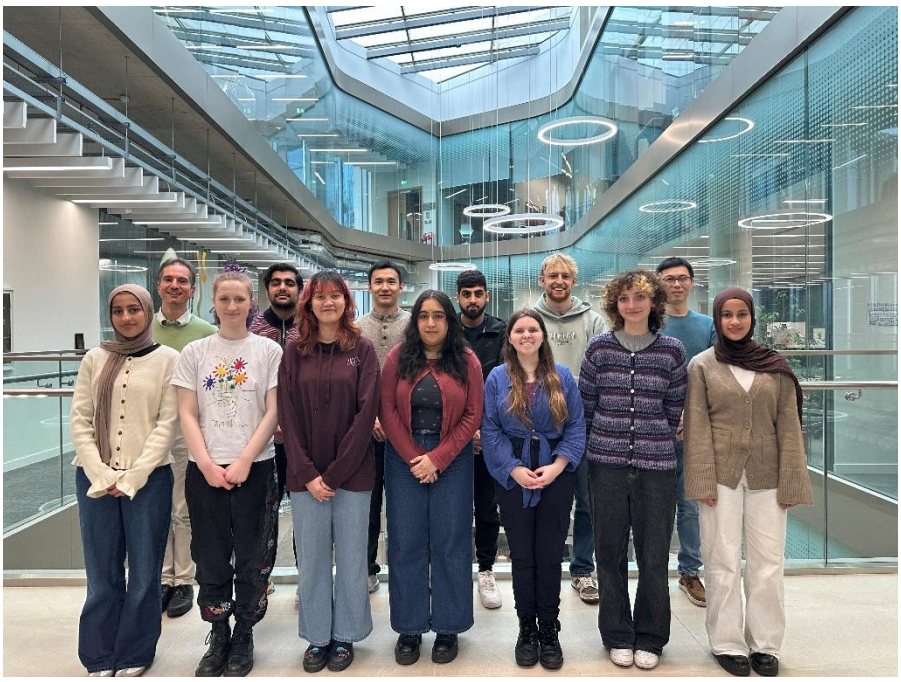
Team Results Document



University of Glasgow

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1. Abstract

For people with Parkinson's, the same dose of medication can work one day and fail the next. The drug to relieve symptoms of Parkinson's patients, Levodopa is notoriously difficult to track as it fluctuates inconsistently day to day. With no way to track their levodopa level, patients are left to face debilitating symptoms and tremors that strike unpredictably throughout the day.

GLAsense is developing a biosensor to change this. At its heart is a smart gel that swells when it comes into contact with levodopa. By combining molecularly imprinted polymers with boronic acid chemistry, the gel responds specifically to levodopa while ignoring similar molecules in the body. As the gel swells, it presses on a sealed pocket of air, and the resulting change in pressure is measured by a piezoresistive pressure sensor. Using swelling pressure as the measurement signal, takes a significant shift away from conventional optical and electrochemical biosensing alternatives.

Through an in-depth co-design study with patients, we have shaped the device around real needs, targeting those who struggle most with unpredictable symptoms. Our goal is continuous, personalised monitoring that gives patients and clinicians earlier warning of changes in drug levels.

2. AP award

2.1. Molecular recognition

Unlike biological recognition elements such as antibodies, enzymes, or aptamers, this biosensor uses molecularly imprinted polymers (MIPs) combined with phenylboronic acid functional groups as a synthetic recognition system (Figure 1). The MIP provides molecular specificity, while boronic acid allows for reversible levodopa binding and hydrogel swelling that the sensor converts to a quantitative reading.

A polyacrylamide gel is polymerised in the presence of levodopa template molecules, which creates imprinted regions that match in shape and size (artificial receptor sites). After the template is removed, these cavities selectively bind levodopa through non-covalent interactions including hydrogen bonding, electrostatic interactions, and steric complementarity (Haupt and Mosbach, 2000). This selective recognition provides the specificity for the sensor to ensure levodopa is the molecule being detected.

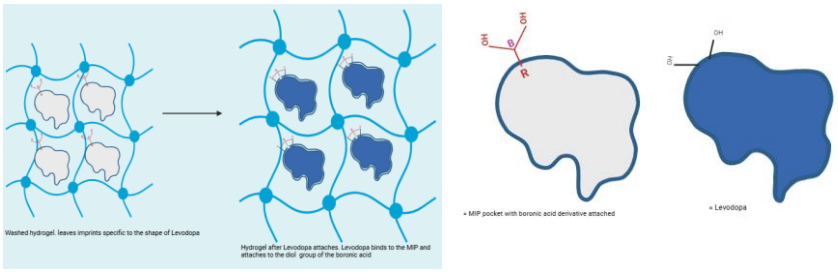


Figure 1: *diagram of hydrogel before and after swelling due to increased Levodopa concentrations.*

Levodopa (L-DOPA) contains a benzene ring with two adjacent hydroxyl groups known as cis-diols which can reversibly bind with phenylboronic acid to form a boronate–levodopa complex (António et al., 2025). At physiological or slightly alkaline pH, only a fraction of the boronic acid groups is ionised in the free state. Binding a cis diol lowers the effective pKa of the boron centre, shifting the equilibrium from the neutral trigonal form to the anionic tetrahedral boronate ester and so increasing the proportion of negatively charged groups within the polymer. The resulting increase in fixed charge attracts counter-ions and creates a Donnan osmotic-pressure difference, causing water to enter the hydrogel and producing swelling. The degree of swelling therefore increases with the amount of bound levodopa across the sensor's operating range. As levodopa concentration decreases, the boronate ester dissociates, reducing the charge density and causing the gel to contract.

Because levodopa contains a single cis-diol, it binds one boronic acid group (1:1) and does not form the crosslinks associated with bis-diols such as glucose. This produces a monotonic swelling response rather than the competing de-swelling effects seen in some glucose-responsive gels (Lin, G., Chang, S., et al. (2010)).

The reversible binding and swelling mechanism allow the hydrogel to repeatedly bind and release levodopa (equilibrium constant ca. 1500M^{-1}), enabling continuous monitoring without permanently modifying the target molecule.

2.2. Physical transduction

The biosensor converts levodopa binding into a measurable electrical signal through a mechanical pressure chain (Figure 2). As levodopa binds within the functional hydrogel, the gel swells and deflects a secondary diaphragm. The gel's swelling is restricted to the direction of the secondary diaphragm by the semi-permeable membrane which sits around the gel. This diaphragm compresses a sealed pocket of air, raising the air pressure within the pocket. Our unique approach uses an off-the-shelf low-cost pressure sensor (Honeywell 40PC001B) to measure this change and output a proportional voltage, giving a signal that scales with the degree of swelling and therefore with the levodopa concentration.

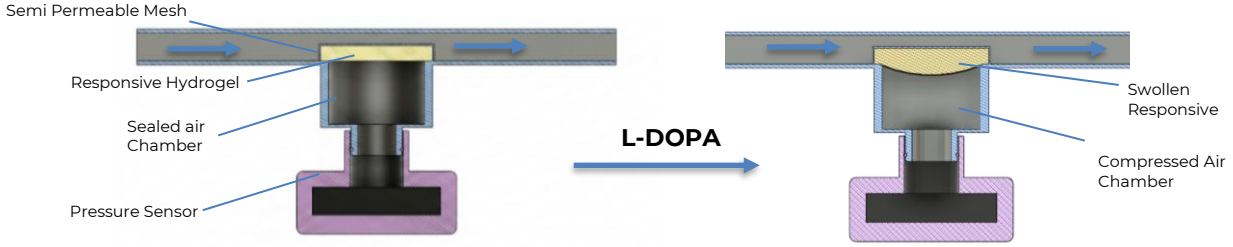


Figure 2: *Mechanical pressure chain inside flow cell deformation in response to L-DOPA.*

This indirect approach allows us to modulate the response range and decouple the gel from the sensing element for easier mounting. The secondary diaphragm's mechanical properties (flexibility through Young's modulus, and thickness) allows to optimise sensitivity to the gel's swelling. The volume of the sealed air pocket is also a key design parameter, as a smaller pocket produces a larger pressure change for a given deflection, also allowing the sensitivity of the transduction to also be tuned.

2.3. Cartridge technology

A flow cell was designed to house the functional hydrogel and deliver interstitial fluid samples to it. Samples enter through an inlet (for the testing event - for patient use, this will be through microneedles, see later), flow across and through the gel, and exit through an outlet, with each new sample displacing the previous one. The internal volume of the flow cell is 20µL kept well below the sample volume of 100 µL so that each incoming sample flushes the previous sample through, allowing consecutive samples to be measured without intermediate cleaning steps, since the reversible boronate binding releases levodopa as the surrounding concentration falls.

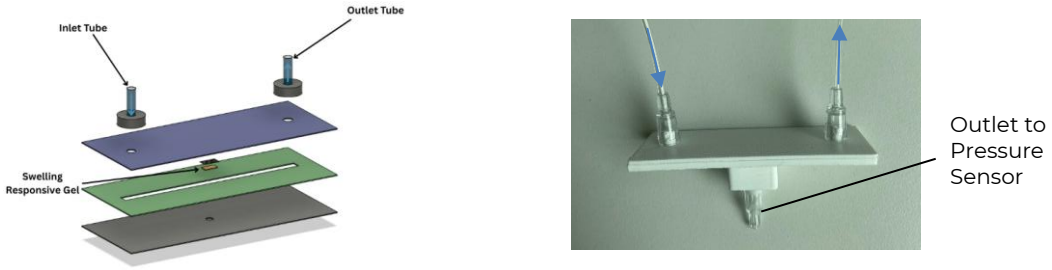


Figure 3: *Exploded view of flow cell & Image of working flow cell*

Within the flow cell, the hydrogel is confined by a semi-permeable membrane that constrains the gel so that swelling is directed against the secondary diaphragm. The membrane permits fluid and levodopa to reach the gel while holding the gel in place against the diaphragm. Continuous biosensing is achieved through the reversible binding of the boronic acid groups within the gel. Because the binding is governed by the concentration of the surrounding hydrogel, the gel swells and de-swells in response to the levodopa concentration of each successive sample, tracking both increases and decreases without a washing step. To ensure this response occurs within the required timeframe, the gel thickness is 350 µm (Othman and Dutta, 2014), so that levodopa diffuses into and out of the gel within the five-minute sampling window. The appropriate gel thickness was calculated using $\tau = L^2/D$ where diffusion time is proportional to the thickness of the gel (calculation shown in Appendix 2.3)

.2.4. Reader instrument and user interaction

The reader converts the pressure sensor's output into a levodopa concentration reading. A custom printed circuit board regulates the supply voltage to the sensor, digitises the sensor's output signal, and measures temperature to allow the reading to be corrected for thermal effects. Details of the PCB and the associated electrical hardware are given in Appendix 2.4.

The digitised pressure reading is then processed in software, where it is compared against a calibration curve that relates the measured signal to a known levodopa concentration. The resulting concentration is displayed to the user on an LCD screen, providing a direct readout without the need for external equipment.

3. IN award: Biosensor innovation

3.1. Wearable sensor

The wearable is a miniaturised version of the benchtop sensor described in Section 2. Instead of a flow cell, it draws interstitial fluid directly from the skin through a porous microneedle array that delivers the sample to the sensing gel by diffusion. The device is a compact skin-worn patch made up of a reusable body and a replaceable bottom face. The reusable body houses the pressure sensor, electronics, and battery, while the replaceable face holds the components that contact the sample and degrade over time: the microneedle array, the skin-safe adhesive, the sensing and reference gels, and the secondary diaphragm. The face clips onto the body with the sealed air channel connecting to the pressure sensor. Replacing only this face, estimated weekly subject to testing, rather than the whole device as with current glucose monitors, reduces waste and supports long-term use. Figure 4 shows the assembly of the wearable.

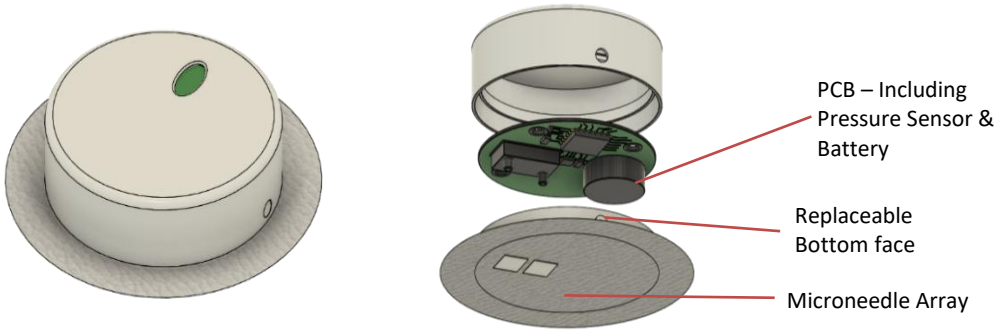


Figure 4: *Wearable Concept*

The alumina-sintered microneedles penetrate the skin while letting components of the interstitial fluid diffuse into the hydrogel within. Similar to our current benchtop device, this rigid microneedle structure constrains the hydrogel radially and allowing the gel to expand in only one direction towards the air transducer space.

The sensing hydrogel contains the boronic-acid functionalised MIPs that together reversibly bind to levodopa. When levodopa binds to the sensing gel, the gel swells, and this swelling is converted into a pressure signal by the transduction assembly, giving a continuous measure of levodopa concentration. Importantly, a reference gel that doesn't respond to the levodopa compensates for drift. Because the binding is reversible, the gel tracks both rising and falling levodopa concentrations, allowing continuous monitoring over time, with a short lag. The detailed recognition chemistry and transduction mechanism are described in Section 2.1 above. The dual gel and microneedle setup is displayed in Figure 5.

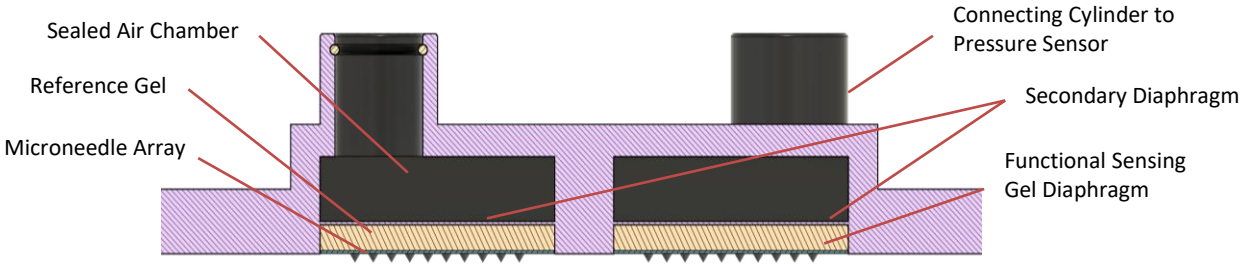


Figure 5: *Diagram of dual gel and microneedle setup.*

The readout electronics digitise the pressure signal and transmit the raw data by Bluetooth to a smartphone, which interprets and displays the levodopa concentration and runs a predictive model used to anticipate changes in drug level.

3.1.1. Technological novelty of wearable sensor

Novelty of the Molecular Recognition

Our biosensor uses an acrylamide-based MIP hydrogel, which is far more robust than typical organic recognition systems, withstanding a wide range of pH and temperature and offering easier, cheaper scale-up. The gel's swelling, in both rate and magnitude, correlates with L-DOPA concentration. This mechanical response is usually overlooked or treated as undesirable in other systems, but by incorporating boronic acid, we make the swelling specific to L-DOPA, turning an incidental property into a reliable, easily interpreted signal. While molecular imprinting and boronic acid recognition have each been used in biosensing and even combined for detection by electrochemical or optical means (Hu et al., 2017, Sakata et al., 2020), to our knowledge they have not been used together to produce a swelling response as the sensing signal. Combining the shape and functional selectivity of the imprinted cavities with the reversible diol binding of boronic acid, and reading the result through swelling, is a novel recognition approach.

Novelty of the Physical Transduction

Our transduction moves away from conventional electrochemical or optical biosensing and instead measures a mechanical change, the swelling of the gel, as a pressure, placing it in the far less common group of mechanical biosensors. Even among swelling-gel sensors, swelling is usually measured by weighing the gel or imaging its size (Liu, Z. Y., et al. (2016)), Arangasamy, R et al. (2026)), methods that need a precise balance or careful alignment and do not suit a small, sealed, wearable device. Measuring confined swelling as a pressure gives a direct electrical signal and can be fully enclosed.

The little existing work that reads gel swelling by pressure presses the gel directly against the sensor, permanently joining the two (Lin, G., Chang, S., et al. (2010) Elsherif, M., et al. (2018)). Our novelty is measuring the swelling indirectly: the gel compresses a sealed pocket of air, and a commercial pressure sensor reads the change in air pressure. This gives two key advantages. Because the gel and sensor are separated by the air pocket, the gel can be replaced without touching the sensor, unlike current biosensors that are discarded whole once the gel wears out. And using a widely available pressure sensor rather than a custom one makes the device cheaper, easier to manufacture, and more reliable.

3.1.2. Technical feasibility of wearable sensor

The sensor depends on the recognition being selective and reversible, that recognition producing a measurable swelling, and the swelling being transduced into a signal. The recognition and swelling mechanism is described in Section 2.1; the evidence for each element is summarised here.

Because levodopa was difficult to source, early testing used glucose as a model analyte, chosen for its chemical similarity and shared diol group. The gel swelled in glucose and returned to baseline in PBS, showing reversibility, and swelled proportionally to concentration (roughly ×2 from 0.05% to 0.1%, ×4 from 0.05% to 1%) (Figure 7 below). Selectivity was tested by comparing glucose against fructose, two chemically similar molecules both containing a diol group. The gel swelled in glucose but not fructose, confirming diol selectivity and that the swelling arises from the recognition elements in the gel (Appendix 3.4). Comparing the active MIP against a plain NIP in glucose solution clearly displayed larger swelling than the NIP which showed little to no swelling, further confirming the response comes from the recognition chemistry rather than the base network (Appendix 3.4). A separate rebinding study using BSA as a model template showed the template rebinding to the imprinted cavities; as BSA is a protein unlike levodopa, this shows the imprinting method works in principle rather than confirming levodopa recognition (Appendix 3.4).

For transduction, a standard gel produced a readable force even for very small changes in water uptake (Appendix 3.4). The pressure sensor responded accurately to a set of known pressures, returned reliably to baseline, and showed negligible drift (Appendix 3.1), confirming swelling can be converted into a stable signal.

A predictive model, validated against published repeated-dose data from Kuoppamäki et al., reproduced the main peaks and declines across five doses with a mean absolute error of 90.85 ng/mL (Appendix 3.2), and is intended to support discussion with clinicians rather than direct dosing. Levodopa-specific swelling, direct analyte-driven force, and microneedle-to-gel transfer remain to be demonstrated.

3.2. Reliability of sensor output

Sources of variability and drift

The reliability of the wearable may be affected by anything that alters hydrogel swelling or levodopa recognition. The dominant source is temperature, which acts in three ways at once: it shifts the gel's swelling equilibrium, changes the sealed air pocket's pressure through the gas law, and causes drift in the sensor itself. Further sources include pH and ionic strength, non-specific swelling, protein fouling, and interference from similar molecules such as dopamine, with protein adsorption also blocking recognition sites and altering diffusion. A more fundamental source is MIP fabrication itself: because imprinting is a self-assembly process, cavity number and quality cannot be perfectly controlled, giving unavoidable batch-to-batch variation that the design is built to tolerate rather than eliminate.

Strategy

These are addressed through complementary approaches: a matched reference channel that cancels drift common to both channels, a replaceable pre-characterised cartridge that limits fouling and degradation and accounts for batch differences, and a calibration routine, triggered on gel replacement and by the predictive model, that removes residual gel-to-gel and air-pocket variation. The novelty and design of these approaches are described in Section 3.2.1, with supporting evidence in Section 3.2.2.

3.2.1. Technological novelty of reliability concept

The sensor uses a differential reference channel: alongside the active MIP channel sits a reference channel containing the plain base hydrogel, with the same polymer network but no boronic acid and no imprinted cavities, together with its own trapped air volume and pressure sensor. Because the base network is common to both channels and they sit side by side within the same device, the reference is exposed to the same physical and matrix conditions as the active gel: temperature, ionic strength, pH, and mechanical disturbance, and swells in response to them in the same way. The one thing it cannot do is bind levodopa, as it lacks both the boronic acid and the imprinted cavities. Any swelling seen in the reference channel is therefore, by definition, unrelated to the target analyte. Subtracting the reference signal from the active signal removes, in a single step, the drift that would otherwise arise from temperature-dependent swelling of the network, thermal expansion of the sealed air pocket, mechanical noise, and non-specific swelling driven by the biological matrix.

The novelty lies in a single reference simultaneously correcting both physical and matrix variability, in situ and in real time. Conventional approaches correct for temperature alone, typically using a separate temperature sensor and a calibration curve. This cannot account for the many other factors that influence hydrogel swelling and diffusion, such as protein concentration, ionic strength, and pH, which differ between individuals and shift over prolonged wear. Because the reference gel is physically identical to the active gel and experiences the same environment, it captures all of these effects together, isolating the levodopa-specific response without needing to measure or model each source individually. Selectivity against structurally similar molecules such as dopamine is provided separately by the imprinted cavities of the MIP, which supply the molecular discrimination that boronic acid alone cannot.

Reliability over longer timescales is further supported by calibration. Because molecular imprinting is a self-assembly process, no two gels are perfectly identical, and the sealed air-pocket volume may vary slightly between cartridges; both would otherwise shift the measured response. Each new gel is therefore calibrated by submerging the sensor in a buffer of known concentration, which corrects the gel-to-gel and air-pocket variation together in a single step. Calibration is triggered automatically after each gel replacement, and by the predictive model, which maintains an expected concentration profile from the patient's dosing and prompts recalibration when readings drift beyond a set threshold. This makes recalibration adaptive rather than scheduled and turns the prediction model into an active check on measurement reliability rather than a passive display.

3.2.2. Technical feasibility of reliability concept

The feasibility of the reliability concept rests on three things: that the variability it corrects is real and significant, that the reference gel responds to those conditions without responding to levodopa, and that the readout itself does not introduce drift.

The variability was confirmed experimentally. Swelling measurements at different temperatures showed a clear increase in gel swelling at 37°C, confirming that temperature directly affects the response and would cause drift if uncorrected (Figure 6). Varying the ionic strength of the surrounding solution likewise changed the gel's swelling and water uptake, confirming that matrix composition is a genuine source of variability (Appendix 3.4). These results demonstrate that the physical and matrix factors the reference channel is designed to cancel are significant in practice, not merely theoretical.

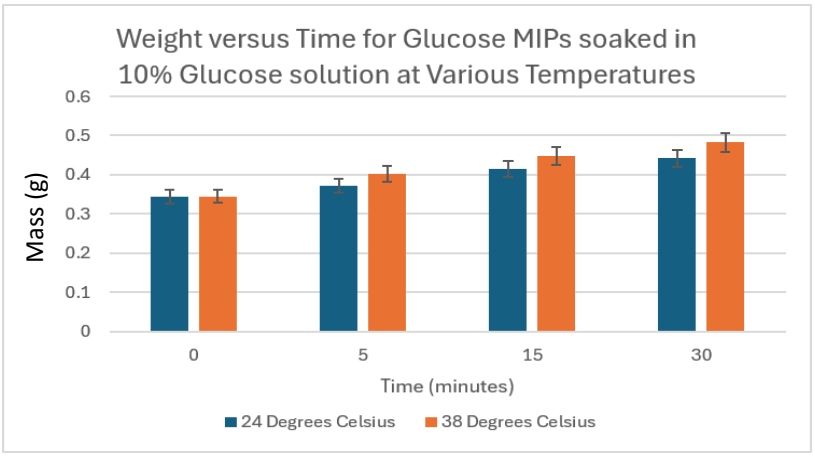


Figure 6: *MIP Swelling in Glucose at 24 Degrees Celsius and 38 Degrees Celsius*

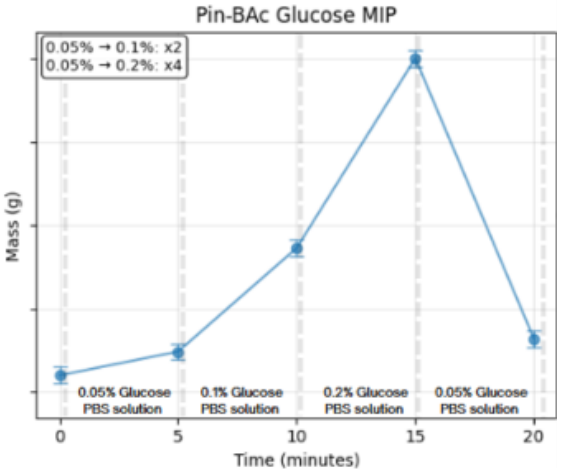


Figure 7: *Pin-Bac Glucose MIP at equilibrium in PBS soaked in various Glucose solutions for 5 minutes each (Full graph in Appendix 3.4)*

The reference gel was shown to behave as a valid reference. Comparing the active MIP gel against the plain NIP gel under the same conditions, the MIP produced a clear swelling response while the NIP showed limited to no swelling (Appendix 3.4). This confirms that the swelling signal arises from the recognition chemistry rather than the base network, and that the reference gel does not reproduce the levodopa-driven response. Subtracting the reference therefore removes shared physical and matrix effects without cancelling the levodopa signal itself.

The readout itself was shown to be stable. Baseline testing of the pressure readout showed negligible short-term drift, and repeated pressure cycles returned consistently to baseline (Appendix 3.1), confirming that the electronics do not contribute drift or memory effects. This establishes the readout as a stable foundation, so the variability observed in the full sensor can be attributed to the physical and matrix sources above rather than to the measurement system.

The boronic acid component of the PIn-BAc glucose MIP showed no response to other diol-containing molecules (Appendix 3.4), supporting the selectivity of the MIP. The gel also responded reversibly to glucose concentration as shown in Figure 7; its weight increased proportionally with glucose concentration, thus following the hypothesised theory of swelling. It returned to its equilibrium weight within five minutes in the original solution, showing it may be used for continuous monitoring due to fast response times in swelling and deswelling.

Together, these results support the feasibility of the concept: the variability is real, the reference responds to it without responding to levodopa, and the readout is stable. The two gels are not perfectly identical, so a fixed difference remains between their baseline responses, but this appears as a constant offset rather than drift and is removed during calibration against a known concentration. The reference channel therefore cancels the variable drift from temperature, matrix and mechanical effects, while calibration removes the constant offset between channels, together providing continuous in-situ compensation across the range of conditions shown to affect swelling.

3.3. Original contributions

3.3.1 Statement from the Team:

The key novelties of the biosensor were conceived and developed by the team. These include the use of hydrogel swelling as the sensing readout through a combined MIP and boronic acid gel, the indirect pneumatic transduction in which gel swelling compresses a sealed air pocket read by a commercial pressure sensor, the replaceable skin-facing face, the differential reference channel, and the multi-part calibration strategy. The device requirements were shaped by input from patients and clinicians, while the technical design and sensing concept were developed by the team. No single innovation came from a specific member of the team, whilst supervisors acted as "critical friends" and advised on areas requiring further investigation. Development and testing were carried out independently by the team, including the design of the 3D-printed swelling measurement rig and all swelling, force and pressure-sensor experiments. External input was limited to general technical advice: in particular PhD student Rebecca Setford advised on preparing and storing MIPs, relevant literature, and nitrogen purging, and a post-doc Eonan Pringle, suggested a monomer-to-crosslinker ratio the team, after assisting with viscoelasticity measurements. Both were using hydrogels for unrelated applications and neither contributed to the biosensor concept. Technical assistance from university technicians was very beneficial to equipment access and safe handling but did not shape the scientific concepts.

3.3.2 Statement from the Supervisors:

I can confirm that the team have developed their idea completely independently. Some of the team members took a course on biosensors as part of their curriculum, that both Chunxiao and I teach in. The course covers the basics of biosensing and provides examples of different sensor systems and strategies. They were also aware of the idea of MIPs from last year's SensUs team. However, they decided to take the challenge of finding a biosensing strategy that they had not seen before, which resulted in their foray into mechanical/pressure sensing. The combination of pressure sensing with MIPs has, to our knowledge, not been attempted before, as key novelty. The group of Professor Alasdair Clark, which shares lab space with the team, includes a PhD student working on MIPs, but she develops optical sensing and the team used a different chemistry from her and from last year's team (as they need to induce the mechanical stimulus by a change in geometry).
Although both supervisors' groups work on biosensors, there is no active project on mechanical sensing and indeed the team had to purchase the components to build it from scratch, leading to an interesting idea to use an off-the-shelf pressure sensor and establish it as a biosensor, as a second innovative aspect. Our role was kept at an advisory level (outlining potential challenges in their strategies), as well as guide access to existing equipment and potentially useful expertise in Glasgow. We are especially proud of the team's focus on the patients and clinicians' voices to build a concept that will have maximum impact, and indeed patients and carers have expressed strong desire to try the team's app (even without the biosensing component).



Team Captain
Morris McDiarmid



Team Co-Captain
Amira Mistkawi



University Supervisor
Julien Reboud



University Supervisor
Chunxiao Hu

3.4. Bonus criteria Innovation

Due to our limited budget and resources, the project required us to adapt. Many developments involved building our own lower-cost equipment to replace apparatus that would otherwise need specialist fabrication or expensive commercial systems. These self-built prototypes made the testing and manufacturing of our gels possible, and along the way we made several discoveries on which there is little to no previous research.

Gel swelling force setup

Early on, the team needed a cheap, continuous way to measure gel swelling, but there was little research on confining a gel and measuring its swelling force. The one established method relied on costly lab scales and a porous glass cylinder custom-made by a professional glass blower, which the team could not source or fabricate (Höhne and Tauer, 2014). It also used a clamp stand to hold a stamp against the gel, which could not maintain a perpendicular contact and gave an unstable compression that drifted as the friction clamp crept under load.

The apparatus was rebuilt using 3D printing. A printed porous cylinder, with porosity set by adjusting infill, confined the gel while letting fluid enter, and a printed fixture constrained the stamp to a single vertical axis for perpendicular, repeatable contact, with a threaded insert giving controlled compression without creep. The result was a low-cost setup giving reproducible, continuous swelling measurements sensitive enough to resolve force increases from very small differences in water uptake (Appendix 3.3).

Nitrogen purging system

Polymerising gels reliably required an oxygen-free environment, as oxygen inhibits the free-radical reaction. Rather than buying a commercial system, a purging setup was built. The common balloon method did not provide the gas flow our process required, so we adapted it into a higher-flow setup, giving reliable control over the gel environment and consistent polymerisation (Appendix).

Unwashed vs washed MIP swelling forces

While testing molecularly imprinted gels, a consistent pattern emerged: unwashed gels produced a greater swelling force yet took up less water than washed ones. This divergence of force and water uptake runs against the trend in standard non-imprinted gels, where greater mass uptake always gives greater force. No reported literature was found testing this, and the observation suggests a practical use as a means of verifying template removal during washing.

Comparing gel formulations

Two monomer-to-crosslinker ratios were compared, a conventional 9:1 from the literature and a 40:0.01 ratio suggested by a PhD researcher, with mechanical properties assessed by rheology as an indicator of swelling behaviour. The 40:0.01 formulation performed best and was carried forward.

Effect of pre-compression on swelling force

Using the setup's controlled pre-compression, pre-loading the gel was tested. The result was the opposite of that anticipated: pre-compression reduced the force produced, and the strongest response came with none at all. Though exploratory rather than fully repeated, this established that the gel is best operated without pre-compression.

Comparative evaluation of transduction methods

Selecting a transduction method meant weighing options against the needs of a wearable, compact, sensitive and robust. Gravimetric measurement required drying and weighing and could not run continuously in a sealed device. Optical methods needed bulky, precisely aligned components. Direct piezoresistive measurement had been demonstrated but enclosed the gel in the sensor, making gel-only replacement impossible. Capacitive and ultrasonic approaches carried difficulties in sensitivity and noise. This pointed to an indirect approach: the swelling gel compresses a sealed pocket of air, and the pressure change is read by a standard sensor, avoiding these shortcomings while remaining simple, sealed, and built from readily available components.

Boronic acid protecting levodopa from oxidation

While making gels, the team observed that the boronic acid appeared to protect the levodopa from oxidation. Levodopa readily oxidises in solution, which would normally degrade the analyte and compromise a measurement, but the boronic acid binding appeared to stabilise it. This is a useful and previously unconsidered benefit, as it suggests the recognition chemistry not only provides specificity and swelling but also preserves the analyte it is sensing, improving the reliability of the gel over time.

4. TP award: Translation potential

4.1. Customer interviews

4.1.1 Identification of Potential Stakeholders

Developing a clinically meaningful biosensor required understanding not only the technical performance of the device, but also how it would fit into patients' daily lives, clinical decision-making and future manufacturing. Therefore, a human-centred co-design approach was embedded from the beginning of the project, involving stakeholders who would ultimately use, interpret and manufacture the technology.

Before any stakeholder engagement began, ethical approval was obtained through the appropriate institutional review process. This ensured that all participants' involvement, data collection and feedback analysis were conducted responsibly, with informed consent obtained before participation and all feedback anonymised. This was approved.

Over an eight-week study, approximately thirty stakeholders contributed to the development of the biosensor, AI prediction model and companion application, including people living with Parkinson's disease, carers, clinicians and industry partners.

The primary stakeholder group consisted of people living with Parkinson's disease recruited through the Glasgow Young Onset Parkinson's Support Group. As future users of the technology, their experiences of medication management, unpredictable OFF periods and daily challenges were essential in defining the clinical problem and practical requirements of the platform.

Carers and family members were included due to their role in supporting medication routines, recognising symptom changes and assisting patients during OFF periods. Their feedback highlighted the importance of accessible information and shared visibility of symptom trends to improve communication between patients, carers and clinicians.

To understand integration into clinical practice, discussions were conducted with a Parkinson's clinician. These focused on current levodopa optimisation strategies, limitations of symptom diaries and what information would genuinely support treatment decisions. The clinician highlighted that levodopa concentration alone would have limited clinical value without additional context, such as symptoms, medication timing and lifestyle factors.

Industry stakeholders, including Flex Medical Solutions and Horao NeuroLabs, were consulted to ensure the technology remained compatible with scalable manufacturing processes and realistic regulatory pathways. Their input helped guide decisions around device design, manufacturability and translation beyond an academic prototype.

By engaging stakeholders across the entire healthcare pathway, from the person wearing the device to the clinician interpreting the data and industry partners manufacturing it, the platform was developed around real-world clinical and commercial requirements.

4.1.2 Interview Approach and Execution

To identify a genuine clinical need, a four-phase iterative co-design study was conducted over eight weeks, combining semi-structured interviews, prototype evaluation and iterative feedback. Before beginning the study, ethical approval was obtained, and all participants provided informed consent before taking part. Participants were informed of the purpose of each session, agreed to anonymous notetaking and audio recording, and all collected feedback was anonymised before analysis.

The first three phases were conducted online to maximise accessibility, while the final prototype evaluation took place in person during the Glasgow Young Onset Parkinson's monthly meeting. Structured discussion guides were prepared before each session to ensure consistency while allowing participants to introduce new perspectives.

Phase 1 – Understanding the Clinical Problem

Participants discussed their experiences of Parkinson's disease, medication routines, symptom fluctuations and challenges associated with unpredictable OFF periods. No device concepts were introduced to minimise bias and allow genuine unmet needs to emerge.

Key findings included: Unpredictable OFF periods significantly affected daily confidence; current symptom diaries provided incomplete information; and patients wanted better understanding of their medication response.
Clinician feedback reinforced these findings, highlighting the limitations of retrospective symptom reporting and the need for objective longitudinal information.

Phase 2 – Concept Generation

Insights from Phase 1 were translated into initial device and application concepts. Participants evaluated possible formats including adhesive patches, wrist-worn devices, textile sensors and implantable approaches based on comfort, discretion, usability and perceived benefit.
This phase identified the adhesive patch as the preferred wearable format due to its discreet and minimally disruptive design.

Phase 3 – Prototype Refinement

A 3D-printed biosensor prototype and smartphone application were evaluated by participants. Feedback directly influenced several design improvements, including: Expanded symptom; categories; Exercise tracking; Mood monitoring; Gastrointestinal symptom logging; Future smartwatch integration; and Evening OFF-period reflections,
Carers also highlighted the value of shared symptom information, while patients recognised that the application could provide benefit independently of the biosensor. This directly influenced the app-first commercial/branding strategy.

Phase 4 – Final Evaluation

The refined biosensor prototype and app were presented for final feedback. Participants suggested minor refinements rather than major redesigns, indicating that earlier co-design phases successfully captured the core user requirements.
Following each session, feedback was reviewed by three team members and coded into recurring themes. These themes were translated into specific design requirements, creating a transparent link between stakeholder input and the final platform.

4.1.3 Interview Results and Conclusions

Analysis of stakeholder feedback identified six major themes that directly shaped the final platform design (Appendix 4.A). **The most significant unmet need identified was uncertainty surrounding OFF periods**. Patients wanted earlier warning of symptom changes rather than simply recognising deterioration after it occurred. This directly shaped the development of an AI-driven prediction model combining levodopa sensing with patient-specific data.
Participants also highlighted that current monitoring methods provide ***incomplete information between appointments***. This informed the integration of continuous sensing and digital symptom tracking to provide a more complete picture of daily disease fluctuations.
Comfort and discretion were critical requirements, leading to the selection of an adhesive microneedle patch as the preferred wearable format. ***Simplicity*** was also prioritised, resulting in an application focused on medication status, symptom logging and predicted trends, with additional analysis available when required.
Clinicians reinforced that isolated levodopa measurements would not be sufficient for treatment optimisation. Therefore, the platform was designed to combine molecular sensing with medication timing, symptoms, meals and activity to provide clinically meaningful insights.
Overall, stakeholder engagement shaped every major design decision, from defining the clinical problem to specifying the wearable format, application features and translation pathway. By combining patient experience, clinical requirements and manufacturing considerations, the platform was developed with a strong foundation for future clinical translation.

4.2. Design of validation study

4.2.1 Selection of the Problem

The co-design study aimed to identify a clinical problem where continuous biosensing could provide meaningful benefit for people living with Parkinson's disease. Across patient interviews, clinician discussions and prototype evaluations, one challenge consistently emerged: Parkinson's management remains largely reactive rather than proactive.

Patients described unpredictable levodopa response and OFF periods as one of the most disruptive aspects of daily life, affecting work, exercise, travel and social activities. As one participant explained, "The worst part is not knowing when it's going to happen." Current monitoring provides only limited insight into these fluctuations. Neurology appointments occur every 6–9 months, while symptom diaries are often completed retrospectively, meaning treatment decisions rely heavily on subjective patient recall.

Clinicians emphasised that levodopa concentration alone would have limited clinical value. Instead, effective dose optimisation requires understanding how levodopa levels change alongside symptoms, medication timing, meals and lifestyle factors.

Young-Onset Parkinson's Disease (YOPD) was selected as the initial target population because it is underrepresented in Parkinson's research despite presenting greater challenges for medication optimisation. Compared with older-onset Parkinson's disease, younger patients develop levodopa-induced dyskinesias and motor fluctuations earlier, experience greater variability in treatment response and often require more personalised dosing strategies [Kostic et al., 1991; Kumar et al., 2003; Aquino et al., 2018].

By combining continuous levodopa sensing with patient-generated data and AI-driven prediction, the platform aims to provide early warning of OFF periods and support personalised therapy optimisation for the population where current approaches are least effective.

4.2.2 Conceptual Design and Use Case

Stakeholder feedback fundamentally reshaped the platform. While the initial concept focused on continuous levodopa measurement, patients and clinicians highlighted that ***concentration data alone would have limited clinical value***. The final system therefore combines molecular sensing with personalised predictions and time sensitive logging too. The platform consists of three integrated components: a wearable biosensor, smartphone application and AI-driven prediction model. (Figure 8.1)

The wearable device is a discreet adhesive microneedle patch containing a hydrogel-based molecularly imprinted polymer (MIP) designed to selectively recognise levodopa in interstitial fluid. Levodopa binding induces hydrogel swelling, generating a measurable pressure change detected by an integrated MEMS sensor. Data are transmitted wirelessly to the smartphone application for continuous monitoring.

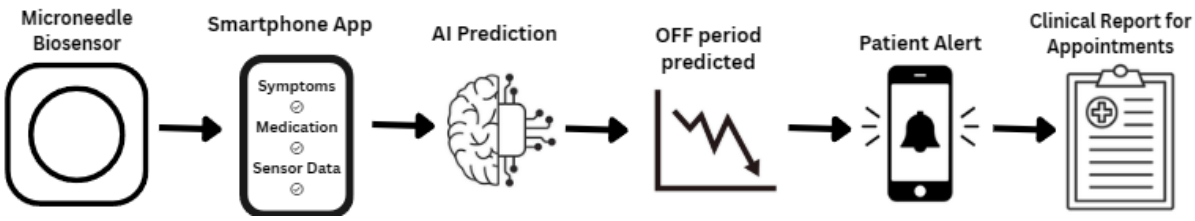


Figure 8.1 The individual components on how the data is taken from the biosensor all the way to clinical reports

The application was developed through iterative co-design. Patients prioritised simplicity and accessibility, leading to a dashboard focused on medication status, symptom logging and predicted levodopa trends. Additional features including mood tracking, gastrointestinal symptoms, exercise logging and smartwatch integration were identified as potential future improvements.

Carers valued symptom tracking independently of the biosensor, while clinicians requested concise summaries rather than raw sensor outputs. Therefore, the platform integrates levodopa trends with medication timing, symptoms and lifestyle factors to provide clinically meaningful information during consultations.

The intended use case is not simply measuring levodopa concentration but learning each patient's individual pharmacokinetic profile. By combining molecular sensing with contextual patient data, the AI model predicts when levodopa levels may fall below the therapeutic range, providing advance warning of approaching OFF periods and supporting personalised treatment decisions.

4.2.3 Validation Study Design

The validation study evaluates the complete clinical pathway, from analytical sensor performance to patient benefit. Rather than validating the biosensor alone, the study determines whether the integrated platform improves Parkinson's management *(Appendix 4.B)*

Stage 1 – Technical and Prediction Validation

Twenty participants taking levodopa will wear the biosensor continuously for seven days during normal daily activities. Four daily venous blood samples will be analysed using HPLC as the reference method. Biosensor measurements will be compared with HPLC results using Pearson correlation, Bland–Altman analysis, mean absolute error and RMSE.

We will also validate the model at the same time on the same cohort. Sensor measurements will be combined with medication timing, meals, activity and symptom logs to generate personalised pharmacokinetic models. Predicted levodopa concentrations and OFF periods will be compared against HPLC measurements and patient-reported symptoms.

Model performance will be assessed using sensitivity, specificity, precision, recall, F1-score and prediction error, with the aim of predicting OFF periods before symptom onset. Target: area (AUC) under the Receiver operating characteristic (ROC) curve above 0.90.

Stage 2 – Proof-of-concept Clinical Validation. Twenty YOPD participants with significant motor fluctuations will be recruited. It is impossible to randomise the use of the device or the app, so the cohort will be their own individual control. They will be monitored for 3 weeks following standard of care and logging in OFF time in a reduced version of the app, also recording PDQ-8 quality of life score, patient and carer confidence (through questionnaire on the app once per week). After the first 3 weeks, new features in the app will be unlocked (prediction, logging, as designed) and recording continued similarly. In a final 3 weeks, the participants will be offered the biosensor in addition. As stated, the primary outcome will be reduction in daily OFF time. Secondary outcomes include medication optimisation, PDQ-8 quality of life score, patient and carer confidence, clinician satisfaction and System Usability Scale scores. We anticipate some loss of participants although the motivation of our conversation with stakeholders would lead us to believe it will be minimal (planning for 10).

Together, these stages assess whether continuous molecular sensing combined with AI-driven prediction has the potential to move Parkinson's management from reactive symptom treatment towards personalised, proactive therapy optimisation in that cohort. The design also evaluates if the biosensor is valuable or (as our stakeholders have mentioned) if the app is enough support to generate most of the benefits. This can be later expanded to generate regulatory data and open to other cohorts *(Appendix 4.B)*.

4.3. Bonus criteria Translation Potential

Translation has been embedded through this project, with patients, carers, clinicians and industry partners shaping the platform from the outset. This ensured the technology addresses a genuine clinical need while remaining practical to manufacture, regulate and integrate into routine care. Rather than developing a standalone biosensor, we have established a clear pathway from laboratory to clinical implementation (Figure 8.2)

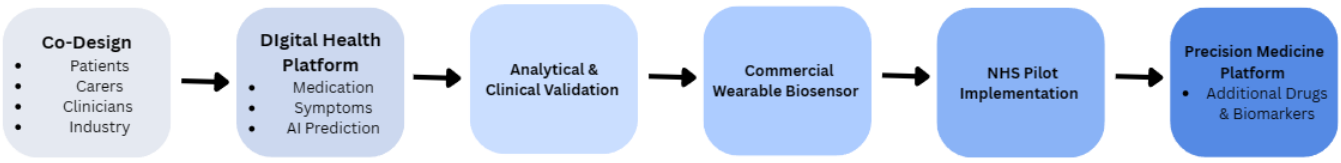


Figure 8.2 The pathway from initial codesign to commercialisation of the product and beyond

Stakeholder interviews demonstrated that the greatest unmet need is not simply measuring levodopa concentration but providing meaningful information that supports clinical decision-making. Our platform combines continuous molecular sensing with symptom tracking and AI-driven pharmacokinetic modelling to predict levodopa response. This enables patients to anticipate OFF periods, provides carers with greater visibility of symptom progression and equips clinicians with objective longitudinal data to optimise treatment (Figure 8.1). Co-design also showed that the smartphone application provides immediate value independently of the biosensor. Therefore, ***our initial commercial strategy*** is to launch a standalone digital health platform offering medication reminders, symptom tracking and trend visualisation. This creates an early user community, delivers immediate clinical benefit and generates anonymised longitudinal data to refine the AI prediction models before hardware release.

Manufacturability has been considered throughout development. The reusable reader uses commercially available flexible electronics, while the disposable patch incorporates scalable components including polymer microneedles, molecularly imprinted hydrogels and medical-grade adhesives. Discussions with Flex Medical Solutions confirmed compatibility with existing roll-to-roll manufacturing and automated assembly processes, supporting cost-effective large-scale production. This includes considering relevant British Standards. Commercial translation will follow a phased strategy, beginning with the standalone digital platform, followed by research and clinical trial deployment, NHS pilot studies and wider clinical adoption (*Appendix 4.D)*.

Regulatory planning includes analytical validation, biocompatibility testing, clinical evaluation and MHRA/UKCA approval, while patent protection will secure the hydrogel chemistry, sensor integration and AI prediction algorithms.

The business model combines reusable hardware, recurring disposable sensor patches and subscription-based digital services, with additional revenue generated through research partnerships and clinical trial deployment.

Beyond Parkinson's disease, the molecularly imprinted polymer technology can be adapted to detect other drugs and biomarkers, establishing a scalable precision medicine platform capable of improving patient outcomes while reducing long-term healthcare costs *(Appendix 4.E)*.

5. Team and support

5.1. Contributions of the team members

Morris McDiarmid
Led the hardware and data processing team, overseeing the pressure-transduction system, flow cell design, and swelling-measurement work. Took lead on the report and acted as the link between the hardware, detection, and translational potential teams to ensure a coherent overall design and led the development of the 3D-printed confined-swelling measurement rig.

Amira Mistikawi
Led the detection team, coordinating the gel development effort, and contributed directly to the development of the functional hydrogel.

Hannah White
Led the translational potential team, including the co-design study with patients and clinicians and the development of the validation study and market strategy. Took second lead on the report and also was a key part of the detection team and contributed to the gel chemistry work on molecular recognition and reversibility.

Najaree Janjerdsak
Carried out extensive work on gel development and laboratory testing and contributed to the microneedle sampling concept.

Haonan Zhao
Built the data-processing model and the AI predictive model, including the pharmacokinetic modelling and app development.

Zeiad J A M Alkandari
Developed the electronic signal-conditioning and pressure-readout hardware, including sensor evaluation, circuit design, and the transition toward a PCB-based system.

Priyanka Virdi
Focused on gel chemistry, working on molecular specificity and on the degradation and interference of the gel in interstitial fluid.

Lina Roy
Contributed to the detection team, supporting gel development work in the laboratory.

Feryaal Mian
Contributed to the detection team's laboratory gel development work and assisted with the co-design study.

Olivia Skinner
Carried out extensive work on gel development and laboratory testing, and contributed to the microneedle sampling concept.

5.2. People who have given support

Dr Julien Reboud

Acted as a project supervisor and critical friend, advising the team on areas requiring further investigation and guiding the direction of the work without contributing to the core technical concepts.

Dr Chunxiao Hu

Acted as a project supervisor and critical friend, providing guidance on the development of the biosensor and advising the team on areas requiring further investigation.

Rebecca Setford

Provided general advice on the preparation and storage of molecularly imprinted polymers and on relevant literature to build the team's understanding, as well as guidance on nitrogen purging. Her own research used hydrogels for an unrelated application.

Eonan Pringle

A PhD researcher who offered general technical advice, including suggesting a monomer-to-crosslinker ratio the team went on to test. His work used hydrogels for a different purpose unrelated to the biosensor.

Zhuoer Zeng

Provided advice on the use of various laboratory tools and equipment.

Derek Wang

Provided advice on the use of various laboratory tools and equipment.

Andy Smith, Mary Catherine, Andrew McDonald, & Gillian Wilson

All 4 were patients that were core members of the CoDesign project and gave insights that shape our device in phases 1-3 of the Codesign.

5.3. Sponsors and partners

RS Components (RS Group)

Provided funding through the RS Student Fund, enabling the team to source piezoresistive pressure sensors, electronic components, and PCB materials for the prototype.

Parkinson's UK / Glasgow Youth Parkinson's Group

Supported the co-design study by providing access to patients, enabling the team to gather stakeholder input that shaped the device requirements and use case. Also allowing us to come to their monthly event to showcase our concept and get feedback for the final phase of our CoDesign study.

Flex Medical Solutions

Provided advice on the manufacturability and real-world design of the biosensor, offering industry insight from a medical device and biosensor manufacturing perspective.

University of Glasgow

Provided laboratory facilities, equipment access, and the host research group environment in which the development and testing were carried out.

Parkinsons Team UHBW

The Parkinson's team at UHBW provided valuable clinical insight into the management of Parkinson's disease. In particular, Dr Hugh Kelly shared extensive first-hand experience from his work within the trust's Parkinson's team, helping the team understand the real-world clinical challenges of levodopa dosing and symptom management.

6. Final remarks

We are not just trying to measure levodopa; we are trying to make levodopa management more personalised and proactive. Our long-term vision is a system combining continuous levodopa sensing, patient symptom and activity information, personalised pharmacokinetic modelling and, ultimately, clinical decision support. Importantly, our co-design work has shown us that this vision has value beyond the sensor itself. A large group of the patients involved in our work with the Glasgow Youth Parkinson's Group have expressed strong interest in using and seeing our symptom and medication tracking app published, even before we are able to bring the biosensor to market. This has reinforced for us that the patient need exists now, and that parts of our solution could provide meaningful value while the biosensor continues to be developed.

We recognise that a competition prototype is very different from a clinically validated, manufacturable product. There is still significant work ahead, including improving sensor performance, testing in increasingly realistic samples, demonstrating reproducibility and reliability, and progressing towards clinical validation and regulatory requirements. However, we do not see the competition as the end of GlaSense. We want to continue developing both the app and biosensor beyond SensUs, using the feedback from patients and clinicians to take our prototype towards a solution that could eventually make a real difference to people living with Parkinson's.

This project would not have been possible without the people who supported us. Foremost, we thank the Glasgow Youth Parkinson's Group for their openness, time and invaluable input throughout our co-design process. We also thank the clinicians, medical professionals and researchers at the Advanced Research Centre who took the time to answer our questions and challenge our thinking. Finally, we thank the SensUs organisers and judges for the opportunity to develop this project, and our supervisors for their continued support and guidance.

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8. Appendix

Appendix 2.3

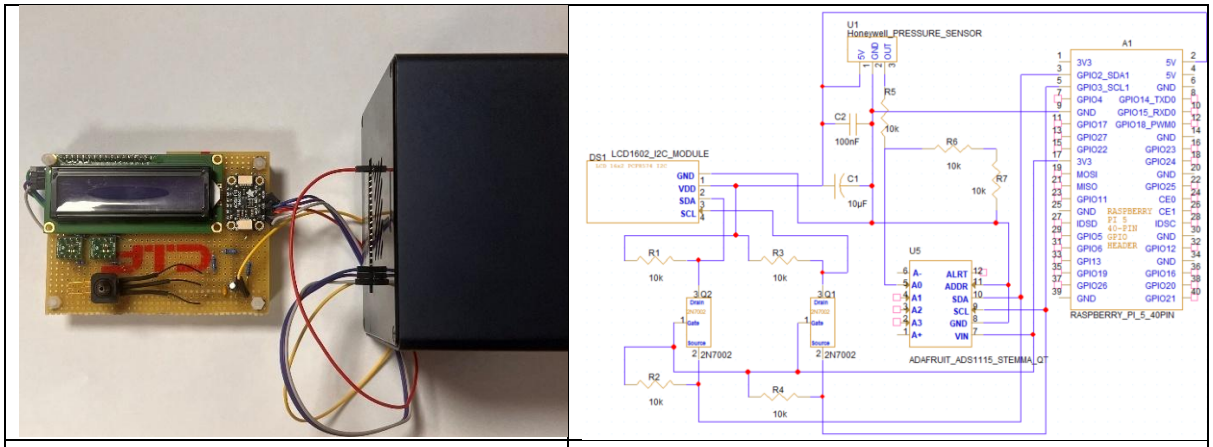
Gel Diffusion Calculation based on https://pmc.ncbi.nlm.nih.gov/articles/PMC11947801/

$$\tau = \frac{L^2}{D}$$

- Taking diffusion (D) as an estimated $5x10^{-10}$ m/s^2 as taken from
- Taking τ as 5 minutes (300s)

The estimated thickness of 387 µm rounded down to 350 µm to ensure diffusion

Appendix 2.4



(a) (b)

Figure: Prototype reader hardware and schematic for the pressure-based biosensor readout. (a) Physical prototype board used for pressure-sensing tests, including the display and pressure-sensor interface electronics. (b) Electrical schematic of the reader circuit, showing the Honeywell pressure sensor, voltage-divider interface, ADS1115 ADC, display connection and controller wiring.

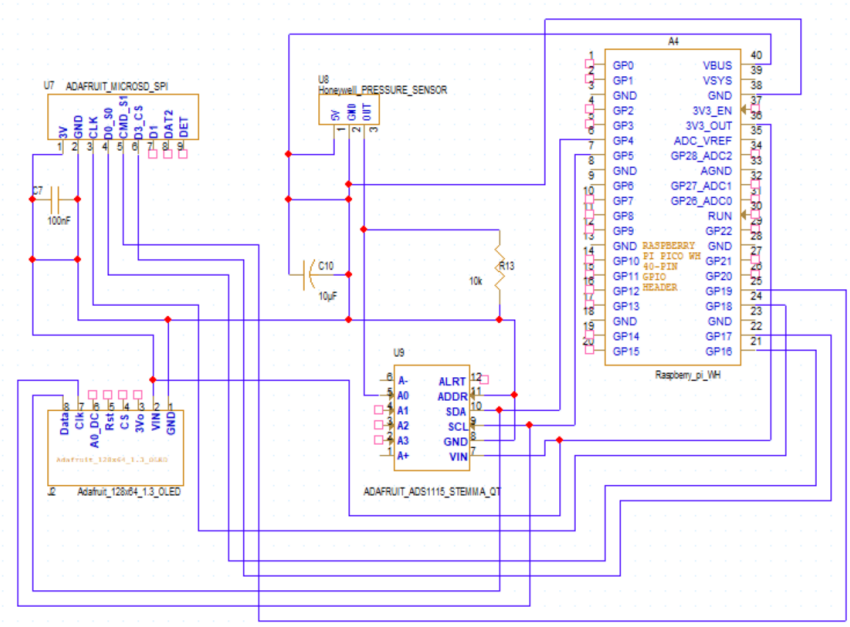


Figure: Circuit schematic of the fabricated Pico WH pressure-sensor reader, showing the Honeywell pressure sensor, ADS1115 ADC, OLED display, MicroSD module and Pico WH connections.

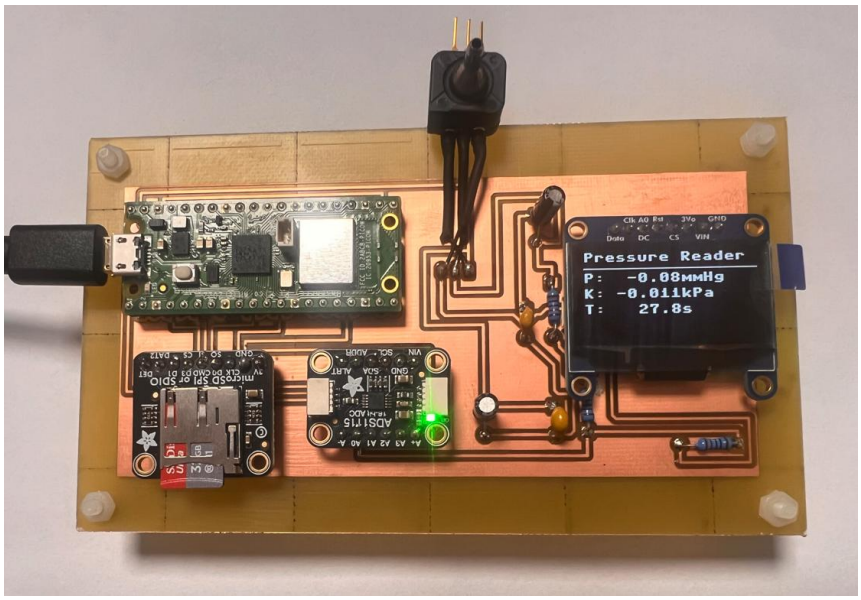
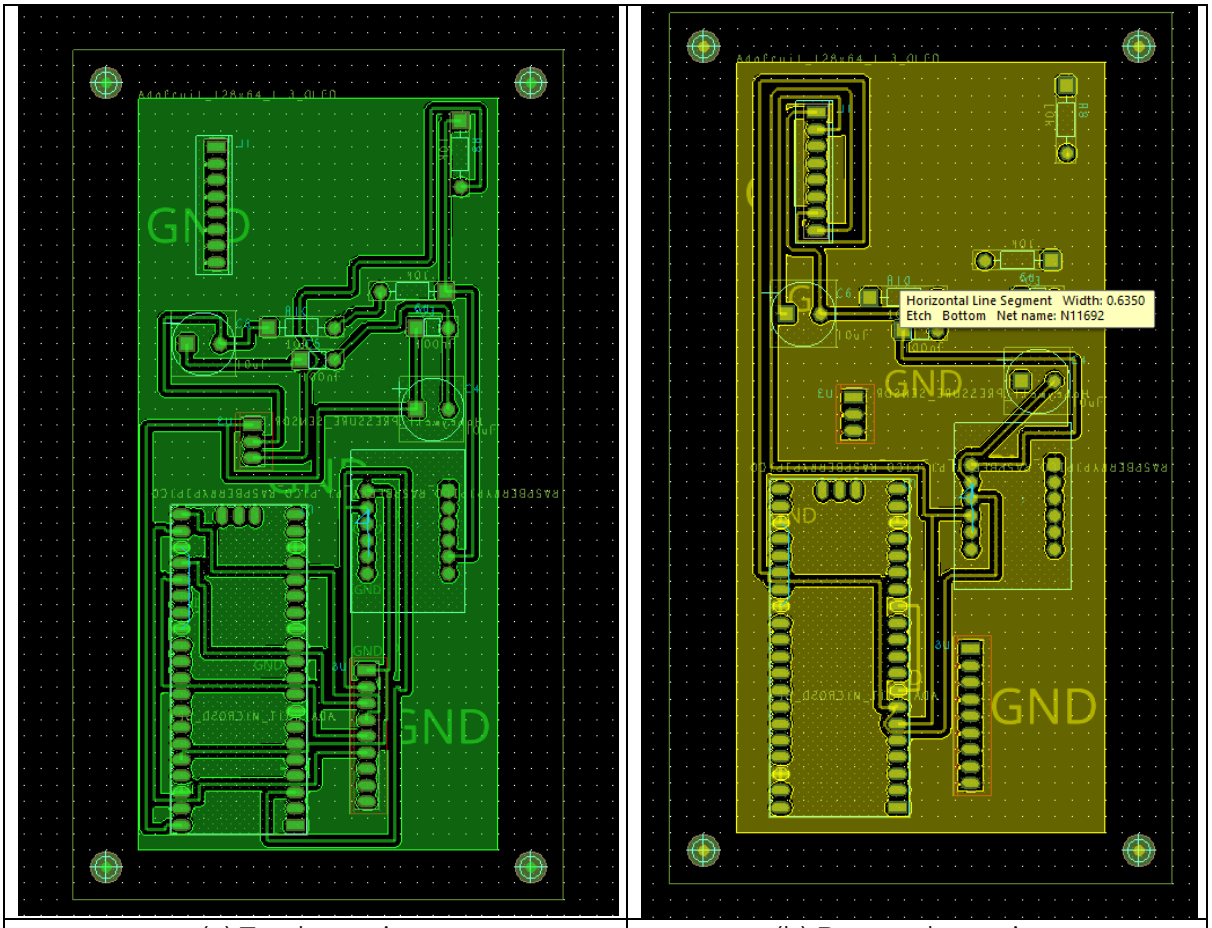


Figure: Fabricated and assembled pressure-sensor reader PCB during functional testing, with the Pico WH, Honeywell pressure sensor, ADS1115 ADC, MicroSD module and OLED display connected.



(a) Top layer view | (b) Bottom layer view

Figure : Routed PCB layer views of the pressure-sensor reader: (a) top copper layer showing component placement and routed signal traces; (b) bottom copper layer showing the ground-plane coverage and routed connections used in the fabricated board.

Appendix 3

Appendix 3.1: Pressure Sensor Results

Figure: Calculated pressure versus time during the repeatability test. The graph shows repeated pressure application and release events, with the five clean middle cycles returning close to the zero-pressure baseline after each release.

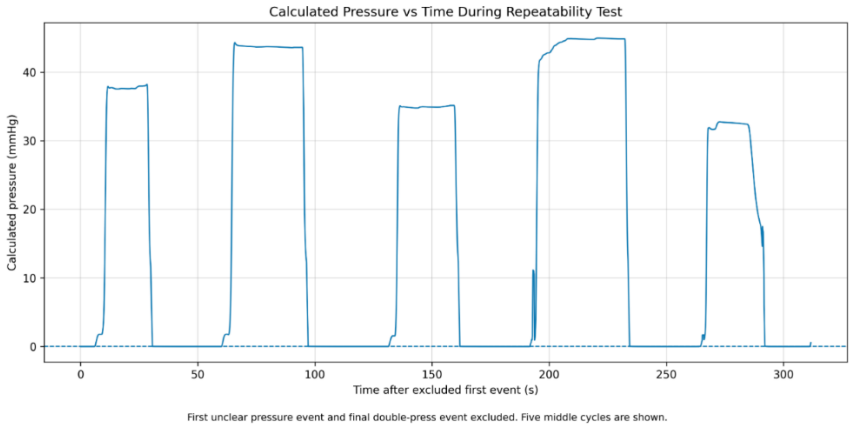


Figure: Calculated pressure versus time during the 618.6 s zero-pressure drift test. The pressure remained close to 0 mmHg, demonstrating a stable baseline for the Honeywell 40PC001B, voltage divider, ADS1115 and Raspberry Pi logging system.

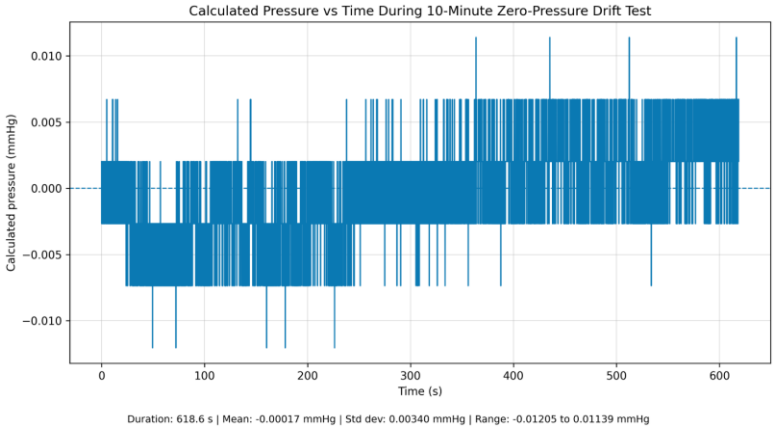
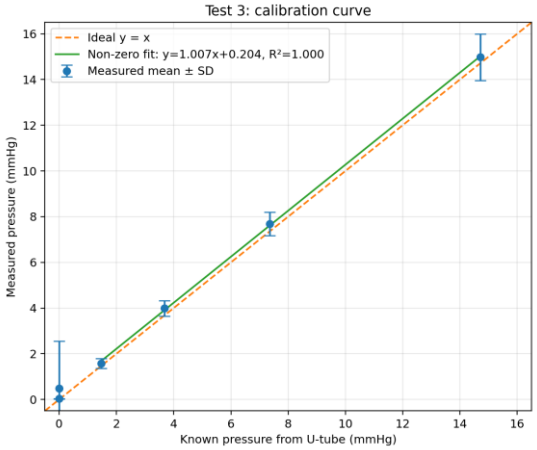


Figure: Calibration curve comparing known U-tube pressure with measured Honeywell pressure.



Appendix 3.2: AI prediction Model Results

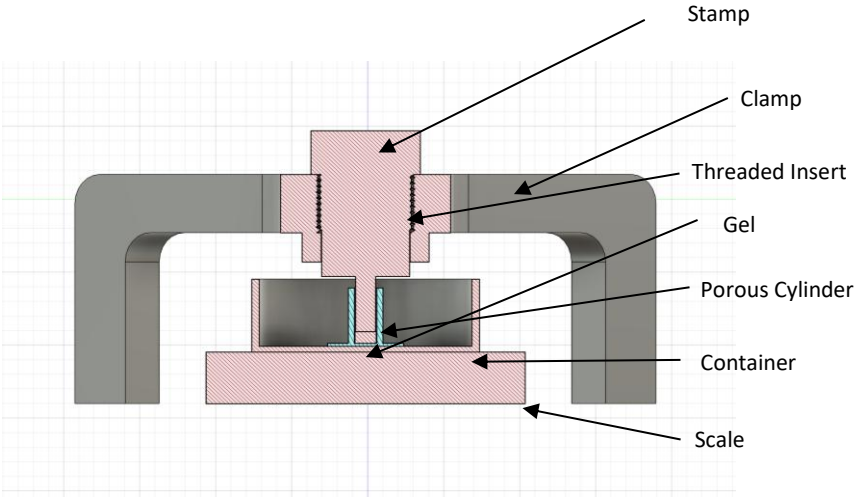
Figure: ***five****-dose Levodopa concentration prediction compared with published experimental data. Black dots: observed concentrations from Kuoppamäki et al. (2009); yellow dots: predictions generated by our AI model.*



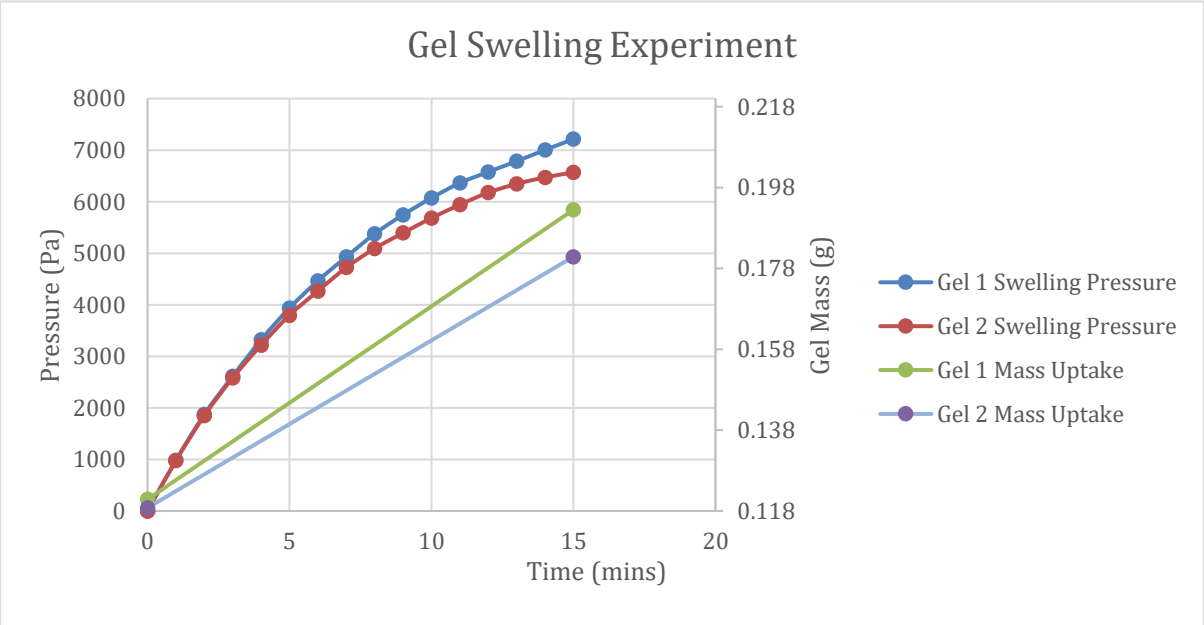
Appendix 3.3: Bonus Innovation

Force testing setup

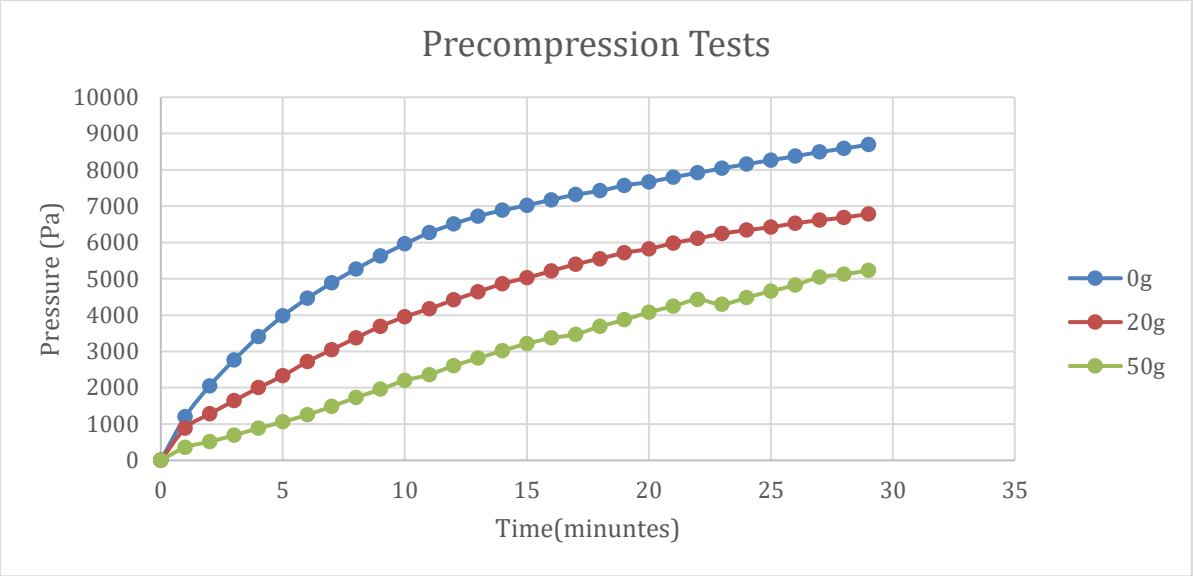


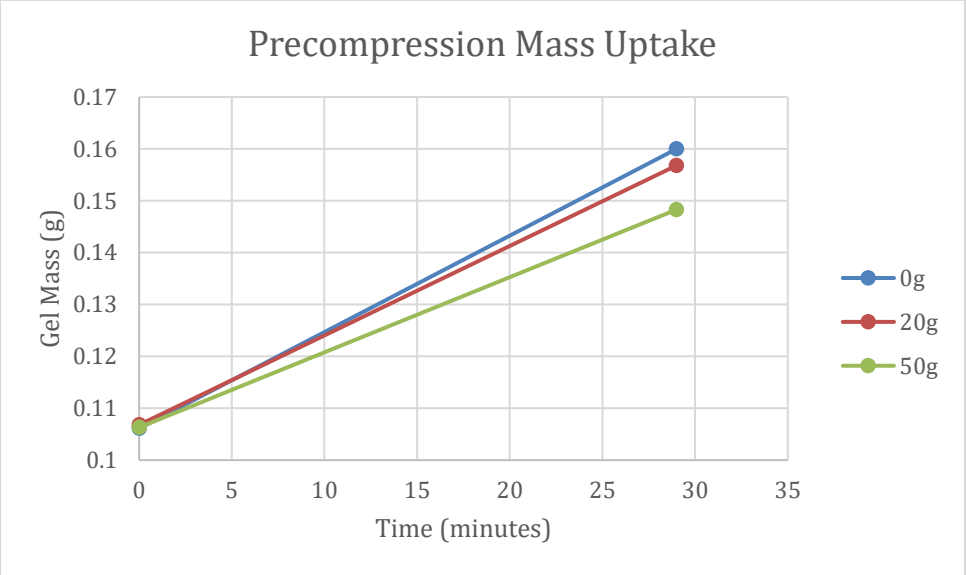


Force Testing Results

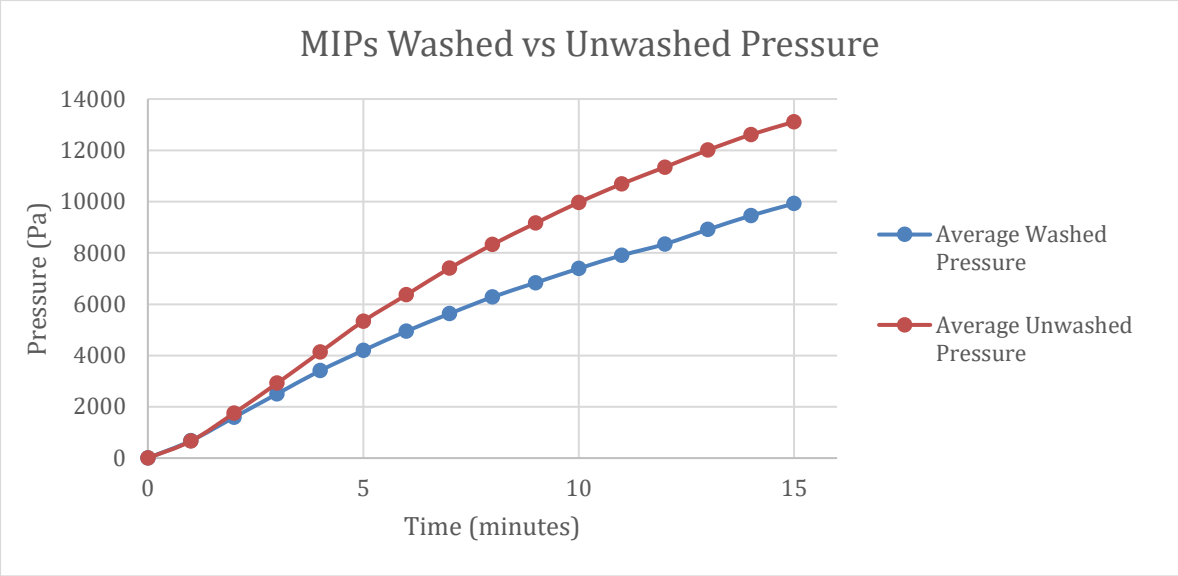


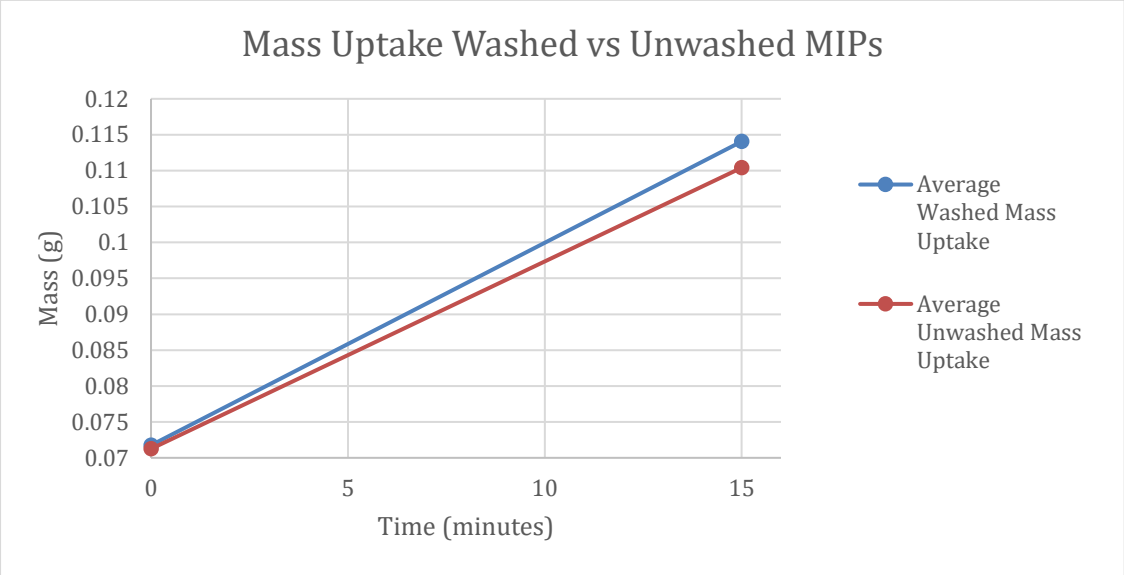
Precompression Tests





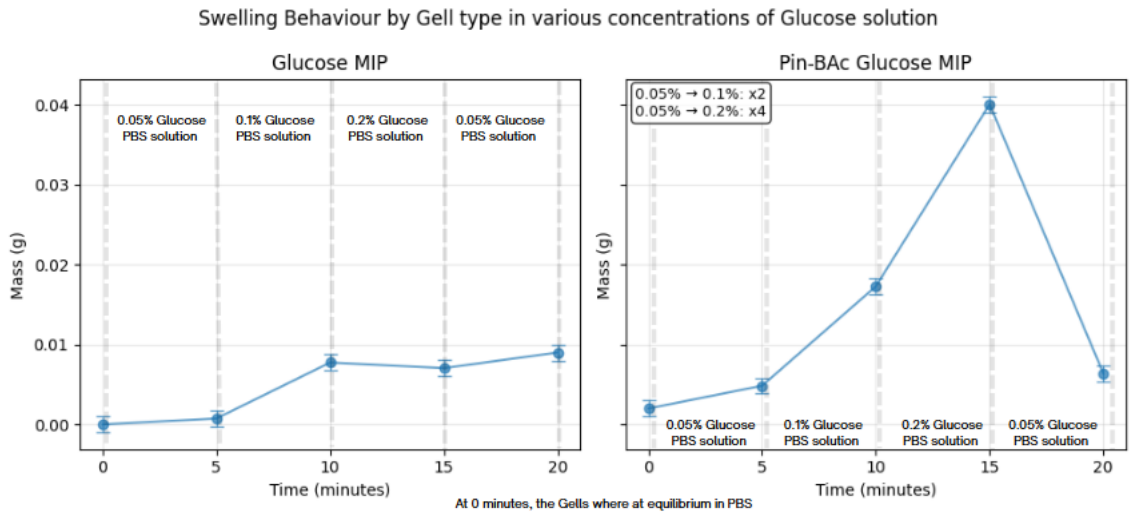
MIPs Washed vs unwashed Swelling



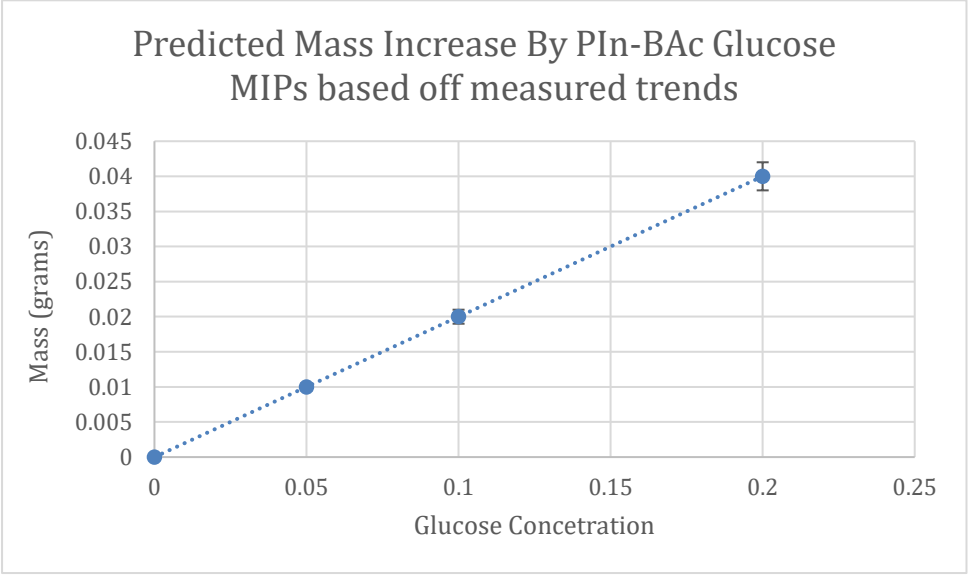


Appendix 3.4: Swelling Experiment Results

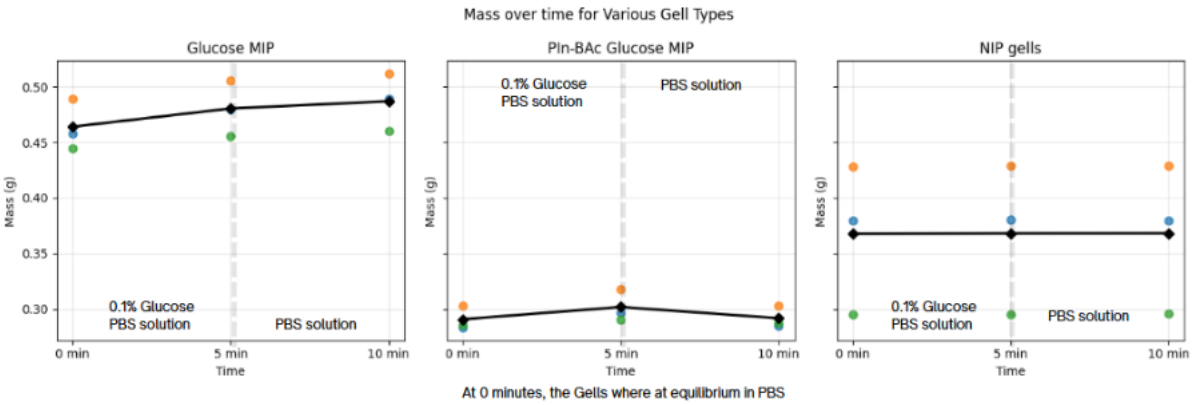
Swelling Behaviour of Glucose MIPs and PIn-Bac(boronic acid) glucose MIPs in various concentrations of Glucose solution after reaching saturation in PBS.



Predicted Mass Increase Of Pin-Bac glucose MIPs in various glucose concentrations predicted using measured data.

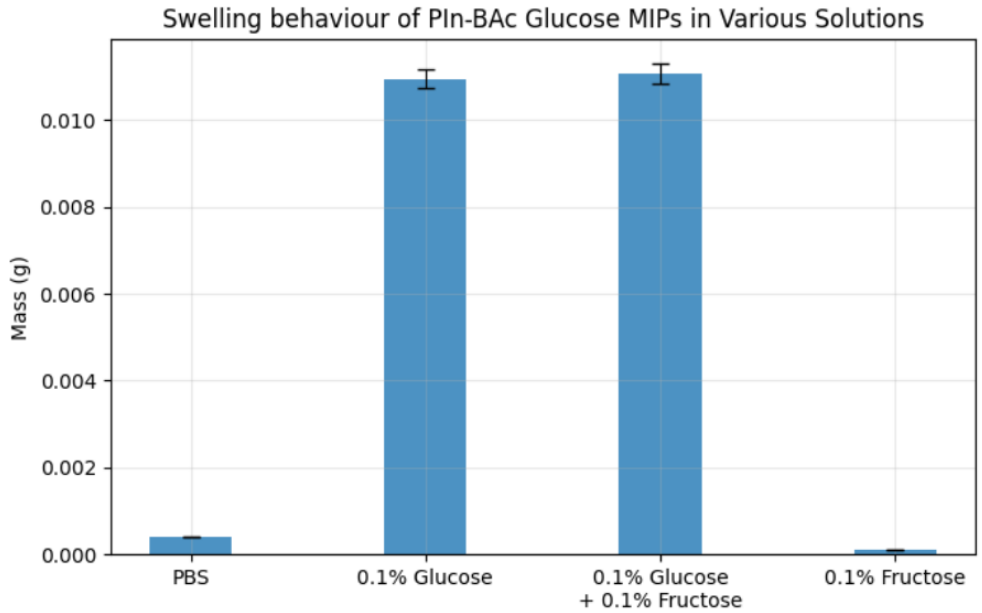


Swelling Behaviour of Glucose MIPs, PIn-BAc glucose MIPs and NIPs in 5 minutes of Glucose solution then 5 minutes in PBS (starting the experiment at equilibrium in PBS)

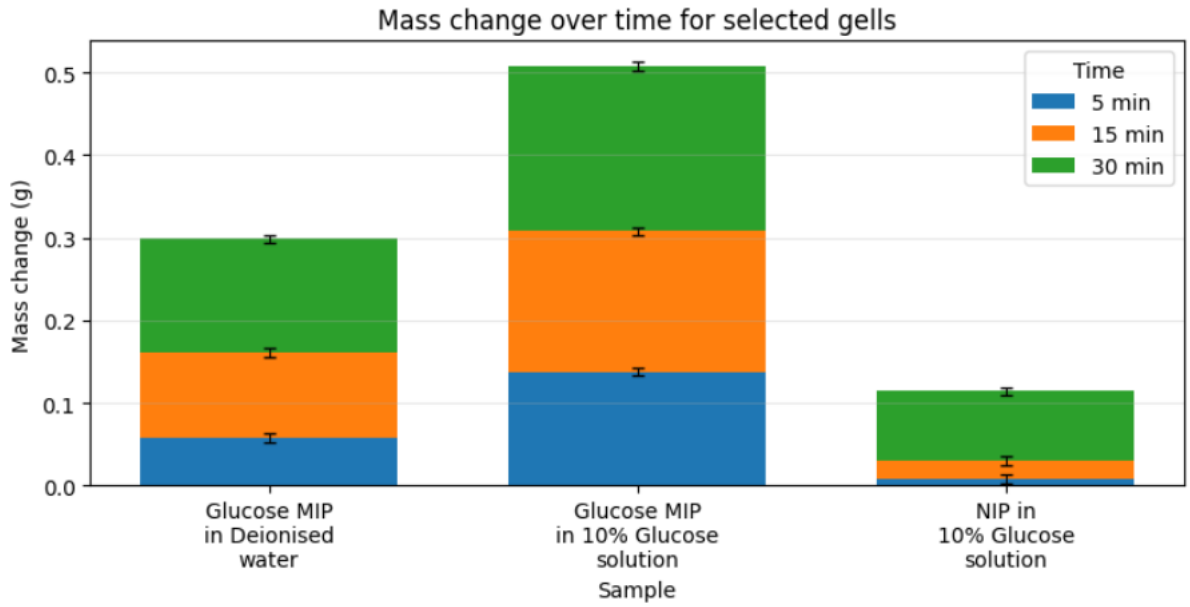


Selectivity Experiment

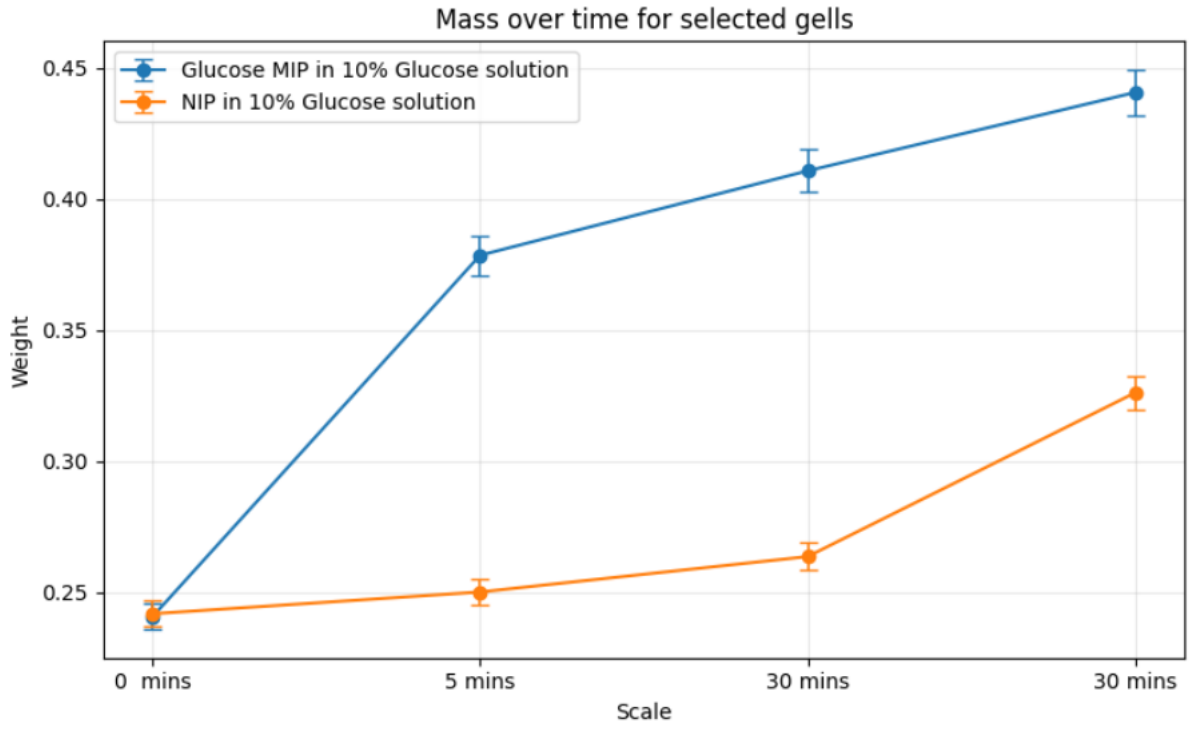
Amount swelling of MIPS in different solutions after soaking in water for an hour. This shows correct selectivity only for glucose.



Mass change for Glucose MIPs in various solutions to show Glucose MIPs swell greater in the Prescence of Glucose



Non-Imprinted polymer vs Molecular Imprinted polymer in 10 percent glucose solution.



Gel swelling force experiment showing difference in force produce with only a 0.01g difference in water uptake.

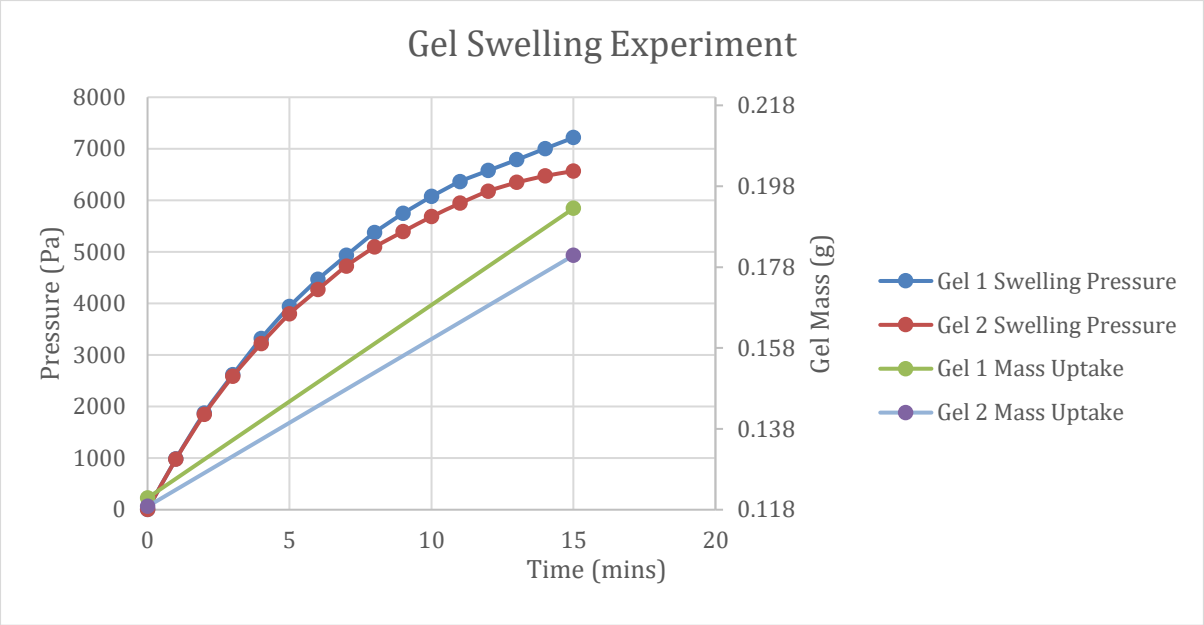


Figure: *BSA rebinding study results (washes vs fluorescence).*

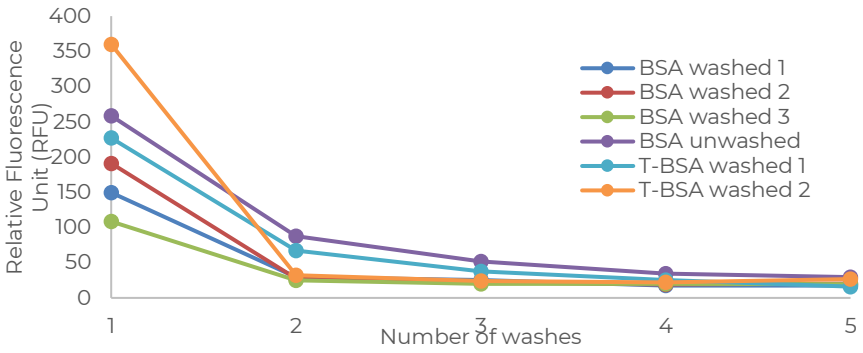
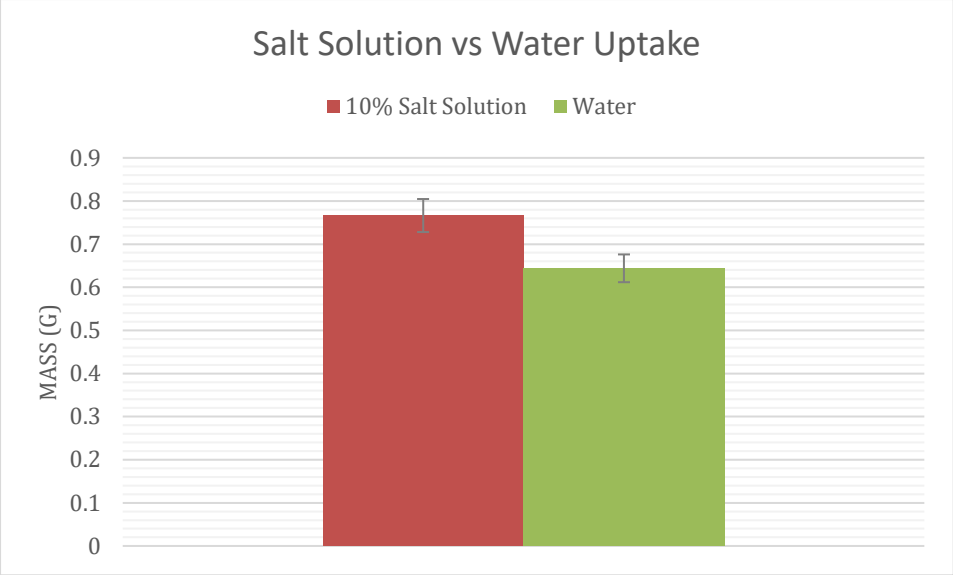


Figure: Salt solution vs Water, mass uptake Comparison


Salt Solution vs Water Uptake
10% Salt Solution
Water
MASS (G)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Appendix 4: Translational Potential

Translating Stakeholder Needs into Design Requirements	
Stakeholder Insight	**Design Requirement**
Unpredictable OFF periods	Predict future levodopa response
Paper diaries inaccurate	Continuous digital monitoring
Clinicians lack objective data	Continuous biosensing
Clinician satisfaction	System Usability Scale
Need context	Integrate symptoms + medication + meals into an app
Hard to navigate phones with poor mobility	Bigger icon choices + text to voice features in app

4.A Translating stakeholder needs into design requirements by taking key themes and translating them into design requirements.



AI Outcome	
Primary Outcomes	**Secondary Outcomes**
Reduction in daily OFF time	Medication adherence
OFF-period prediction	PDQ-8 quality of life
Analytical Accuracy	Carer confidence
Clinician satisfaction	System Usability Scale

4.B the Validation pathway for how the product shall be validated (left)

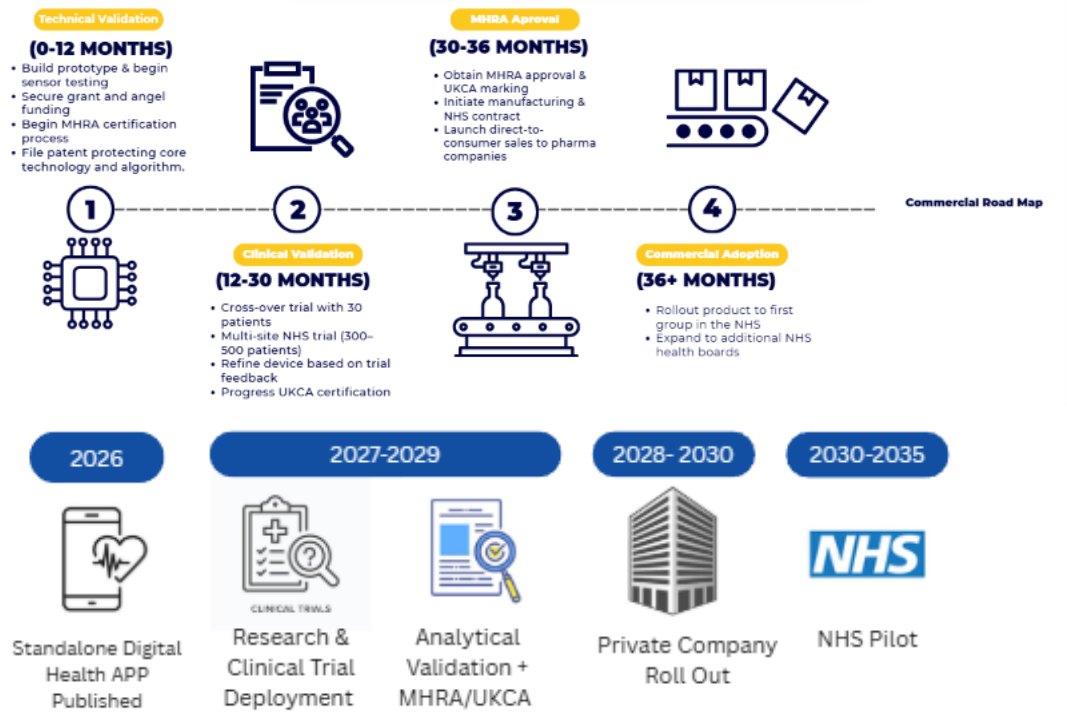
The AI outcomes (right) with primary and secondary outcomes

Sustainable business model		
Product	**Revenue**	**Costomer**
Reusable reader	One-off hardware sale	Private Patients / NHS / Private Companies
Disposable microneedle patch	Recurring consumable	Private Patients / NHS / Private Companies
AI & digital platform	Subscription licence	Private Patients / Private Companies
Clinical dashboard & AI & Digital platform	Enterprise licence	NHS Trusts
Research platform	Partnership & licensing	Pharma / CROs / Academia

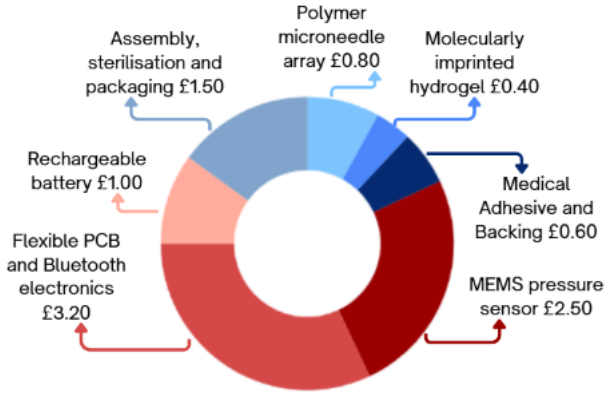
Stakeholder value proposition			
Patients	**Clinicians**	**Industry / Commercial Partners**	**Healthcare System**
Predict OFF periods	Objective levodopa data	Recurring revenue through sensors, software and analytics	Fewer hospital admissions
Medication reminders	Longitudinal monitoring	Opportunities for licensing, partnerships and expansion into new biomarkers	Reduced outpatient burden
Symptom tracking	Dose optimisation	Commercialisable biosensor platform	Improved resource allocation
Improved confidence	Personalised treatment	Scalable manufacturing	Lower long-term costs

4.C the sustainable business model (left) for the customer and revenue for each product

The stakeholder value proposition (right) for each of the targeted groups



4.DThe timeline for rollout of the biosensor



4.E The cost model breakdown for each biosensor. Data taken from:

United States Patent and Trademark Office (2023) US Patent No. 11,565,099. Available at: https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11565099 (Accessed: 1 August 2026).

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