинической валидации, решения проблем биофуллинга, калибровки, энергоснабжения, безопасности данных и биосовместимости.

Ключевые слова: внутриротовой биосенсор, умная стоматология, слюна, мониторинг в реальном времени, pH-сенсор, глюкоза, лактат, MMP-8, mouthguard, Bluetooth.

ABSTRACT

This article evaluates the current potential of smart intraoral biosensors for real-time monitoring of oral health. It is a secondary evidence synthesis based on systematic reviews, prototype sensor studies, salivary biomarker meta-analyses published from 2023 to 2026, and selected Uzbek literature on salivary diagnostics and electrochemical sensors. A 2024 systematic review screened 2,384 records and included 11 studies describing nine intraoral devices; eight studies investigated continuous monitoring and three point-of-care applications. Seven biomarkers were studied, with salivary glucose evaluated in six studies. A mouthguard glucose biosensor demonstrated a working

range of 5–1000 $\mu\text{mol/L}$ and stable telemetry for more than five hours. A wearable uric-acid mouthguard transmitted amperometric measurements wirelessly at 2 Hz. A 2026 dual-site intraoral pH sensor achieved calibration $R^2 \geq 0.99$ and intraclass correlation coefficients of 0.977–0.999. A 2024 mouthguard turbidity sensor quantified 1–4000 FTU and measured 553 FTU in a saliva sample compared with 576 FTU by spectrophotometry. For periodontal monitoring, a 2024 meta-analysis found salivary MMP-8 to be 273.26 ng/mL higher in periodontitis than in healthy controls. Smart intraoral biosensors may enable continuous assessment of caries-related acidification, xerostomia, oral hygiene, periodontal activity, and selected systemic biomarkers. However, most systems remain proof-of-concept prototypes; biofouling, calibration drift, biocompatibility, energy supply, wireless security, and validated clinical thresholds remain major barriers to routine dental deployment.

Keywords: intraoral biosensor, smart dentistry, saliva, real-time monitoring, pH sensor, glucose, lactate, MMP-8, wearable mouthguard, Bluetooth biosensor.

KIRISH

Og'iz bo'shlig'i murakkab va dinamik biologik muhit bo'lib, unda pH, harorat, so'lak oqimi, elektrolitlar, metabolitlar, oqsillar, fermentlar, mikroorganizmlar va oziq-ovqat bilan bog'liq o'zgarishlar daqiqalar ichida yuz beradi. An'anaviy stomatologik diagnostika ushbu jarayonlarning faqat muayyan vaqtdagi holatini qayd etadi, holbuki kariyes va periodontal kasalliklar kabi jarayonlar doimiy dinamikaga ega.

Aqlli intraoral biosensorlar ushbu cheklovni bartaraf etishga qaratilgan yangi texnologik platformadir. Biosensor biologik yoki kimyoviy analitni elektroximik, optik, piezoelektrik yoki transistor asosidagi signalga aylantiradi; mini-elektronika esa ma'lumotni Bluetooth Low Energy, NFC yoki RFID orqali smartphone yoki cloud tizimiga uzatishi mumkin.

So'lak real-time monitoring uchun ayniqsa qulay biofluid hisoblanadi. U non-invasiv olinadi va glyukoza, laktat, uric acid, pH, natriy, kaliy, kaltsiy, fosfat, ftorid, cytokine va protein markerlarni o'z ichiga oladi. Shu bilan birga saliva flow, viskozlik, ovqatlanish, sutkalik ritm va biofilm sensor signaliga ta'sir qiladi.

Timpel va hammualliflarning 2023-yilgi sharhi glucose, lactate, fluoride, calcium, phosphate va pH ni intraoral sensorlar bilan in-situ kuzatish stomatologik va tizimli health monitoring uchun muhimligini ta'kidlaydi. Biroq hozirgacha uzoq muddatli va

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barqaror real-time intraoral measurementni bajaradigan ishlaydigan sensorlar soni kam.

2024-yilgi systematic review intraoral biosensor texnologiyasining klinik yetukligini maxsus baholagan. 2384 manbadan atigi 11 tadqiqot inclusion criteria ga mos kelgan, bu sohaning ilmiy jihatdan tez rivojlanayotgan, ammo hali kichik dalil bazasiga ega ekanini ko'rsatadi.

Stomatologik nuqtayi nazardan eng muhim biosensor vazifalaridan biri pH monitoringdir. Og'iz pHining shakar qabulidan keyingi tez pasayishi dental plaque acidogenicity, enamel demineralization va kariyes xavfi bilan bog'liq. Bir martalik chairside pH o'lchovi bu kinetikani to'liq ko'rsatmaydi; wearable sensor esa postprandial pH recovery curve ni qayd etishi mumkin.

Ikkinchi istiqbolli yo'nalish periodontal biomarker monitoringidir. Salivary MMP-8, IL-1 β va MMP-9 periodontal tissue destruction va inflammatory activity bilan bog'liq. Real-time yoki frequent biosensor measurement klinik probingdan oldin molekulyar faollik signalini aniqlash imkoniyatini nazariy jihatdan yaratadi.

Mouthguard, retainer, tooth-mounted hydrogel, cavity sensor, smart pacifier, dental floss va toothbrush-based sensorlar intraoral platforma sifatida sinovdan o'tgan. Ularning afzalligi sensorni biologik manbaga yaqin joylashtirish va natural oral activity davomida ma'lumot olishdir.

Asosiy qism

O'zbekistonda so'lak diagnostikasi va elektrokimyoviy sensorlar bo'yicha ilmiy qiziqish kengaymoqda. Abdullaeva va hammualliflar (2025) saliva ning oral homeostasis va systemic diagnosticsdagi rolini yoritgan; Xushboqov va Eshkaraev (2025) elektrokimyoviy sensorlarning real-time tibbiy monitoringdagi ahamiyatini tahlil qilgan. Mahalliy stomatologik ishlarda so'lakning mineral va biokimyoviy tarkibi ham diagnostik obyekt sifatida o'rganilgan.

Tadqiqotning maqsadi stomatologiyada aqlli intraoral biosensorlarning hozirgi texnologik imkoniyatlarini dalillar asosida tizimlashtirish, real-time pH, glyukoza, laktat, uric acid, turbidlik va periodontal biomarker monitoringini qiyoslash, klinik qo'llanish sohalarini aniqlash hamda cheklov va rivojlanish yo'nalishlarini baholashdan iborat.

Ushbu maqola birlamchi laborator yoki klinik tajriba emas, balki ikkilamchi dalillar sintezidir. Asosiy manbalar sifatida intraoral wearable biosensor systematic reviewlari,

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in-situ salivary sensor reviewlari, mouthguard biosensor prototiplari, 2026-yilgi continuous pH pilot study, periodontal salivary biomarker meta-tahlillari va O'zbekiston manbalari tanlandi.

Texnologiyalar to'rt guruhda baholandi: (1) electrochemical enzymatic sensors — glucose, lactate, uric acid; (2) potentiometric ion/pH sensors — pH, sodium, potassium, calcium, fluoride; (3) optical sensors — turbidlik va biofilm bilan bog'liq signal; (4) immuno/electrochemical biosensors — MMP-8, IL-1 β va boshqa periodontal biomarkerlar.

2024-yilgi systematic review 2384 topilmani screening qilib, 11 study ni final synthesisga kiritgan. 9 xil device platforma qayd etilgan; 8 study continuous biomarker monitoring, 3 study POC approach bo'lgan. 7 biomarker o'rganilgan va glucose 6 study bilan eng ko'p tahlil qilingan. Faqat 5 study in-vivo komponentga ega bo'lgan.

Arakawa va hammualliflarning mouthguard glucose sensorida Pt working electrode va Ag/AgCl reference electrode PETG mouthguardga integratsiya qilingan. Glucose oxidase membrane orqali artificial saliva ichida 5–1000 $\mu\text{mol/L}$ oralig'ida signal olingan va phantom jaw sharoitida wireless telemetry bilan 5 soatdan ko'proq real-time monitoring bajarilgan.

Kim va hammualliflarning lactate mouthguard platformasi printable enzymatic electrode va lactate oxidase asosida ishlagan. Keyingi sharhlarda inson saliva testingida lactate response bilan reference qiymatlar orasida korrelyatsiya koeffitsienti 0,988 va 2 soatlik monitoringda barqaror signal qayd etilgani ko'rsatilgan.

Uric-acid mouthguard sensor uricase-modified screen-printed electrode, potentiostat, microcontroller va BLE transceiverdan tashkil topgan. Wireless board har 0,5 sekundda signalni sampling qilib, ya'ni 2 Hz chastotada uzatgan; artificial saliva ichida 600 μM gacha calibration bajarilgan.

2026-yilgi pH pilot study maxsus mouthguardga anterior va maxillary molar buccal sohasida ikki pH sensor o'rnatgan. Standard solutionsda barcha sensor measurements uchun $R^2 \geq 0,99$, ICC 0,977–0,999 bo'lgan, bu calibration va repeatabilityning juda yuqori ekanini ko'rsatadi.

2024-yilgi salivary turbidity mouthguard sensor 405 nm LED va phototransistorni double-layer mouthguardga joylashtirgan. Dynamic range 1–4000 FTU bo'lib, reported salivary turbidity 400–800 FTU intervalini qamrab olgan. Bitta saliva sample sensor bilan 553 FTU, spectrophotometer bilan 576 FTU o'lchangan.

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Periodontal biomarkerlar bo'yicha 2024-yilgi MMP-8 meta-tahlil 20 periodontitis study va 1725 participant asosida periodontitisda healthy controlga nisbatan MMP-8 mean difference 273,26 ng/ml ni ko'rsatgan. Gingivitis vs healthy MD 122,82 ng/ml, periodontitis vs gingivitis MD 112,04 ng/ml bo'lgan.

Systematic-review darajasidagi dalil intraoral biosensorlar klinik jihatdan hali boshlang'ich bosqichda ekanini ko'rsatadi. 11 study ichida 8 tasi continuous monitoringga qaratilgan bo'lsa-da, faqat 5 study in-vivo komponentga ega bo'lgan. Bu laboratory feasibility bilan kundalik klinik foydalanish o'rtasida sezilarli translational gap borligini bildiradi.

Glyukoza mouthguard sensorlari eng ko'p o'rganilgan platformadir. 5–1000 $\mu\text{mol/L}$ salivary glucose intervali healthy va hyperglycemic oral concentrationsning keng qismini qamrab oladi. Sensorning 5 soatdan ortiq telemetry bilan ishlashi wearable oral platformaning uzoqroq continuous monitoring imkoniyatini ko'rsatgan.

2026-yilgi pH device ko'rsatkichlari real-time oral monitoringning yangi bosqichini bildiradi. $R^2 \geq 0,99$ calibration accuracy va ICC 0,977–0,999 repeatability sensorning analitik ishonchliligini ko'rsatadi. Shu bilan birga intraoral rehydration paytida ikki anatomical location orasida barqaror bo'lmagan farqlar kuzatilgani oral cavity ichida pH spatial heterogeneity mavjudligini ko'rsatadi.

Turbidity sensor oral hygiene holatini doimiy baholash uchun yangi surrogate marker sifatida taklif etilgan. Sensor 1–4000 FTU oralig'ida ishlagan va bitta real saliya sample uchun spectrophotometric measurementga juda yaqin natija bergan. Bunday optical biosensor biofilm/debris, salivary secretion va dryness bilan bog'liq dinamik o'zgarishlarni kuzatishda ishlatilishi mumkin.

Periodontal biosensorlar uchun MMP-8 eng kuchli evidence-supported targetlardan biridir. 2024-yilgi meta-tahlilda periodontitis patients salivary MMP-8 concentration healthy controlsdan o'rtacha 273,26 ng/ml yuqori bo'lgan; gingivitisda ham +122,82 ng/ml oshish qayd etilgan. Bu markerning disease continuum bo'yicha gradatsion signal berishini ko'rsatadi.

Aqlli intraoral biosensorlarning asosiy konseptual afzalligi stomatologik tashxisni statik "bir martalik ko'rik"dan dinamik biologik monitoringga o'tkazishidir. Misol uchun, bir bemorning resting salivary pH qiymati normal bo'lishi mumkin, lekin shakar iste'molidan keyin pHning pasayish chuqurligi va normalga qaytish vaqti uning kariyes xavfini yaxshiroq aks ettirishi mumkin.

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pH real-time sensing dental caries va erosion uchun eng klinik tushunarli use-case hisoblanadi. Critical pH individual mineral composition va saliva bufferingga bog'liq bo'lgani uchun kelajakdagi sensor faqat raw pH emas, acid exposure area-under-curve, recovery time va repeated daily episodes kabi digital phenotypeni hisoblash imkonini berishi kerak.

Glyukoza biosensorlari texnik jihatdan eng ko'p o'rganilgan bo'lsa-da, salivary glucose va blood glucose o'rtasidagi munosabat doimiy va universal emas. Diabetes monitoring uchun mouthguard glucose sensor clinical blood glucose device o'rnini egallashdan oldin individual calibration va large-scale validation talab qiladi.

Laktat, uric acid va boshqa metabolitlar oral-systemic interface uchun qiziqarli targetlardir. Laktat biofilm metabolism va exercise physiology bilan, uric acid oxidative balance va metabolic disease bilan bog'liq. Biroq dentistry use-case uchun signal oral disease endpoint bilan bevosita bog'lanishi kerak.

Periodontal biosensing alohida klinik qiymatga ega bo'lishi mumkin. MMP-8 concentration periodontitis severity bilan bog'liq va tissue breakdownning biochemical signali hisoblanadi. Agar wearable immunosensor MMP-8ni repeatedly o'lchay olsa, supportive periodontal care intervalini individual disease activity bo'yicha moslashtirish mumkin.

XULOSA

Aqlli intraoral biosensorlar og'iz bo'shlig'ining pH, metabolitlar, elektrolitlar, turbidlik va biomarker profilini real vaqt rejimida kuzatish orqali stomatologik diagnostikani dinamik monitoring modeliga o'tkazish potentsialiga ega.

2024-yilgi systematic reviewda atigi 11 study va 9 device aniqlangani, kiritilgan ishlarning aksariyati proof-of-concept bo'lgani ushbu texnologiya hali klinik yetuk bosqichga kelmaganini ko'rsatadi.

Glucose mouthguard platformasi 5–1000 $\mu\text{mol/L}$ diapazonda va 5 soatdan ortiq telemetry bilan, uric-acid sensor 2 Hz wireless sampling bilan, lactate sensor esa reference bilan $r=0,988$ correlation bilan ishlagan. Bu electrochemical wearable platformaning texnik feasibilitysini tasdiqlaydi.

2026-yilgi dual-site pH sensor $R^2 \geq 0,99$ va ICC 0,977–0,999 ko'rsatib, kariyes va erosion riskini vaqt va anatomik joy bo'yicha kuzatish uchun kuchli texnik asos yaratgan.

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Salivary turbidity mouthguard sensorining 1–4000 FTU diapazoni va spectrophotometer bilan yaqin natijasi oral hygiene va dryness monitoring uchun optik sensorlar ham istiqbolli ekanini ko'rsatadi.

Periodontal disease uchun MMP-8 kuchli target hisoblanadi: meta-tahlilda periodontitda healthy controlsga nisbatan +273,26 ng/ml farq aniqlangan. Biroq continuous intraoral protein sensing hali experimental bosqichda.

Routine clinical deployment oldidan biofouling, calibration drift, biocompatibility, battery/wireless safety, data privacy va actionable clinical threshold masalalari hal qilinishi kerak.

O'zbekistonda eng maqbul rivojlanish yo'li pH/turbidity kabi nisbatan sodda removable smart mouthguard yoki retainer pilotlaridan boshlash, keyin multiplex biochemical biosensor va AI-integratsiyalangan risk monitoring tizimlariga o'tishdir.

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