Quantum Sensing for Biomedical Applications

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About QED-C
QED-C is an industry-driven consortium managed by SRI. With a diverse membership representing industry, academia, government, and other stakeholders, the consortium seeks to enable and grow the quantum industry and associated supply chain. For more about QED-C, visit our website at quantumconsortium.org.

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Executive Summary

Biomedical sensing faces challenges ranging from biological, physical, and chemical complexity and noisy environments to regulatory requirements and clinical implementation. Quantum sensing offers several compelling solutions to these challenges that could provide important benefits over classical tools. The location and noise often associated with biomedical measuring — for example, sensing tissue deep in the body, surrounded by veins and nerve endings — make accurate measurements difficult. Tools that do exist are often invasive, expensive, and rigid, and/or require a lot of physical space. For example, superconducting quantum interference devices (SQUIDs) can take measurements with very high sensitivity but they are expensive; require ultra-low temperatures and magnetic shielding, resulting in a large footprint; and have little flexibility in form factor. Supplementing or replacing classical sensors with new quantum sensors that overcome some of these limitations could have significant implications for treatment availability and improve medical outcomes.

Improved sensors could impact diverse aspects of biomedicine. For example, quantum sensors offer the possibility of significantly more efficient and accurate medical diagnoses for patients, thanks to their increased sensitivity and novel options for form factor. These attributes could enable quantum sensors to collect vast amounts of data about patients and medical conditions, and thus facilitate drug and treatment development and earlier diagnosis of disease. The advantages of quantum sensors encourage new ideas about solutions, quantum use cases, and business models across the biomedical industry — from prenatal care to cancer detection and treatment.

Several types of quantum sensors have high potential for biomedical applications and innovation, including optically pumped magnetometers (OPMs), optical frequency combs, and nanodiamonds with nitrogen-vacancy (NV) centers. High-feasibility, high-impact use cases for these and other quantum sensors include

- subcellular imaging,
- brain imaging,
- maternal and fetal imaging,
- tissue oxygenation imaging,
- systemic disease detection,
- biophoton detection for disease diagnostics, and
- microbiome analysis.

This report describes the limitations and advantages of both existing and developing quantum sensors, reviews the process for developing and commercializing quantum sensors for biomedical applications, and explores in detail the potential use cases listed above. Additionally, it offers three recommendations for developing quantum sensors that are readily usable in biomedical applications:

1. **Increase collaboration between quantum sensor developers and end users:** There are clear limitations to sensors currently used in the biomedical field, and quantum sensors can play an important role in addressing them. However, to do so, quantum sensor developers must be aware of these use cases and their unique needs. There are many ways to increase awareness and initiate collaboration between the developers and the clinicians who would use the sensors. For example, quantum sensor experts should proactively reach out to clinicians by participating in their conferences and meetings, such as those hosted by the American Medical Association, the National Academies of Sciences, Engineering, and Medicine, and the Medical Device Manufacturers Association. QED-C could reach out to conference organizers and offer to host special sessions at which quantum sensor developers share information about the instruments they are developing and hear insights from the clinicians present.

   Another option to spur collaboration across sectors is for federal funding agencies such as the National Institutes of Health (NIH) and the National Science Foundation (NSF) to require proposing teams include investigators from multiple disciplines, sectors, or stakeholder communities. For example, NSF's Convergence Accelerator program requires project teams to include researchers from a mix of disciplines and sectors. This type of requirement for research grants would force developers to consider the clinicians' needs from the start and help ensure that the sensor developed as part of the grant is practical and useful for the end user community. Additionally, including clinicians in the development and commercialization process could reduce reluctance in the healthcare industry to adopt new technology. Participating clinicians would understand how quantum sensors work and the benefits they offer to healthcare and could spread the word to their colleagues and advocate to their clinic administrators.

2. **Establish incubation and collaborative labs for testing:** The lack of testbeds across the quantum community makes it difficult to evaluate the performance of quantum sensors and identify their advantages over their classical counterparts. Sensor testing equipment can be prohibitively expensive and is not available to many research groups or small/startup businesses. Quantum sensor innovation would be enabled by establishing one or more incubators or user facilities with shared instrumentation and other components with which the sensor must interoperate. Such facilities would support research by and promote interaction among physicists, engineers, biologists, clinicians, regulatory scientists, and data

scientists. This would likely lead to organic cross-sector collaboration on R&D. Such a testbed could be established at existing national labs, such as those owned by NIH or Department of Energy, or at university research centers that are available for use by external researchers.

3. **Fund high-impact, high-feasibility biomedical research:** Federal agencies and venture capital firms funding biomedical research should consider the use cases detailed in this report as high priorities for the quantum sensor and biomedical communities. For example, research support for the development of robust, useful OPMs could have benefits for a variety of healthcare applications, including brain and fetal imaging. Similarly, small business funding for quantum sensor startups could support knowledge sharing and foster partnerships that would eventually lead to a cross-sector, multidisciplinary project team.

Introduction

Biomedical sensing faces challenges ranging from biological, physical, and chemical complexity and noisy environments to regulatory requirements and clinical implementation. New technologies must demonstrate advantages over the incumbent that overcome barriers to replacing protocols, standards of care, and entrenched players.

Quantum sensing offers several compelling solutions to biomedical challenges and could provide important benefits over classical tools. The location and noise often associated with biomedical measuring — for example, sensing tissue deep in the body, surrounded by veins and nerve endings — make accurate measurements difficult. Tools that do exist are often invasive, expensive, and rigid, and/or require a lot of physical space. For example, superconducting quantum interference devices (SQUIDs) can take measurements with very high sensitivity but they are expensive; require ultra-low temperatures and magnetic shielding, resulting in a large footprint; and have little flexibility in form factor. Supplementing or replacing classical sensors with new quantum sensors that overcome some of these limitations could have significant implications for treatment availability and improve medical outcomes.

Improved sensors could advance diverse aspects of biomedicine. For example, quantum sensors offer the possibility of significantly more efficient and accurate medical diagnoses for patients, thanks to their increased sensitivity and novel options for form factor. These attributes could enable quantum sensors to collect vast amounts of data about patients and medical conditions, thus facilitating drug and treatment development and earlier diagnosis of disease. Furthermore, quantum sensors encourage ideas about new solutions, new quantum use cases, and new business models across the biomedical industry — from prenatal care to cancer detection and treatment.

Following are examples of quantum sensors that have high potential for biomedical applications and innovation:

- **Optically pumped magnetometers (OPMs):** OPMs are capable of measuring very weak magnetic fields without the need for cryogenic cooling, unlike SQUIDs, which require a cryogenic environment.[1] The high sensitivity of OPMs makes them suitable for macroscopic detection of weak magnetic fields, such as those generated by the

[1] Tim M. Tierney, Niall Holmes, Stephanie Mellor, José David López, Gillian Roberts, Ryan M. Hill, Elena Boto, et al. 2019. Optically Pumped Magnetometers: From Quantum Origins to Multi-Channel Magnetoencephalography. *NeuroImage* 199: 598–608. doi: 10.1016/j.neuroimage.2019.05.063

brain or the heart.[2] In addition, OPMs offer great flexibility in form factor. For example, developers are evaluating OPMs that fit around a head and around a pregnant woman's torso to take measurements of the brain and fetus, respectively. Both applications offer patient comfort levels that are far better than most existing tools.

- **Optical frequency combs:** Frequency combs assess an unknown optical frequency by measuring the repetition rate of a continuous train of light pulses, which lies in the larger, easy-to-measure radio frequency range.[3] Researchers are investigating how to use frequency combs to conduct ultrasensitive breath analysis in real time. In addition to detecting intoxication, this sensor may detect biomarkers for respiratory and gastrointestinal conditions.[4]

- **Optically addressable spins:** Optically addressable spins contained within a host such as a diamond can perform single electron magnetic resonance, enabling nanoscale spatial resolution of a sensing target. Nitrogen-vacancy (NV) centers are the most mature platform and can operate at room temperature, making them ideal for ambient quantum nanosensors. These particles can be brought very close to or inside cells to take highly localized measurements. NV centers could help study metabolism and probe electrical activity of neurons. Nanodiamonds with NV centers can serve as in vivo nanoscale temperature sensors.[5] NV centers can be used for multiple measurement functionalities, and the short sensor-to-sample distance makes them especially useful for cellular and subcellular measurements.

- **Quantitative magnetic resonance imaging (MRI):** Existing MRI technology produces qualitative readouts that are interpreted by clinicians. The National Institute of Standards and Technology (NIST) has developed measurement standards and protocols to transform MRI into a quantitative tool for unambiguously diagnosing and monitoring disease.[6] These calibration standards enable direct comparison of images across machines and over time, and they ensure that MRI images provide quantifiable and traceable data.

- **Bose-Einstein condensate microscopic (BEC-M) sensors:** A BEC is formed when a collection of atoms is cooled to extremely cold temperatures. Trapped cold atoms are highly sensitive to changes in magnetic fields. To conduct sensing, a BEC is

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[2] Nabeel Aslam, Hengyun Zhou, Elana K. Urbach, Matthew J. Turner, Ronald L. Walsworth, Mikhail D. Lukin, and Hongkun Park. 2023. Quantum Sensors for Biomedical Applications. *Nature Reviews Physics* 5, no. 3: 157–69. doi: 10.1038/s42254-023-00558-3
[3] NIST. 2024. Optical Frequency Combs. https://www.nist.gov/topics/physics/optical-frequency-combs
[4] NIST. 2008. Optical "Frequency Comb" Can Detect the Breath of Disease. https://www.nist.gov/news-events/news/2008/02/optical-frequency-comb-can-detect-breath-disease
[5] Aslam et al. (2023), doi: 10.1038/s42254-023-00558-3
[6] NIST. 2018. What Are Imaging Phantoms? https://www.nist.gov/physics/what-are-imaging-phantoms

trapped at the measurement site so that its density profile can be directly imaged.[7] BEC-Ms have high spatial resolution and can create reliable measurements, even in the presence of large background fields.

- **Quantum imaging using entangled photons and squeezed light:** Light squeezing is a technique that reduces uncertainty in either the phase or amplitude of light by increasing the uncertainty of the other. The use of entangled and squeezed light can then be applied to imaging to enhance precision, reduce the number of photons needed to conduct imaging, and image without the need to label cells with injected dyes.[8]

There are trade-offs in using different quantum sensors, such as signal-to-noise ratio, selectivity, and spatial resolution. For example, NV diamonds are among the sensors with the best resolution, but they are highly sensitive to magnetic noise. SQUIDs also have high sensitivity, but they are very expensive to buy, install, and maintain. Scalability, ease of use, ease of system integration, and size, weight, power, and cost (SWaP-C) all will need to be considered when selecting the right quantum sensor for a given application. Multimodal sensing, which uses multiple types of sensors — classical and/or quantum — to collect biomedical data, could diminish some of these trade-offs and provide more comprehensive health information.

This report details some of the types of quantum sensing technologies available, the biomedical use cases in which they show promise, and business and government actions that can be taken to spur the development and adoption of novel quantum sensing technologies in medicine. It is informed in part by a workshop that convened experts from both the biomedical industry and the quantum R&D community. See Appendix A for the workshop methodology, Appendix B for the workshop-generated list of 186 use cases, Appendix C for participants' ideas on uses of a $250,000 grant, and Appendix D for a list of the participants.

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[7] Stephan Wildermuth, Sebastian Hofferberth, Igor Lesanovsky, Elmar Haller, L. Mauritz Andersson, Sönke Groth, Israel Bar-Joseph, Peter Krüger, and Jörg Schmiedmayer. 2005. Microscopic Magnetic-Field Imaging. *Nature* 435, no. 7041: 440. doi: 10.1038/435440a

[8] Daniel Soh and Eric Chatterjee. 2023. Label-free quantum super-resolution imaging using entangled multi-mode squeezed light. *New Journal of Physics* 25, no. 9: 093001.

Commercializing Quantum Sensors

In addition to technological challenges for developing quantum biomedical sensors, there are challenges for commercializing the nascent technology. **Figure 1** illustrates the high-level pathway to commercialization for biomedical applications. The figure is not intended to represent a straightforward linear path from research to market acceptance. The process of bringing new technologies to the marketplace is rarely so direct. Rather, it is usually characterized by multiple feedback loops by which exposure to downstream concerns from customers, clinicians, regulators, investors, and others leads to revisions in the new technology. This pattern is very likely to be the case for quantum sensors in biomedical applications, and the figure shows the continuous technology development throughout the commercialization pathway.

Obstacles to Commercialization

There are many roadblocks in the process of translating basic research in a lab to a commercialized product with a public health benefit. As a result, it is not uncommon for startups leading the basic and preclinical research to fold before they can start marketing a new medical device, halting progress toward improved standards of healthcare. The following are a few of the obstacles likely to be encountered when scaling quantum sensor technology from research to biomedical lab bench to bedside:

- Difficulty developing a sensor that can operate in clinical settings
- insufficient interdisciplinary collaboration
- limited funding for technology development and scaling
- lengthy and burdensome regulatory processes
- insufficient data on clinical effectiveness
- time and money investment required to demonstrate advantage over incumbent technology
- lack of sufficient market
- difficulty obtaining insurance approval

Quantum sensors often require specialized environments to function, a requirement that creates technical and portability issues. For example, some quantum sensors need extensive magnetic shielding to operate effectively. This requirement both hinders the ability to miniaturize the devices that use these sensors and makes clinical implementation costly, constraints that limit their use in hospitals, biomedical research labs, and elsewhere in the field. This is particularly inhibiting in rural areas, which often lack facilities that could allow for these sensors.

Another significant problem is the disconnect between the technologists who validate effects, mechanical engineers and industrialists who develop the technology, and clinicians who could field-test the technology. Technologists have an in-depth understanding of quantum science and the technology that the sensors rely on, but they are not always fully aware of the practical needs of real-life use cases. One such practical consideration is the need to take account of patient-specific factors in designing the device. For example, the design of a device intended for use in a pediatric care setting must consider the reality that children are likely to move around, which can be a problem if a sensor requires patients to stay still for an extended period of time.

Funding is also a barrier to the commercialization of quantum sensors. Most federal funding focuses on areas other than health and medical applications. For example, the National Quantum Initiative Supplement to the President's FY 2024 Budget describes quantum information science (QIS) programs and authorizes funding for NIST, the Department of Energy (DOE), and the National Science Foundation (NSF), but does not mention the National Institutes of Health (NIH) or related health and medical funding beyond acknowledgment that some NIST QIS R&D funding is relevant to healthcare.[9] Medical applications often arise as a secondary use of sensors developed for security, defense, or other industrial applications. Commercial funding for quantum medical applications is also limited because investors seek technology with broad applications in large markets. While the large number of hospitals and clinical offices around the world indicates a large potential customer base, many sensors are initially developed to focus on a specific healthcare application with a niche market and unique specifications. Until instruments are standardized and more readily accessible to clinicians, it will remain difficult to transition quantum sensors to broader applications without additional funding.

Quantum Sensor Development Process and Strategies

There are several key milestones for the quantum sensor development and adoption process. Before building devices, developers should work with clinicians to identify critical requirements for biomedical sensing and create a sensor based on those requirements. For example, biomedical devices often need to be integrated into existing systems, requiring customization for each potential application. It is also important that developers work with clinicians to create sensors that are easy to use.

Sensor developers should then begin trialing the sensor and obtaining the human and nonhuman animal data necessary for Food and Drug Administration (FDA) approval.

[9] National Science and Technology Council. 2023. *National Quantum Initiative Supplement to the President's FY 2024 Budget*. Washington. https://www.quantum.gov/the-national-quantum-initiative-supplement-to-the-presidents-fy-2024-budget-released/

Gathering sufficient clinical data to support the efficacy of a quantum device is both costly and resource intensive, and these trials are usually subject to Institutional Review Board oversight and approval, which can add additional time to the process of commercialization. But both the FDA and investors demand robust clinical data regarding safety and efficacy to justify further development. Once clinical trial data are submitted, FDA approval typically takes about two years.

Next, the developers will need to obtain buy-in from payers, including insurance companies in the United States — the largest healthcare market — as clinicians will not be interested in providing expensive treatments that won't be covered by national health plans or insurance. The sensor developer will need to apply to the American Medical Association for a new Current Procedural Terminology (CPT) code(s) for the device before healthcare professionals can bill insurance for use of the sensor; the CPT application process typically takes about two years. Once all regulatory approvals are obtained, the device manufacturers can work on scaling up manufacturing, which should help to reduce costs and improve consumer access.

Some use cases do not require FDA approval, primarily those in preclinical biomedical research, such as lab-based assays and imaging. The development of technology in this domain still requires trust in novel technologies; the slim margin for error and potentially grave consequences for patients require the developers of new technology to prove a higher standard of efficacy and reliability than in other quantum use case applications. There must also be a clear pathway to profit in order to obtain investor buy-in. This can be demonstrated by considering the variety of potential applications for the novel technology and the benefits the technology could bring society through its assessment of environmental exposures, such as airborne toxins, and its ability to improve health outcomes and patient comfort.

Figure 1 identifies areas where NIH and FDA could help facilitate commercialization, largely based on the two agencies' core roles in supporting research into and stewarding the approval of new medical devices. NIH could also provide opportunities for interdisciplinary teams (i.e., physicists, biologists, and clinicians) to work together on research and proof-of-concept development.

In addition to the ideas shown in **Figure 1Error! Reference source not found.**, workshop participants identified three strategies to reduce commercialization barriers. The first was to look for opportunities to gather clinical data beyond healthcare delivery settings. Given the importance of data for FDA approval and for attracting investment, it may be useful to deploy health-related quantum sensors outside of healthcare settings, such as wellness centers and sports facilities, where FDA approval is not always required for use. This would allow for the collection of valuable data that could support the regulatory approval and commercialization processes.

Second, participants suggested expanding the idea of the potential customer for biomedical sensors. For example, pharmaceutical companies might be motivated to fund the development of sensors that can detect medical issues early, particularly if a company has developed a drug for that particular condition. Insurance companies may also be interested, especially in situations where early diagnosis allows for the most impactful drug intervention.

Third, there is a need for standardization. Most quantum sensors currently on the market are highly specialized to the application and can vary significantly in components and performance metrics. This impedes scaling up the manufacturing of quantum sensors and can make them either not well suited to the intended use case or prohibitively expensive. More testbeds and benchtop instrumentation could support data collection on performance metrics of quantum sensors. The data could then be used to both demonstrate where quantum sensors have an advantage over classical sensors and help set standards for performance that are applicable to a range of use cases.

Figure 1: Pathway to Commercialization for Quantum Sensor Biomedical Applications: Agency and Industry Roles

Ongoing Technology Development

Research

- **Industry role:** Identify a biomedical need and begin researching how a quantum sensor could address it
- **NIH role:** Fund intramural and extramural research focused on investigating quantum sensing phenomena in biological systems
- **NSF & DOE role:** Provide funding for development of fundamental technologies
- **NIH role:** Identify gaps and opportunities in current quantum sensing biomedical research to help shape future research agendas
- **NIH role:** Convene conferences and workshops to bring together researchers, industry experts, and policymakers to discuss advances and challenges in quantum sensing technologies

Proof of Concept Development

- **Industry role:** Develop and test a quantum sensor prototype, including running clinical trials, to address identified biomedical need
- **NIH role:** Fund extramural research focused on developing initial prototypes for biomedical quantum sensor applications
- **NIH role:** Provide access to specialized test facilities and equipment for innovators working on quantum sensing technologies
- **NIH role:** Strengthen collaboration via programs designed to bridge the gap between technology development and clinical needs by facilitating greater cooperation between physicists and clinicians
- **NIH, NSF, DOE, and NIST role:** Collaborate on funding and R&D of fundamental technology to accelerate technology development and transfer

Regulatory Approval

- **Industry role:** Apply for FDA approval of the new sensor
- **FDA role:** Provide guidance on the regulatory requirements and standards needed for approval
- **FDA role:** Review and evaluate clinical trial data submitted by applicants to validate the safety and efficacy of the sensor in real-world conditions
- **FDA role:** Conduct public meetings and advisory committee sessions to gather input from stakeholders on regulatory standards and guidelines

Business Planning and Scaling

- **Industry role:** Apply for a Current Procedural Terminology code so use of the new sensor can be reimbursable by health insurance
- **Industry role:** Market the new sensor to clinicians and hospital administrators
- **NIH role:** Fund business incubators and accelerators that support startups and small companies developing quantum sensors
- **NIH role:** Collaborate with economic development agencies to provide resources and mentorship for scaling up production and business operations

Postmarket Monitoring

- **Industry role:** Continue collecting data on sensor performance to drive future innovations and improvements
- **FDA role:** Monitor postmarket performance and compliance through surveillance programs and periodic reporting
- **FDA role:** Update regulatory guidelines and standards based on new data and technological advances

Biomedical Use Cases for Quantum Sensors

The potential use cases for quantum sensors in the biomedical setting are vast, spanning multiple sensor types and systems of the body. During the workshop, biomedical and quantum experts shared ideas for applying quantum sensors to biomedicine and identified 186 potential use cases (Appendix B). The primary quantum sensors suggested for these use cases were NV color center diamonds (NV diamonds), magnetometer-based sensors such as magnetocardiography (MCG) and magnetoencephalography (MEG), spectrometer-based sensors such as nuclear magnetic resonance (NMR) spectroscopy, and frequency microcombs.

These sensor use cases were seen as applicable to numerous body systems and clinical concerns. Infectious diseases, cancer, drug metabolism, and diagnostics were the four most common areas of clinical relevance noted by participants. Most of the infectious disease use cases would involve studying specimens and the breath with frequency microcombs, and there was considerable interest specifically in SARS-CoV-2-related use cases. Breath analysis was also suggested for chronic obstructive pulmonary disease (COPD), asthma, lung cancer, and diabetes.

OPM-MEG sensors were proposed for many use cases, especially those that would image low magnetic fields from the brain, heart, fetuses, and muscles. This functionality could enable earlier diagnosis and improved treatment for chronic and neurodegenerative diseases, including epilepsy, Alzheimer's, dementia, and Parkinson's, as well as traumatic brain injuries, heart failures, and fetal health. Because OPMs offer greater flexibility than SQUIDs, they are especially well suited for improving diagnosis and care for babies and children who often move around a lot. This offers new opportunities for autism research and care for other mental health illnesses.

Cancer use cases were identified for opportunities to improve both diagnosis and treatment modalities through the application of quantum technology such as quantum dots, magnetometer-based sensors, biophoton detection, and frequency microcombs. Quantum sensors may provide unique information not accessible through classical sensors (e.g., magnetic/electrical field effect patterns in diseased and normal tissues and cells) and therefore could also be used in basic research to better understand cancer, for example in studies of cell death, cell temperature dynamics, and drug binding, toxicity, and uptake.

Drug metabolism more broadly was of great interest for a range of conditions. Suggested use cases described the potential for better drug metabolism sensors to help in drug discovery and development, accurate dosing, patient compliance, and tracking treatment efficacy against illness. These use cases were based on NMR, NV diamonds, OPM-MEG, and other (unspecified) sensor modalities.

Many of the identified use cases focused on new or improved tools for diagnostics generally, with an emphasis on imaging-based diagnostics systems; other ideas related to assay-based diagnostics. Suggestions included combining frequency combs with ultrasound, new pathways for miniaturization (for example, with handheld or micro-MRIs), and leveraging quantum dots in lateral flow assays.

Ideas for potential clinical applications of quantum sensors also included using frequency microcombs and magnetic sensing for gut health issues, MEG and NV diamonds to study the brain, magnetometers and other sensors to treat injuries, and NV diamonds to improve methods for basic biomedical research.

Discussion of these use cases yielded valuable insights and further development of ideas. Each breakout group in the workshop prioritized their top two or three use case ideas (left side of **Figure 2**) to present to the full group. These ideas were then consolidated into 11 broad ideas, shown in the middle. This was followed by a robust discussion of the impact and feasibility of the ideas, including insights on how feasibility can be determined both by the technology itself and by federal and other large funding bodies' interest in actualizing potential advances. Seven of the consolidated use cases (right side of **Figure 2**) were then further developed, often into more specific applications.

Figure 2: Filtering of Biomedical Use Case Ideas in Workshop Discussions
MEG = magnetoencephalography; MRI = magnetic resonance imaging; OPM = optically pumped magnetometer

Implementation Details of Selected Use Cases

Workshop participants expanded on the seven selected use cases and discussed desired features and functionalities, timelines, and critical stakeholders for implementation. Across use cases, the implementation process of quantum sensing technology will depend on an interdisciplinary workforce from science, government, healthcare, and administration. For example, scientists — primarily quantum physicists, biologists, and biomedical engineers — will need to collaborate in developing the quantum sensors, with input from clinicians. Federal agencies will likely be involved as funders and supporters of the biomedical research. To obtain regulatory approval from the FDA, regulatory and reimbursement consultants, insurers, and clinical advocates all may play a role. As quantum sensors come on the market, buy-in from hospital administrators and clinicians will be critical for technology adoption. Implementation and deployment of quantum sensors for the selected use cases could likely be streamlined through increased collaboration among these groups throughout the process.

Subcellular Imaging

The improved sensitivity of and access to biomedical data that many quantum sensors offer over current tools could be transformative for imaging at the subcellular level. For example, a microscope that is functional in a 3D space could image molecules and physical parameters, such as minute temperature changes due to drug-receptor interactions and mitochondrial activity. This advancement could support drug discovery by enabling improvement in the binding of agents to biological samples, help treat diseases by providing more accurate measurement of drug delivery, signal drug delivery pathways, and provide a single platform that can obtain multimodal data from a single sample.

Creation of a subcellular microscope will require the separate development of the functionality for imaging physical, molecular, and chemical properties. These will then be integrated in a single microscope with multiple sensors that capture the desired data in living cells. This sensor system can use an array of NV diamonds to obtain submicron maps of cellular temperature and magnetic field gradients originating from drug treatments. The arrays should be able to map electrical field gradients both across cell membranes and within cells and should be large enough to map several interacting cells.

The sensors in the microscope should be able to measure, perform, or capture submicron magnetic and electric field mapping, temperature, and pH. They should also be able to measure protein biosynthesis, reactive oxygen species, and oxidative stress.

The ability to capture physical and chemical parameters should include intracellular administration of NV diamonds, application of laser illumination and microwave irradiation, measurement of magnetic resonance spectra, and measurement of viscosity through rotational motion in a magnetic field.

The timeline for development of subcellular microscopes starts with the development of a proof of concept of multimodal integration, which is estimated to take at least 3–4 years, longer if research on individual sensing capabilities that are to be integrated is not advanced enough to start. Once this proof of concept starts providing data for observed cells, the research can be translated out of the lab and into industry.

Brain Imaging

Magnetoencephalography using OPMs is a nascent quantum-sensor-based medical imaging technology that measures the magnetic fields generated by neural activity in the brain. It is highly sensitive to the weak magnetic fields of the brain; provides excellent spatial resolution, enabling precise localization of brain activity; and has excellent temporal resolution, capable of capturing rapid changes in brain activity on the millisecond scale.

OPM-MEG works by optical pumping of alkali atoms (such as rubidium) via a laser, which creates a polarized state in the atoms. Neural activity in the brain produces minute magnetic fields that interact with the polarized atoms, causing changes in their spin states, and these changes are detected using atomic spectroscopy. A second laser measures the shifts in the atoms' energy levels, which correspond to the strength and direction of the magnetic fields produced by the brain. This process yields a functional view of brain activity.

Unlike traditional MEG systems that use superconducting sensors requiring cryogenic cooling, OPM-MEG employs highly sensitive optically pumped magnetometers that operate at room temperature. This innovation offers significant advantages in terms of portability, patient comfort (because it is noninvasive), and the ability to conduct more flexible and naturalistic brain studies.

For all these reasons, OPM-MEG has several significant potential clinical applications. It is particularly useful in diagnosing and planning surgeries for epilepsy by localizing abnormal neural activity. Its use in functional brain mapping helps identify essential regions for language, motor control, and sensory processing, aiding neurosurgical procedures. Its comfort and portability make it suitable for studying neurodevelopmental disorders in children, such as autism and ADHD. Additionally, OPM-MEG can monitor brain activity in stroke and traumatic brain injury patients, be used to investigate psychiatric conditions like schizophrenia and depression, facilitate the study of sleep disorders, and aid in early diagnosis of neurodegenerative diseases like Alzheimer's and Parkinson's.

OPM-MEG has the potential to replace both SQUID MEG, which uses sensors that require cryogenic cooling to maintain their superconducting state, and electrocorticography (ECoG), which involves placing electrodes directly on the exposed surface of the brain to measure electrical activity. ECoG requires a craniotomy, a surgical procedure that removes a part of the skull and is therefore extremely invasive. Similarly, OPM-MEG may be complementary to conventional electroencephalogram (EEG), which measures the brain's electrical activity through numerous electrodes applied directly to the head and is likely of similar inconvenience to the patient as SQUID MEG.

Because it measures brain activity in a highly accurate manner, OPM-MEG also has potential application in cognitive science generally. Developers believe the approach can provide better brain imaging at significantly lower cost than SQUIDs and classical sensors, and the cost is expected to decline with technology adoption.

Currently, OPM-MEG systems are primarily used in research settings to study brain activity and investigate neurological conditions. The goal for OPM-MEG technology developers is to make its use for clinical imaging much more routine, so that doctors, radiologists, and other clinicians needing neurological imaging would request OPM-MEG for patients with diagnosed or suspected neurodegenerative disease conditions.

Maternal and Fetal Imaging

Quantum sensors have the potential to improve health outcomes for both fetuses and mothers. In 2021 the fetal mortality rate in the United States was 5.73 fetal deaths per 1,000 live births,[10] compared to a death rate of 0.22–4.73 for the US population ages 1–54 years.[11] There are several common causes for sudden fetal death, including congenital malformations and maternal conditions. Still, about one third of fetal deaths go unexplained.[12]

The depth of the uterus causes the biomagnetic fields for fetal heart and brain signals to be weaker than their adult counterparts, requiring more sensitive sensors to monitor them. Historically, echocardiography has been used to measure electrical waveform intervals for cardiac rhythm, but it can provide imprecise and inaccurate results in fetuses. Fetal magnetocardiography (fMCG) is a quantum-based technology that offers

[10] Elizabeth C.W. Gregory, Claudia P. Valenzuela, and Donna L. Hoyer. 2023. Fetal Mortality: United States, 2021. *National Vital Statistics Reports* 72, no. 8. https://www.cdc.gov/nchs/data/nvsr/nvsr72/nvsr72-08.pdf
[11] Jiaquan Xu, Sherry L. Murphy, Kenneth D. Kochanek, and Elizabeth Arias. 2022. Mortality in the United States, 2021. *NCHS Data Brief* 456. https://www.cdc.gov/nchs/data/databriefs/db456.pdf
[12] Gregory, Valenzuela, and Hoyer (2023).

far more precise and accurate evaluation of fetal rhythm by measuring magnetic waves.[13] fMCG is especially useful for diagnosis and prognosis of fetal arrhythmias, which are a common cause of fetal death, but it can also be used to detect an adverse maternal environment, cardiomyopathy, and hydrops, among other fetal and maternal conditions. Similarly, fetal magnetoencephalography (fMEG) is a quantum-based noninvasive method for measuring brain activity in fetuses; it enables assessment of intrauterine cognitive development while promoting maternal comfort.[14] Results can be used to diagnose conditions earlier, advise treatment for the mother, and improve the prognosis for both mother and fetus.

The most common type of fMCG sensor is a SQUID, but this is expensive, has a large footprint, requires lots of shielding, and is rigid, requiring the mother to rest in an uncomfortable position for about an hour. All of these factors limit SQUID availability in clinical settings. OPMs have many advantages over SQUIDs, including their small sensor footprint and lower cost. They also offer more flexibility in configuration, which improves maternal comfort and allows the same system to be used at different stages of pregnancy. Research is being conducted to use OPMs for measuring pelvic floor muscles during pregnancy and uterine contractions.

To achieve widespread availability of OPMs for all mothers, stable, cheap, and easy-to-use OPMs need to be developed. This step is estimated to take about three years, but could be inhibited by a lack of collaboration among researchers, clinicians, and quantum system developers. OPM system developers can then apply for FDA approval, followed by assignment of a CPT code, a process collectively taking about five years. Once all approvals are in place, OPMs can be commercialized and standards of care developed, which is estimated to take five years. OB/GYNs, pediatricians, cardiologists, and hospital and women's clinic administrators all will play a crucial role in advocating for their facilities to purchase an OPM. Imaging technicians will need to be trained on how to use them.

OPMs would likely first be found in tertiary hospitals but could eventually be common in imaging centers. Once researchers develop OPM systems that don't require magnetic shielding, they could be available in labor and delivery centers as well. Implementation of OPMs may facilitate early diagnosis of adverse conditions and environments and reduce stillbirths, all while promoting patient comfort.

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[13] Sarah Strand, Janette F. Strasburger, and Ronald T. Wakik. 2019. Fetal Magnetocardiogram Waveform Characteristics. *Physiological Measurement* 40, no. 3. doi: [10.1088/1361-6579/ab0a2c](10.1088/1361-6579/ab0a2c)

[14] Carolin J. Sheridan, Tamara Matuz, Rossitza Draganova, Hari Eswaran, and Hubert Preissl. 2010. Fetal Magnetoencephalography—Achievements and Challenges in the Study of Prenatal and Early Postnatal Brain Responses: A Review. *Infant and Child Development* 19, no. 1: 80–93, doi: [10.1002/icd.657](10.1002/icd.657)

Tissue Oxygenation Imaging

The concept of tissue oxygenation imaging aims to measure hypoxic tissue at the suborgan (millimeter) level to identify abnormalities such as ischemia, injury, infections, cancer, and other medical conditions. Such imaging would allow for the detection of pathologic conditions far earlier than is possible with current technology. The variety of form factors available for quantum sensors could enable imaging in bedside and outpatient office settings.

One possible mechanism for imaging deep tissue is a quantum-based instrument or spectrometer that uses tracers that bond to oxygen or reveal functional abnormalities in an affected organ. The sensor will need to provide accurate oxygen level measurements of deep tissue through noninvasive procedures. This technology would be designed for use by doctors across various specializations, including trauma, cardiology, cancer, orthopedics, gastroenterology, critical care, and neurology. Eventually, it could even be developed and scaled up for use in sports medicine clinics, given the likely interest in monitoring tissue oxygen enrichment in high-performance athletes.

Experts estimate that the timeline for development of the technology would include one year of research, two years to solve key challenges, and one year for development; however, obtaining the necessary regulatory approvals could extend this process.

Systemic Disease Detection

Quantum sensor technologies could improve the detection of many systemic diseases through real-time biomarker monitoring. OPMs are excellent candidates for this application, as they can detect weak electromagnetic signals at the measurement site. Such sensors, including nanodiamonds with NV centers, frequency comb breathalyzers, and gas detectors, would have medium- and long-term monitoring capabilities because they would be wearable or transdermal (implantable; experts believe implantation would be only minimally invasive). The sensor would work on deep tissue to detect ongoing infection, inflammation, ischemia, fibrosis, hypoxia, and other conditions. Multimodal sensing could help isolate specific conditions and diseases.

The R&D timeline for this use case is unclear and dependent on the readiness and quality of incumbent disease technology and the ability to integrate quantum sensors into it. Once the quantum technology is developed, has regulatory approval, and is widely adopted, the use of OPMs rather than existing tools for systemic disease detection will make it possible to detect diseases earlier, lower costs of medical care, and collect biomarker information that is not currently available because it is not detectable using current technologies.

Biophoton Detection for Disease Diagnostics

Ultraweak biophotons emitted by diseased cells — for example, cancerous cells — have signature frequency profiles that are distinguishable from healthy cells.[15] With the development of quantum-based biophoton detection, these unique frequency signatures could be used in research for detecting disease or in clinical settings as a noninvasive diagnostic tool. Early applications could be for skin cancer but in the future could include noninvasive applications to deeper tissue.

One technology that could be used for biophoton detection is single-photon avalanche diodes (SPADs), which are optimized to detect individual photons and their arrival times with high temporal resolution. Benefits of this technology include its spatial resolution and signal-to-noise ratio, enabling more accurate measurements. Early success of deploying SPADs would be indicated by frequency characterization that showed standard frequency signatures for specific diseases, such as melanoma, consistent across a large sample set. Near-term progress would be complete characterization of melanoma's frequency profile within two years, and to have treatment approaches guided by biophoton signatures within five years.

Microbiome Analysis

Quantum sensors could provide near real-time information about the microbial composition and biodiversity of the body's microbiome. It is increasingly clear that the microbiome is correlated to multiple health outcomes, and its health and diversity are postulated as a proxy for overall health. The biomedical field currently has too few tools to assess microbiome composition and how it changes over time, and quantum sensor technologies could help fill this gap and enable faster analyses.

The use of quantum sensors would greatly facilitate analysis of bacteria, fungi, and other microbes from the gut microbiome at an individual level using stool samples or at the population level using wastewater. There may also be interest in other microbiomes, such as the skin microbiome, which is easier to access. Individual microbiome analysis could provide insights into personal health and wellbeing, and population-level analysis could be used for wider public health goals. Quantum sensor modalities that could be

[15] Nirosha J. Murugan, Michael A. Persinger, Lukasz M. Karbowski, and Blake T. Dotta. 2020. Ultraweak Photon Emissions as a Non-Invasive, Early-Malignancy Detection Tool: An In Vitro and In Vivo Study. *Cancers* 12, no. 4. doi: 10.3390/cancers12041001

leveraged for microbiome analysis include frequency combs,[16] color centers,[17] and quantum dots for tagging,[18] though more research and clinical trials are needed.

Because knowledge of how microbiomes change and adapt in real time is limited, quantum sensors would likely first be applied to microbiome analysis research, which would ideally lead to opportunities to use the technology for diagnostics, prognostics, and treatment.

Developing quantum sensors for analyzing the gut microbiome would require a long timeline for R&D — at least five years — to first characterize small molecular metabolites and metabolomes before attempting metagenomic applications. Workshop participants believed that the R&D would mainly be in industry, but additional R&D activity and financial support could also come from federal research funding agencies, universities, national labs, venture capital funds, and nonprofits. Once research has enabled development of a quantum sensor that can analyze the gut microbiome, this tool could be used to improve identification of species and changes in composition in a diagnostic timescale. Furthermore, the quantum-based tool could be used to increase knowledge about the gut microbiome overall.

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[16] Joshua A. Whitaker-Lockwood, Sarah K. Scholten, Faisal Karim, André N. Luiten, and Christopher Perrella. 2024. Comb spectroscopy of CO_2 produced from microbial metabolism. *Biomedical Optics Express* 15, no. 3: 1553–70. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10942673/

[17] Valentin Radu, Joshua Colm Price, Simon James Levett, Kaarjel Kauslya Narayanasamy, Thomas David Bateman-Price, Philippe Barrie Wilson, and Melissa Louise Mather. 2020. Dynamic Quantum Sensing of Paramagnetic Species Using Nitrogen-Vacancy Centers in Diamond. *ACS Sensors* 5, no. 3: 703–10. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7106109/

[18] `https://pubmed.ncbi.nlm.nih.gov/38594377/

Recommendations

The following recommendations for developing and commercializing quantum sensors and increasing their adoption in biomedical applications are based on inputs from the workshop and subsequent discussions with experts in the field.

1. **Increase collaboration between quantum sensor developers and end users:** There are clear limitations to sensors currently used in the biomedical field, and quantum sensors can play an important role in addressing them. However, to do so, quantum sensor developers must be aware of these use cases and their unique needs. There are many ways to increase awareness and initiate collaboration between the developers and the clinicians who would use the sensors. For example, quantum sensor experts should proactively reach out to clinicians by participating in their conferences and meetings, such as those hosted by the American Medical Association, the National Academies of Sciences, Engineering, and Medicine, and the Medical Device Manufacturers Association. QED-C could reach out to conference organizers and offer to host special sessions at which quantum sensor developers share information about the instruments they are developing and hear insights from the clinicians present.

   Another option to spur collaboration across sectors is for federal funding agencies such as NIH and NSF to require proposing teams include investigators from multiple disciplines, sectors, or stakeholder communities. For example, NSF's Convergence Accelerator program requires project teams to include researchers from a mix of disciplines and sectors. This type of requirement for research grants would force developers to consider the clinicians' needs from the start and help ensure that the sensor developed as part of the grant is practical and useful for the end user community. Additionally, including clinicians in the development and commercialization process could reduce reluctance in the healthcare industry to adopt new technology. Participating clinicians would understand how quantum sensors work and the benefits they offer to healthcare and could spread the word to their colleagues and advocate to their clinic administrators.

2. **Establish incubation and collaborative labs for testing:** The lack of testbeds across the quantum community makes it difficult to evaluate the performance of quantum sensors and identify their advantages over their classical counterparts. Sensor testing equipment can be prohibitively expensive and is not available to many research groups or small/startup businesses. Quantum sensor innovation

would be enabled by establishing one or more incubators or user facilities with shared instrumentation and other components with which the sensor must interoperate. Such facilities would support research by and promote interaction among physicists, engineers, biologists, clinicians, regulatory scientists, and data scientists. This would likely lead to organic cross-sector collaboration on R&D. Such a testbed could be established at existing national labs, such as those owned by NIH or DOE, or at university research centers that are available for use by external researchers.

3. **Fund high-impact, high-feasibility biomedical research:** Federal agencies and venture capital firms funding biomedical research should consider the use cases detailed in this report and the ideas listed in Appendix C as high priorities for the quantum sensor and biomedical communities. For example, research support for the development of robust, useful OPMs could have benefits for a variety of healthcare applications, including brain and fetal imaging. Similarly, small business funding for quantum sensor startups could support knowledge sharing and foster partnerships that would eventually lead to a cross-sector, multidisciplinary project team.

Appendix A: Methodology

This report explores quantum sensing as it relates to biomedical applications and is largely informed by an in-person workshop organized by the QED-C Use Cases Technical Advisory Committee. The June 17–18, 2024, workshop took place in Washington, DC, and was attended by 50 stakeholders from the healthcare sector, quantum technology sector, government, and academia.

The workshop participants looked at a variety of quantum sensors and their potential to improve diagnostics and patient care, and identified 186 specific use cases, listed in Appendix B. Many of these ideas focused on the nervous system and specifically the brain.

Workshop Goals: Surface High-Impact, Feasible Ideas

- Identify biomedical imaging and detection use cases for quantum sensors and the capability requirements necessary for application.
- Prioritize top use cases based on impact, feasibility, and the current state of the art.
- Identify technology gaps that need to be filled to enable application and adoption of quantum sensing technologies.
- Recommend strategies for filling the technology gaps and thereby supporting realization of the top use cases.

Structure: Encourage Collaboration, Fresh Thinking

The workshop was designed to maximize collaboration opportunities among attendees with knowledge of quantum sensing and biomedical sectors. All participants were sent the following resources in advance describing how quantum sensors could impact the biomedical field.

- Demonstration of a magnetic sensor detecting biomagnetic signals [video]: https://www.sri.com/press/story/sri-led-team-demonstrates-a-magnetic-sensor-that-detects-biomagnetic-signals/
- Overview of applications of quantum sensors in biomedical applications [article]: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9896461/
- Narrative overview of the history and technological milestones of quantum technology in medicine [article]: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10689891/
- NIH presentation of exemplars of quantum sensing in biomedical sciences [slide deck]: https://oir.nih.gov/sigs/qis-quantum-sensing-biology-interest-group

The workshop began with presentations from experts in the quantum sensing and biomedical sectors to provide context, describe the state of the art, and ensure that all participants had a baseline knowledge of both quantum technology and relevant biomedical concepts. Sergey Polyakov of NIST opened by discussing the limitations of classical sensors and the opportunities quantum sensors present in biomedical applications. He emphasized that current technology cannot keep up with the need for discovery because of the immense complexity of biology. Most diseases have only a few potential treatments, and some have none. Of the treatments developed, 95% fail to make it to the market. Quantum sensors, with their promise of increased sensitivity and precision, offer the potential to accelerate the development of new treatments and improve diagnostics capabilities.

Peter Krüger of Physikalisch-Technische Bundesanstalt and Stefan Bogdanovic of SandboxAQ provided an introduction to quantum sensors. Krüger started by explaining the potential of magnetic sensing in biomedical applications. Electromagnetic activity is present in the brain and both the central and peripheral nervous system. Sensors can detect this activity, and quantum magnetometry clearly outperforms classical sensors. Krüger noted that there are trade-offs between quantum and classical sensing. SQUIDs (the oldest quantum magnetometers) and atomic magnetometers currently offer the best performance. The former offer ultralow noise, large bandwidth, dynamic range, moderate shielding requirements, and good long-term stability, but they require cryogenic environments and have a large stand-off distance. OPMs excel in precise spectroscopy and devices with these magnetometers can be closer to the measured object, enhancing sensitivity. But OPM technology is sensitive to noise and needs ruggedization, validation, and standards.

Bogdanovic reviewed the potential of quantum sensors in detecting cardiovascular disease. Current technology, EKG, fails to detect all types of cardiac attacks. MCG could detect them but not every medical facility has a device because it is large and expensive. Physicians need something small and portable that can be at a patient's bedside to detect an attack. SandboxAQ has been developing a sensor using NV centers. Bogdanovic stressed the need to understand both the user and the real-world situation the sensor would be used in. Nurses and doctors must be able to use a device built with quantum sensors in the situations where and when they need them. Otherwise, the device will be left unused.

Next, Peter Maurer of the University of Chicago gave an overview of the status of quantum biosensor R&D in academia. He discussed the complexities of life sciences and the necessity of sensors to understand them. Quantum sensors generally offer much better precision than that of classical sensors, and clocks are the first and best example of this quantum advantage. In the biomedical context, quantum sensors need to operate in real-world conditions (e.g., room temperature and nonvacuum conditions). Maurer highlighted the development of nanoscale NV center sensors over the past 20 years and noted that they may be the next generation of quantum sensors in the biomedical field. Efforts are being made to miniaturize this technology and to improve spectral resolution and sensitivity. Despite these advances, the technology remains in the proof-of-concept stage because of challenges such as low magnetic fields and weak signals that are hard to interpret.

The afternoon featured a panel discussion on the lab-to-market transition of quantum sensors for biomedical applications, with speakers Cecil Lynch (Accenture), Conor Hart (Quantum Catalyzer), Young Jin Kim (Los Alamos National Lab), Paige Derr (NIH), and Orang Alem (FieldLine). The panelists agreed that successful commercialization requires not just technology advancement but a strong focus on user experience. Collaboration across disciplines, especially between physicists and clinicians, is essential to overcome silos and enhance practical applications. The scalability of quantum sensors, regulatory hurdles, and early funding directed toward medical application were identified as significant challenges. The panel also touched on some potential approaches to ease the lab-to-market transition, including focusing on wellness centers, which do not require FDA-approved devices, and targeting pharmaceutical companies for funding as quantum sensors offer the potential for early disease diagnosis when drug intervention could make a difference.

The panel discussion was followed by seven “lightning talks” on ways quantum sensors could have an impact on the biomedical field. Ashok Ajoy from the University of California, Berkeley, discussed quantum sensing combined with droplet microfluidics for biological applications. Bettina Cuneo from the University of Arizona College of Medicine presented on fMCGs and their clinical use cases. Hari Eswaran from the University of Arkansas for Medical Sciences explored the use of OPMs for fetal applications. Marco Torelli of Adámas Nanotechnologies talked about enabling diamond quantum sensors for the marketplace. Nik Dontschuk from the University of Melbourne described a diamond-based platform for label-free optical voltage imaging in vitro. Paul Quayle of Great Lakes Crystal Technologies discussed diamond quantum sensors for biosensing applications. Finally, David Woolger from Cerca Magnetics presented on OPM-MEG brain scanners.

Following the presentations, workshop participants were divided into groups that were balanced among attendees from the biomedical industry, quantum technology industry, academia, and government.

Ideation of Use Cases: Diagrams of the Body's Systems

Conversations during the ideation session were guided by diagrams on a poster board of four of the body's systems: muscular, nervous, cardiovascular, and pulmonary. The poster boards also included sections labeled "cell level" and "subcell level" for cases that did not neatly map to one of the four systems.

Workshop Process: Idea Generator

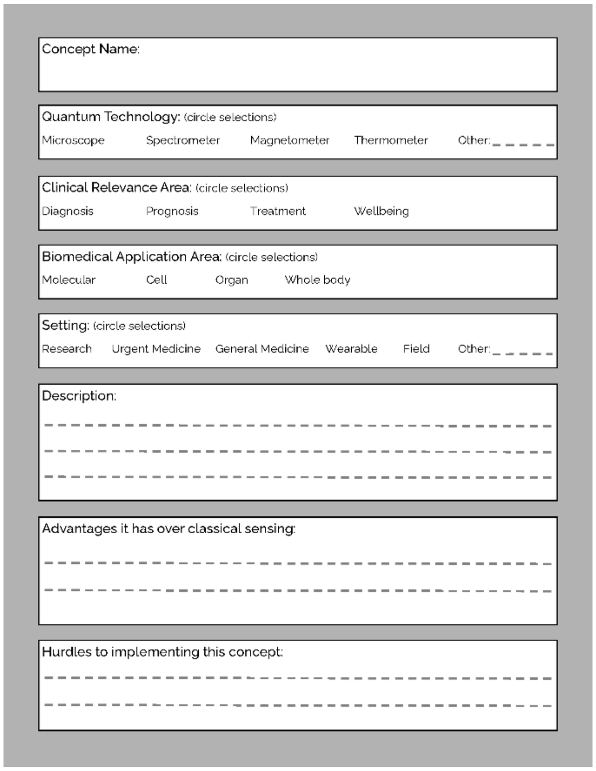
The workshop was designed to generate as many ideas as possible, methodically select those that participants thought would be the most important, and then develop the remaining ideas into meaningful and actionable concepts.

Brainstorm, Analysis, Selection

Participants were assigned to small groups for a 40-minute ideation session. First, each participant generated ideas in a 10-minute individual brainstorm session and noted on the system diagram where they thought a sensor would be helpful or most applicable. If an idea did not seem to fit within a body system, or at the cell or subcell level, participants were encouraged to put it in the blank space on the diagrams. The groups then took 25 minutes to discuss their ideas, and finally five minutes to vote for the ideas they thought had the most potential. To vote for top ideas, participants were each given three sticky dots to place on the diagrams; they could put all their dots on one idea or split them across several ideas. Visualizing the vote helped the groups prioritize choices together and make decisions at the end of a work session. This exercise produced 186 ideas (Appendix B), most involving the nervous system; the pulmonary system yielded the fewest ideas.

Concept Cards: Winnowing Ideas

Each group determined the two or three top ideas based on the ones with the most dots and created a "concept card," with the name of the concept, the quantum technology best suited to execute the idea, the clinical area of relevance, the area of biomedical application, the setting, a description of the concept, its advantages over classical sensing, and hurdles to implementation. The groups had 20 minutes to fill out the concept cards. Each group ended up with two to four cards that they presented to all the participants. To make the next step easier, similar ideas were consolidated into 11 summarized concepts.



Concept Name:

Quantum Technology: (circle selections)
Microscope Spectrometer Magnetometer Thermometer Other: _ _ _ _ _

Clinical Relevance Area: (circle selections)
Diagnosis Prognosis Treatment Wellbeing

Biomedical Application Area: (circle selections)
Molecular Cell Organ Whole body

Setting: (circle selections)
Research Urgent Medicine General Medicine Wearable Field Other: _ _ _ _ _

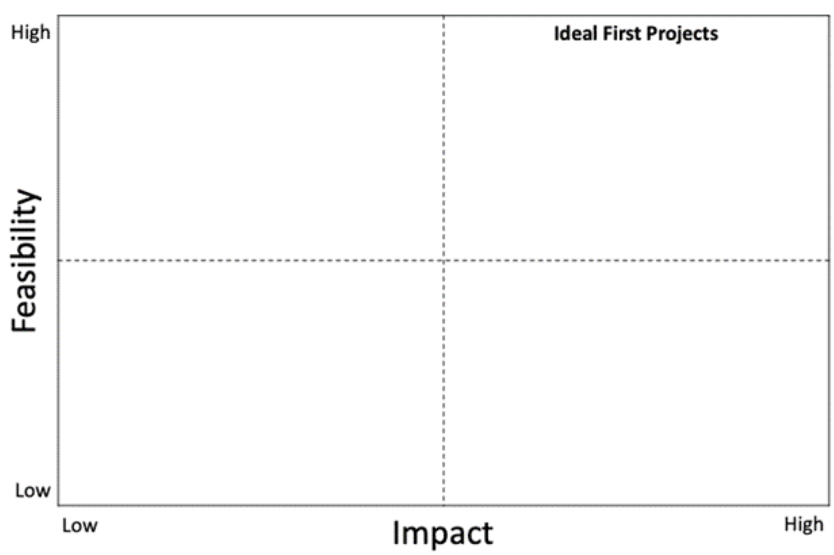
Description:

Advantages it has over classical sensing:

Hurdles to implementing this concept:

A Flexible Rating System to Promote Expansive Thinking

The consolidated concepts were then evaluated by the collective group. Through a facilitated discussion, attendees ranked the eight top ideas based on impact and feasibility in comparison with each other. Factors influencing *why* participants thought one idea was more feasible or impactful than another were not necessarily apparent during the discussions.



Concept Poster: How to Execute

The workshop attendees agreed to focus on the eight concepts that ranked highest on impact and feasibility for development in concept posters (shown below). They were instructed to use the top idea as a basis for the poster but could develop the concept in the direction they felt best. The concept posters included a description of the concept, how it works, the problem space it occupies, key features, types of professions or industries ("personas") that would be impacted by the implementation of the concept (e.g., healthcare providers, hospitals), and key metrics and outcomes to measure success. The posters also identified potential team members and suggested a timeline to complete the project.

Following the group presentations of completed concept posters, participants were asked to write on an index card recommendations for the best ways to spend a hypothetical $250,000 grant related to quantum sensors in the biomedical space. Appendix C lists the submitted ideas. Many of them involve using the funding to directly support R&D activities for new and/or improved sensor modalities and capabilities. Other ideas call for using the funds to support commercialization and small business activities to bring quantum sensors for biomedical applications to market.

Concept Poster & Collaboration Plan

Concept Name

Description

Persona

How it works

Features

Problem Space

Success Metrics/Outcomes

Team Members:

Timeline:

	Start	_	_	_	_	_	_	_	Finish
Research									
Solve									
Develop									

Appendix B: Use Cases for Quantum Sensors in Biomedical Applications

This table presents all 186 ideas as identified by workshop participants. For most ideas, the body system noted is as the individual participants assigned them based on the limited choices they had for body systems (cardiovascular, muscular, pulmonary, nervous, cell, and subcell). Where necessary for improved accuracy, ideas have been reclassified. Ideas have been only lightly edited.

Concept	Body System
Blood biomarkers for neurodegenerative disease	Cardiovascular
Blood oxygenation	Cardiovascular
Blood: ferritin level. RDS level (for sepsis)	Cardiovascular
Cardiovascular (ACS, amyloidosis, Afib, arrhythmias)	Cardiovascular
Combined fetal maternal monitoring	Cardiovascular
Detection of iron in blood (not protein level) circulatory	Cardiovascular
Dose-level tracking/compliance	Cardiovascular
Early prediction of: 1) CHF 2) PAH 3) Arrhythmia 4) ATTR 5) Clotting function & risk 6) organ vascular infarction 7) Renal blood flow in renal failure and prerenal azotemia 8) Adrenal failure 9) Classification of FSP	Cardiovascular
Environmental exposure in workplace	Cardiovascular
Environments that cause exposure --> ability for workers to get tested for exposure	Cardiovascular
Ex vivo blood analysis, NV particles	Cardiovascular
Extracellular charge catalyst for leg/arm blood	Cardiovascular
Fetal MCG	Cardiovascular
Fetal OPM MCG	Cardiovascular
FMCG (fetal magnetocardiography) for pregnancies with maternal diabetes, stillbirth history, inherited arrhythmias for fetuses, arrhythmia genetic disease, cardiac anomalies, nm-cardiac anomalies, FH & CHD OPMs	Cardiovascular
FND on heart. MEC based on particles	Cardiovascular
Frequency comb ultrasound imaging, guidance, treatment enhancement	Cardiovascular
Future breast cancer	Cardiovascular

Hard to know iron in blood --> currently ferritin; anemia is missed; better way of iron --> way outside of iron; direct measurement. Range of iron magnetic phases	Cardiovascular
Identifying tissue hypoxia and radical production	Cardiovascular
Internal bleeding, hemoglobin effect	Cardiovascular
Localizing sickling in patients with SS disease	Cardiovascular
Metabolites in blood with high throughput methods of q. sensing	Cardiovascular
Protein detection at low limit of detection (<1 pg/ml)	Cardiovascular
Quantum reporter molecules	Cardiovascular
Rapid feedback of dosage efficacy for illness	Cardiovascular
RF reporting of in vivo microenvironment sensing data	Cardiovascular
Vascular tone	Cardiovascular
At-home T-cell counting and analysis	Cell-Level
Bacterial characterization atom-by-atom (template-free) in vomit/stool	Cell-Level
Bioimaging with entangled photons	Cell-Level
Cellular assays/transcriptomics/detection of cellular metabolism	Cell-Level
Comprehensive scans to identify diseases affecting multiple body parts and where the symptoms are not always clear cut, for example fibromyalgia	Cell-Level
Declining diseases at single cell. Single molecule detection	Cell-Level
Drug screening: OPM + ultrasound --> SURFs (super-resolution force spectroscopy)	Cell-Level
Earlier diagnostics: OPM + chemical exchange; specific detection of biomarkers.	Cell-Level
Finding metastases early, including localizing cancer stem cell niches	Cell-Level
Free-space photonic detection of extracellular + proteomics	Cell-Level
Identify the molecular target(s) of potential drugs discovered in phenotypic screens	Cell-Level
Leveraging quantum sensors to better understand how cell dies to aid in cancer diagnosis & research	Cell-Level
Mapping the temperature within the cell	Cell-Level
Micro MRI (handheld)	Cell-Level
Microbiome characterization for wellness	Cell-Level
Microbiome tracking, monitoring	Cell-Level

Molecular recognition (e.g., viral infection) protein-protein bonds on cell surface	Cell-Level
Multiplexing detection in conjunction of conventional technology	Cell-Level
Neutron capture quantum dots for cancer treatment (boron, gadolinium) and/or imaging. Quantum dots/NV+B ND	Cell-Level
NMR at the tissue scale. Iron-rich tissue (2D slices)	Cell-Level
NV, NMR spectrometer, subcellular metabolic analysis	Cell-Level
NV-like sensor operating at LN2 or higher temp for magnet sensing	Cell-Level
Organ-level function: cardiac, MEG, MCG, neuromuscular, inflammatory arthritis, samples for biomarker detection	Cell-Level
Predictive preclinical tests; drug development	Cell-Level
Quantum cytometry	Cell-Level
Quantum dots for photoacoustic image guidance with photothermal cancer treatment	Cell-Level
Quantum dots in lateral flow assays	Cell-Level
Quantum sensors integrated into a quantum network (exotic topologies with advanced statistics)	Cell-Level
Tumor treatment: temperature inside tumor (thermal therapy)	Cell-Level
1) Chronic pain 2) ALS 3) Muscular dystrophy 4) Post trauma recovery prediction 5) Sports injury detection	Muscular
Action potential measurements	Muscular
ADHD; PTSD; Parkinson's; MS	Muscular
Alveolar liquid analysis of metabolites template-free	Muscular
Do muscular trigger points cause focal abnormalities measurable with magnetometers?	Muscular
Early detection of joint, tendon, and muscle injury	Muscular
Eye liquid biopsy (<50 microliters), metabolomics/proteomics to detect systemic diseases (e.g., neurodegenerative)	Muscular
Frequency comb spectroscopy	Muscular
GI motility	Muscular
MMG	Muscular
MMG	Muscular
OPM for placentography: pre-eclampsia; fetal growth restriction; maternal disease; fetal anomalies; hydrops; post-date placenta	Muscular
OPM-MCG	Muscular

OPM-MCG	Muscular
OPM-MCG cardiac assessment for ER (evolving myocardial infarction)	Muscular
OPM-MEG	Muscular
OPM-MEG	Muscular
OPM-MEG	Muscular
OPM-MEG (magentoencephalalograpy); epilepsy; ASD scanning; mTBI; Dementia; Drug efficacy	Muscular
OPM-MMG or SQUID for uterine contractions	Muscular
Peripheral sensing	Muscular
Swallowing and GI motility	Muscular
Unlike for born patients, fetal ECG is not diagnostic. Also use for FMEG (need a SQUID) in patients with fetal growth restriction or congenital heart disease	Muscular
1) ALS 2) Parkinson's 3) Dysautonomia 4) MS 5) Demyelination 6) Diaphragm denervation 7) Alzheimer's and dementia	Nervous
A few neurons imaging?	Nervous
AI aided smart measurement & data processing for brain activity sensing	Nervous
Brain computer interface with high BW (bidirectional)	Nervous
Brain computer interfaces	Nervous
Brain function monitoring	Nervous
Brain injury/trauma assessment	Nervous
Brainstem imaging OPMs	Nervous
Cheaper & widely available fMCG OPMs for fetal heart arrhythmias	Nervous
Dementia	Nervous
Detecting neuron connectivity in real time	Nervous
Detecting the onset of a seizure w/ MEG	Nervous
Diffusion MRI for brain connections with hyperpolarized agents	Nervous
Early detection of Alzheimer's	Nervous
Epilepsy	Nervous
Eye function	Nervous
Fluorescent neural viral detection for SARS-Cov-2; detecting brain fog from Covid	Nervous
Heart OPM + ECG	Nervous

High-res brain MCG to detect visual cortical dysfunction in children	Nervous
Imaging of neurological system to see how signals pass from one to another place with quantum-enabled microscopes with higher resolution	Nervous
Low level concussion/sports injury (OPM probably)	Nervous
Magnetic sensor for prosthetics control	Nervous
MEG, MEG-ULF MRI, MCG, MCG-ULF MRI, brain-spine interaction, brain-muscle interaction	Nervous
Mental health	Nervous
MMG for nerve, phantom pain	Nervous
MRI enhancement for white matter tracts and disorders (glia not neura)	Nervous
MRI precision enhancement w/ OPMs	Nervous
MRI sensitivity with NMR ensemble sensing	Nervous
NDNV for neural firing study	Nervous
Nervous connection for artificial limbs	Nervous
Neural voltage signals. Bulk diamond NV^-/NV^0. Pain measurement	Nervous
Noninvasive nerve conduction testing	Nervous
NV color center nanodiamond microtesla detection for magnetic treatment of cellular inflammation & ROS detection	Nervous
OCT perception	Nervous
OPM brain SQUID for verification	Nervous
Parkinson scanning	Nervous
Peripheral nerve propagation OPM + SQUID	Nervous
Precise antiseizure medication prescription	Nervous
Probes down spine	Nervous
Quantum PET with positronium	Nervous
Replication of epilepsy in a culture for accurate medication	Nervous
Speech centers; not sure what sensor is best	Nervous
Spinal cord imaging with OPMs	Nervous
Spinal OPM scanning	Nervous
Traumatic brain injury rapid assessment	Nervous
Traumatic brain injury, detector in the helmet	Nervous
1) ATTR detection 2) Renal protein deposition 3) Diabetes monitoring by breath	Other

Brain organoid response to drugs (i.e., gamma band responses to drugs such as ketamine)	Other
Breath test for Alzheimer's, related dementia, mild cognitive impairment (MCI)	Other
Cancer, biopsies, breast cancer screening	Other
Chemical sensors for surgery	Other
Digestive tract movement	Other
Gut function, cancer detection, treatment monitoring	Other
High throughput proteomics	Other
Localization and characterization type of inflammation	Other
Magnetic field therapeutics skin cancer	Other
Oculomics 50 microliters of eye fluid to detect diseases (only very small); volume --> issue; MMR spectroscopy --> metabolic screen (Breathalyzer) --> possible - CNS	Other
pH in digestive system, with NV diamond	Other
Prostate/MRI and similar organs with hyp. pyruvate	Other
Proteomics detection of viral (SARS, COVID, H1N1) production in discharge	Other
Quantum dots for diagnostics: CRISPR/Cas13a, SARS-Cov-2 detection respiratory	Other
Skin: sweat monitor	Other
Subdermal thermometry; wound healing (surgical monitoring), muscle, bone; track how surgical sites are healing (subdermal); IR measurement; noninvasive; compartment syndrome; temperature (thermal detect can sense deep tissue?); poke under skin, break barrier (opportunity to break through skin); micro-needle packages	Other
Allergic response, early pneumonia detection, segmentation of viral vs bacterial infection; covid or other prediction of ICU admission	Pulmonary
Biophoton detection: Diagnostics/cancer	Pulmonary
Breath analysis (test) for early-stage lung cancer detection (NSCLC & SCLC)	Pulmonary
Breath analysis for recurrence of lung cancer after surgery & chemotherapy	Pulmonary
Breath analysis: COPD, diabetes, TB, asthma, other long term lung diseases	Pulmonary
Breath analysis: longitudinal monitoring of microbiome changes in the gut	Pulmonary

Breath analysis: personalized medicine related to microbiome status	Pulmonary
Breath analysis: wellness monitoring pre-/postexercise breath change	Pulmonary
Breathalyzer analysis multiplex: asthma & pneumonia, fungi, viral, bacterial	Pulmonary
Breathalyzer used for headspace analysis from outer liquid specimens	Pulmonary
Detecting inflammation in the airway prior to asthma	Pulmonary
Frequency comb, breath diagnostics, covid?	Pulmonary
Frequency combs for biomolecule detection and bioaerosols	Pulmonary
Imaging oxygen-rich tissue	Pulmonary
Lung oxygen conduct NV center	Pulmonary
Magnetic sensing for GI --> magnetic labeling with endoscope?	Pulmonary
Measure the distribution of alveolar air pressures (critical care application)	Pulmonary
NDNV - chemical sensing --> mucus/saliva	Pulmonary
Quantum dots for treatment with therapeutic potentials	Pulmonary
Sensing smooth muscle contractions (vascular, airway, uterine)	Pulmonary
Tabletop MMR for breath analysis for illness detection	Pulmonary
Viral vs. bacterial lower respiratory tract infections	Pulmonary
1) Transcriptomics understanding 2) Cancer resistance 3) Cell component failures 4) Drug binding 5) Drug toxicity 6) Drug uptake	Subcell-Level
Attached to mitochondria, measure T, RDS. Attach to cell membrane, measure T. pH	Subcell-Level
Biochemical binding assays. Bulk diamond/magnetic beads	Subcell-Level
Biophysics: OPM + DNA rulers. E.g., how does protein synthesis work? Answer: ribosome function! Frameshift & power stroke	Subcell-Level
Cell viscosity (rotation of NVND)	Subcell-Level
Cheap & broad application. The use of diamonds	Subcell-Level
Continuous monitoring	Subcell-Level
Detection of ongoing tissue fibrosis (relevant for fibrotic disease activity/detection/treatment)	Subcell-Level
Function structure relationship	Subcell-Level
Imaging technology for metabolic activity to replace PET	Subcell-Level

Immunology; LFA assay with 100x WDW	Subcell-Level
Implants: w/ embedded NVND. Temperature, magnetic field, electric field	Subcell-Level
Measuring few out of many. (Early disease detection, quality control, etc.)	Subcell-Level
Metabolomics in tumors. FND injection, hyperpolarization, and HP transfer to metabolites. NMR of metabolites.	Subcell-Level
Multidimensional datasets from noninvasive sensors	Subcell-Level
Nanodiamond free radical + drug delivery	Subcell-Level
NV use for cancer cell using magnetic probe nanomagnetic particle	Subcell-Level
NV-sensors for reactive oxygen species	Subcell-Level
Quantification of process	Subcell-Level
Real-time monitoring	Subcell-Level
Template-free glycomics detection	Subcell-Level

Appendix C: Ideas for Spending a $250,000 Grant

Fund next-generation NV center diamond tech ▪ NV center diamond has immense potential to advance bioimaging and drug discovery through improved understandings of the subcellular function of a variety of drugs and biological systems ▪ However, more sophisticated NV diamond devices need development to improve stability and sensitivity
2-year grant to study problem of hyperpolarization transfer from hyperpolarized nanodiamonds to pyruvate, to enable MRI functional spectroscopy at room temperature for cancer staging
Annual meeting of Quantum Sensor Society for Biomedical Applications, with exhibition ▪ For 3-4 years ▪ Rent space for industry booth to make it sustainable
Build a multimodal, multiplexed microscope for subcellular imaging
Build an OPM array for imaging spinal cord plus peripheral nerve imaging
Build OPMs for fetal and material applications through industry-academic partnership funding
Create a close collaboration between sensor development fMCG clinicians and maybe even people responsible for FDA approval of medical devices to navigate the hurdles
Demonstration of single-cell metabolomics with chemical resolution
Develop novel magnetic sensor for study of protein folding
Efforts for domestic, sealed production of high-quality, N-concentration controlled HPHT diamond
Fetal MCG and related technologies
High-resolution voltage imaging of neurospheroid cluster with aggregate axion branches in partnership with NIH NCATS utilizing NV^0-based diamond imaging microscope
Build an fMCG unit and OPMs and a shield that would be portable and able to be used in labor and delivery units for material fetal care
fMCG collaboration including component developer, system integration research, and clinic to make system
Phase 1 R&D derisking feasibility scoping project for a phase 2 prototype that may cost ~$1.8m-$12m prototype

▪ Activities: researcher engagement, modeling experiments, cost analyses ▪ Results: Fact book, cost projection of Phase 2 proof-of-concept model or simulation of prototype
▪ Rent/trial photonic single detectors, modulators, and NV color sensors ▪ Buy fiber optics to connect tools ▪ Collect retinal fluid, and have photonic detector with better identifying NV color sensor tuning ▪ Goal: Identify SARS-Cov-2 population in retinal fluid to determine long COVID incidence
Small business grant for ▪ Attending conferences to build connections with clinicians ▪ Market research (similar to NSF I-Corps) ▪ Targeted workshop like this one but include users (doctors), patients, hospital executives, insurance, pharma, early-stage investors, industry associates ▪ POC type of project for preliminary data
Support fetal MCG using OPMs
Support for small business to engage with NIH or other researchers at the pre-SBIR stage where the goal is to produce a custom or prototype or proof of concept that addresses an important need but commercial visibility is not yet clear; this is to access the know-how and engineering capabilities in companies quickly

Appendix D: Workshop Participants

Thank you to all of the workshop participants for sharing their time and perspectives.

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Stefan Bogdanovic, SandboxAQ

Nadia Carlsten, SandboxAQ

Yun Chen, Johns Hopkins University

Bettina Cuneo, University of Arizona College of Medicine

Dominique Dagenais, National Science Foundation

Paige Derr, National Center for Advancing Translational Sciences, National Institutes of Health

Nikolai Dontschuk, University of Melbourne

Carl Dukatz, Accenture

Hari Eswaran, University of Arkansas for Medical Sciences

Barbara Goldstein, National Institute of Standards and Technology

Alexei Goun, Aperta Systems, LLC

Tony Gover, National Eye Institute, National Institutes of Health

Connor Hart, Quantum Catalyzer

Young Jin Kim, Los Alamos National Laboratory

Berk Kovos, SynthBits

Peter Krüger, Physikalisch-Technische Bundesanstalt

Cecil Lynch, Accenture

Peter Maurer, University of Chicago

Kirk McGregor, Iff Technologies

Celia Merzbacher, QED-C

Allison Nugent, National Institute of Mental Health, National Institutes of Health

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Paul Quayle, Great Lakes Crystal Technologies

Lucia Rathbun, Twinleaf LLC

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