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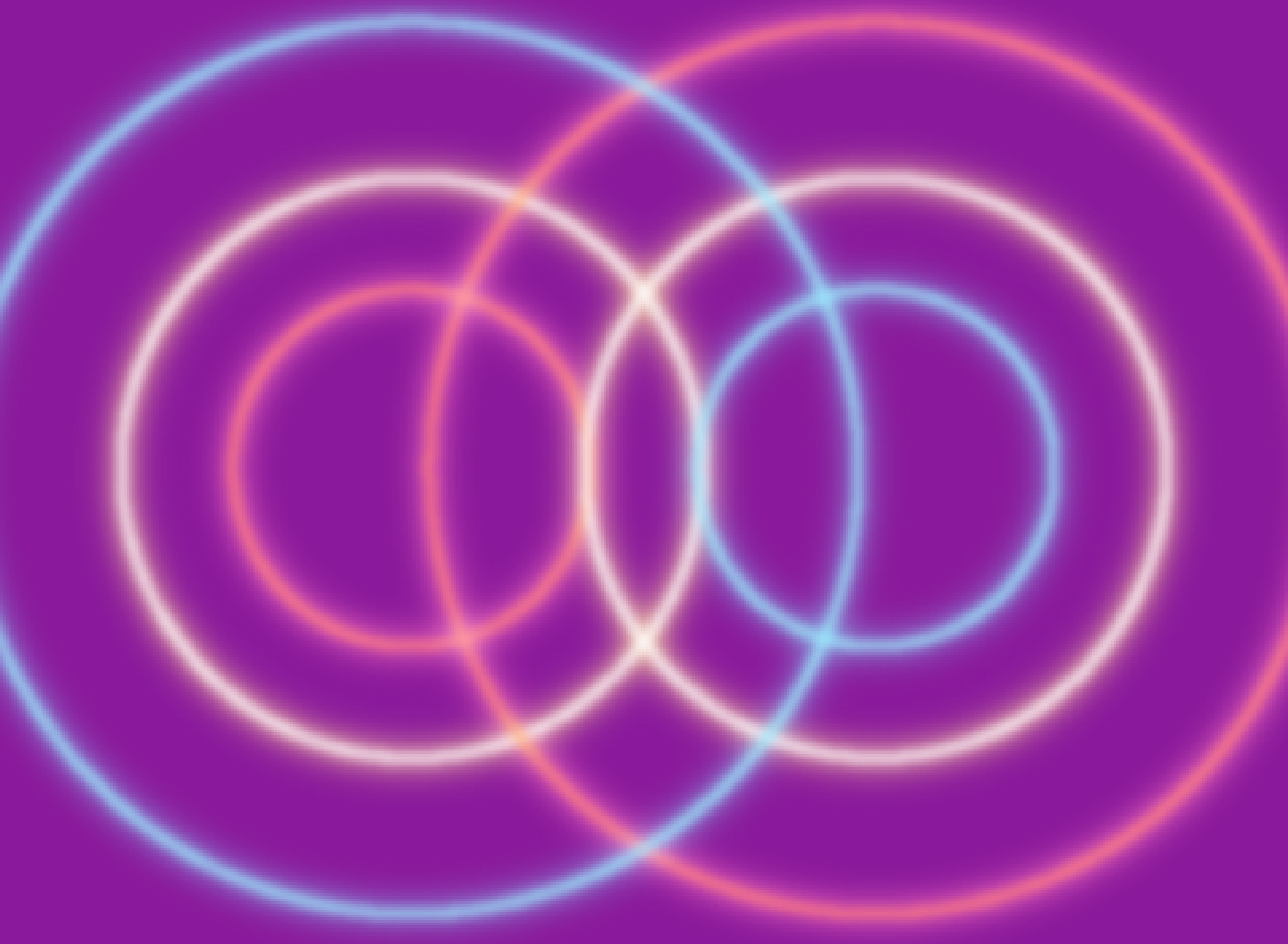
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME 10 years

Quantum for Life

How UK life sciences and healthcare can benefit from quantum technologies



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Disclaimer

This work is not intended to be an exhaustive review, but instead to provide an overview of technologies and potential applications. This report contains overviews of research projects, and such information may be incomplete or replaced with more advanced research as time progresses. Although all company case studies mentioned in this report are UK-registered, in some cases the work undertaken may have been overseas, and the companies involved may have non-UK partners.

Foreword

Barely a decade ago, if the research community had asked more widely what quantum was, the answer would have been an esoteric science – perhaps referencing cats that could be dead or alive.

The focus on quantum was manifested by the exclusively academic and university attendance at the first annual National Quantum Technologies Showcase in 2015. In the 10 years since, there has been a remarkable transition.

The 2023 showcase held at the Business Design Centre in London was primarily attended by companies, demonstrating that quantum is no longer a solely academic pursuit: it's a thriving ecosystem which includes industry and end users. The UK has undoubtedly led the world in this transition from emerging technology to commercially viable opportunity, but it is an ongoing journey.

The defence and security sectors are typically early adopters of new technologies, and quantum is no exception. Quantum computing has been an example of significant investment in disruptive technology looking a decade or more ahead. In contrast, the transition of new technologies into healthcare seems more challenging. Remarkably, quantum is already giving rise to start-up companies targeting healthcare applications.

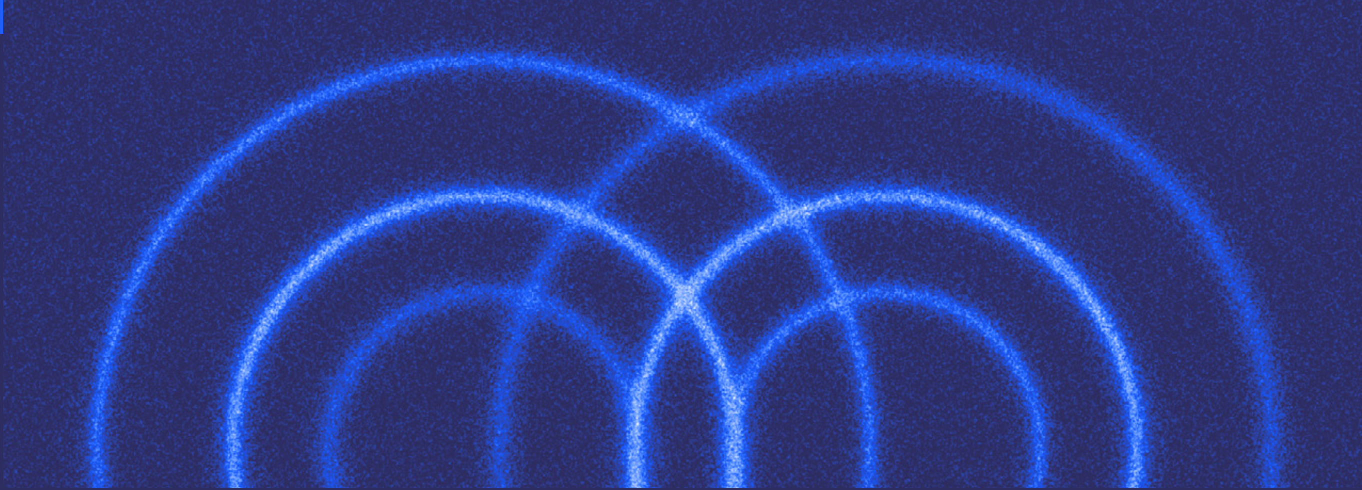
It seems that the key to these transitions is linking quantum scientists and engineers with those who understand clinical need, and have first-hand experience of championing new technologies within a clinical setting. Only when clinical efficacy is formally demonstrated through clinical trials can the NHS fully engage.

This report highlights opportunities for quantum to contribute to a more efficient healthcare system through enhanced medical devices, new drugs, more secure patient information and hospital optimisation. But perhaps even more importantly, the report highlights examples of where this is already working.

There's a lot that can be learned from these trailblazing individuals and organisations. In the future, it would be fascinating to hear not just about their specific technology or use cases, but how they have ensured their innovation's transition from lab to bedside, and sustained their projects through a decade of development to deliver patient benefit.

Professor Miles Padgett

Principal Scientist, Quantum Enhanced Imaging Hub, University of Glasgow



Executive Summary

Quantum is one of five UK government-critical technologies which will enable the UK to take advantage of key strengths and empower the future economy – the other four being AI, engineering biology, future telecommunications, and semiconductors.

2024 marks 10 years since the launch of the UK National Quantum Technologies Programme, and since then we have seen a hugely increased number of new and existing companies developing quantum technologies. This rapidly evolving UK landscape has led to the early commercialisation of medical imaging devices, such as a new approach to magnetoencephalography.

This dynamism can be partly attributed to over £220 million in quantum projects delivered by Innovate UK (over £14 million specifically for healthcare and life science applications) between 2018 and 2024.

The objective of this report is to give those working in healthcare and life sciences an understanding of what quantum technologies can do now, and what they will be capable of in the near future. It is shown that these devices can broadly be separated into two categories: quantum enhanced technologies, which improve upon current practices, and transformative quantum technologies, providing completely new approaches.

The report also covers the applications of these technologies, such as improving diagnoses and monitoring of known diseases, optimising healthcare environments, discovering quick and efficient methods to simulate novel drugs and ensuring patient information is kept secure.

Overall, the report demonstrates that quantum technologies are set to be transformative in healthcare and life sciences by reducing the size of devices, time, cost, and expenditure, while increasing the overall performance and accuracy of current methods.

Introduction

Quantum technologies can offer revolutionary new solutions to challenges faced by the life science and healthcare sectors, through an array of new devices that exploit the principles of quantum mechanics.

Quantum sensing, for example, can transform the medical imaging industry, providing a better understanding of the human body and enabling new targeted treatments. There are new cameras that can detect the arrival of single photons of light with precise timing, and devices that use single atoms or microscopic crystal flaws as ultra-sensitive detectors for magnetic fields. These technologies can enhance existing imaging approaches such as X-rays, PET scans and MRI.

Quantum sensors have also led to wearable brain scanners, new approaches to cancer diagnosis and improved detection of biomarkers in blood samples; researchers are exploring entirely novel techniques such as imaging through the body with light.

Meanwhile, quantum computers are set to transform drug discovery. The ability of quantum systems to be in multiple states simultaneously means it could be possible to simulate the chemistry of drugs and proteins far more effectively than any conventional computer. These systems can also help optimise healthcare supply chains and allocate scarce resources, potentially enabling more patients to be treated.

The UK is a world leader in quantum technology, home to the second highest number of quantum companies, behind only the United States[1]. The UK National Quantum Technologies Programme, launched in 2014, led to an acceleration in quantum research and the launch of a plethora of UK companies. Quantum was therefore named one of the five critical technologies named in the UK Science and Technology Framework[2].

To further solidify the commitment to quantum technologies, the UK government released the National Quantum Strategy[1] which pledged to invest £2.5 billion in quantum technologies in the 10 years starting from 2024. The strategy states that by driving the adoption of these devices, the UK could be a world leader in health and life sciences. In addition, a series of five National Quantum Strategy Missions focusing investment into particular goals were announced later the same year. These aim to deliver strategic impact to the UK, by providing wider benefits beyond the stated target[3].

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1. Department for Science Innovation & Technology, “National Quantum Strategy,” 2023.
2. Prime Minister’s Office 10 Downing Street; Department for Science Innovation and Technology, “The UK Science and Technology Framework,” 6 March 2023. [Online]. Available: https://www.gov.uk/government/publications/uk-science-and-technology-framework/the-uk-science-and-technology-framework.
3. Department for Science, Innovation & Technology, “National Quantum Strategy Missions,” 22 November 2023. [Online]. Available: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions.

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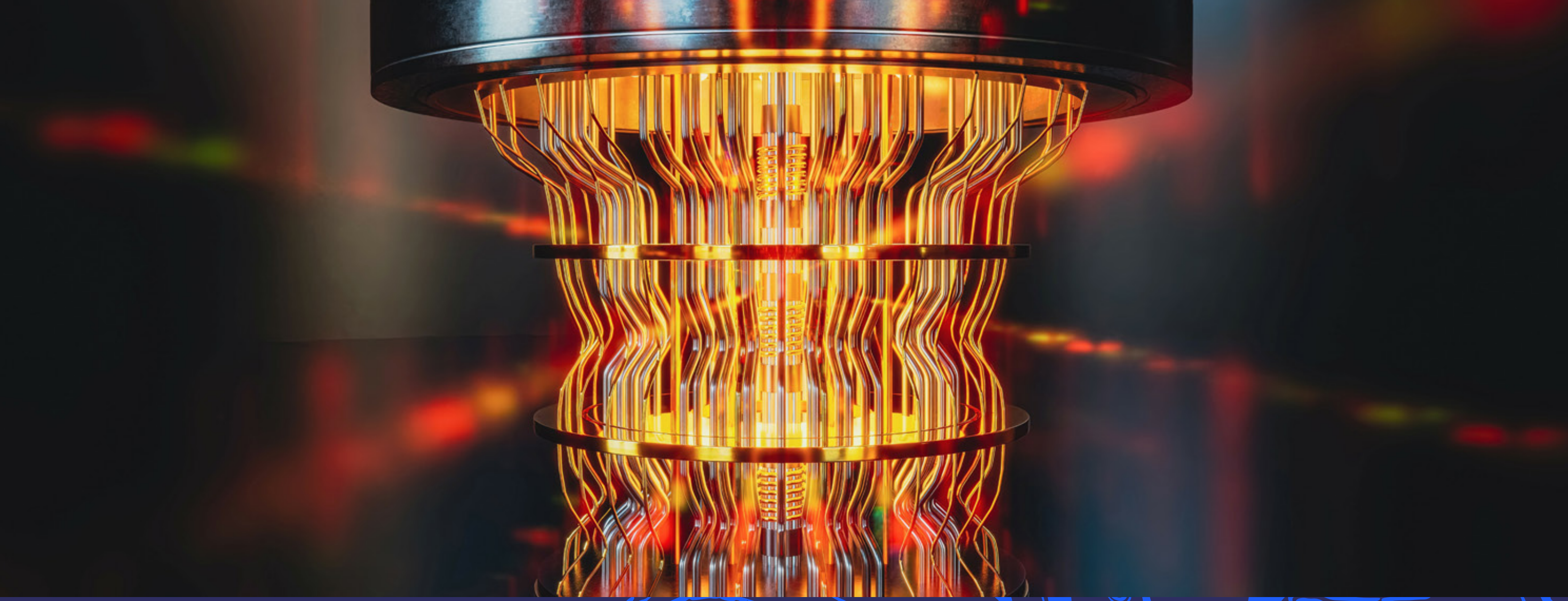

This report aims to raise awareness in the healthcare industry by highlighting UK quantum capabilities in healthcare and life sciences and discussing how to improve them. Below, we give examples of activity in academia and UK-registered companies covering three main areas: computing, communication, and sensing (which includes imaging & timing)[4 5 6]. Each section provides a list of possible applications within healthcare and life sciences and describes how the industry has been supported.

What is Quantum Mechanics?

Classical physics, such as Newton's laws of motion, can describe the behaviour of matter at human scales and high temperatures. But as scientists discovered in the early 20th century, when considered at nanoscopic scales (or temperatures close to absolute zero) matter and radiation behave in an entirely different way.

Light behaves simultaneously as a wave and as a particle. Electrons in atoms are restricted to having certain fixed energies. Particles can share a subtle connection known as entanglement. These and many other counterintuitive phenomena are described by the physical theory of quantum mechanics. In recent years, this understanding, and our growing control of quantum states of matter, has been exploited to create a range of new quantum technologies.

4. R. Ur Rasool, H. Ahmad, W. Rafique, A. Qayyum, J. Qadir and Z. Anwar, "Quantum Computing for Healthcare: A Review," Future Internet, vol. 15, no. 94, 2023.
5. N. Aslam, H. Zhou, E. K. Urbach, M. J. Turner, R. L. Walsworth, M. D. Lukin and H. Park, "Quantum sensors for biomedical applications," Nature Reviews Physics, vol. 5, p. 157–169, 2023.
6. F. Bruckmaier, K. Liu and K. Berghoff, "The future of industrial applications about diamond-based quantum sensing," QuantumDiamonds GmbH, 2023.

Quantum Sensing and Imaging

Quantum sensors use atoms, ions and other particles as highly sensitive measuring devices. Among other things, they can measure gravity and acceleration, electromagnetic fields, temperature, single photon wavelength or polarisation, and time.

According to Mordor Intelligence, quantum sensing is thought to have a global value of $0.61 billion in 2023, and by 2028 this is expected to grow to $1.12 billion[7, 8], with another source stating that it could be worth up to $5 billion by 2030[9].

Existing imaging technologies in life science and healthcare often have drawbacks, such as low sensitivity, involving invasive methods, being expensive and limitations on the type and scale of samples. Using precise control and detection on a quantum level, new imaging techniques can help alleviate these drawbacks, whilst allowing for superior imaging both *in vitro* and *in vivo*.

Did you know?

Quantum sensors have a long history of use in healthcare. Superconducting quantum interference devices, or SQUIDs, have been used for brain imaging since their development in 1968[10].

Imaging techniques are among a slew of new quantum sensors that improve on current industry approaches across a range of life science applications. These devices have been developed mostly inside university labs, so the next logical steps are testing them under real-world conditions, and then moving to commercialisation.

7. Mordor Intelligence, "Quantum Sensors Market Size & Share Analysis - Growth Trends & Forecasts (2023 - 2028)," 2023. [Online]. Available: https://www.mordorintelligence.com/industry-reports/quantum-sensors-market#:~:text=The%20Quantum%20Sensors%20Market%20size,period%20(2023%2D2028)..

8. The Data City, "UK Quantum Computing Industry," 2024. [Online]. Available: https://thedatacity.com/rtics/quantum-economy-rtic0051/.

9. McKinsey, "Shaping the long race in quantum communication and quantum sensing," 2021. [Online]. Available: https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/shaping-the-long-race-in-quantum-communication-and-quantum-sensing.

10. D. Cohen, "Magnetoencephalography: Evidence of Magnetic Fields Produced by Alpha-Rhythm Currents," SCIENCE, vol. 61, no. 3843, pp. 784-786, 1968.

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This is already happening in some cases; QDTI, a spin out from Harvard University, has launched its quantum sensor approach for rapidly detecting biomarkers (see Detecting Biomarkers with Diamonds)[11].

This emerging industry still faces many challenges. Devices must be robust and suitable for a clinical environment, and must pass through a rigorous regulatory process to ensure they are safe. Depending on how a technology interacts with the patient, clinical adoption can take years.

Fortunately, the UK industry has support to overcome these challenges and move to commercialisation. This is being delivered through the third of the national quantum strategy missions that specifically focuses on quantum sensing in healthcare.

One goal is to deliver technologies to improve brain imaging and cancer detection; another is to provide a technology pipeline to ensure the UK makes the most out of quantum sensing and imaging technologies. The mission states that by 2030, "every NHS Trust will benefit from quantum sensing-enabled solutions, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment" [12].

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11. Element Six Ltd (UK); Quantum Diamond Technologies Inc, "Quantum diamond biomarker detection," PhotonicsViews, vol. 19, pp. 48-50., 2022.

12. Department for Science, Innovation & Technology, "National Quantum Strategy Missions," 22 November 2023. [Online]. Available: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions.

National Quantum Strategy Mission 3: By 2030, every NHS Trust will benefit from quantum sensing-enabled solutions, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment.

This timeframe is backed up by current Innovate UK project end dates (Figure 1), and by a 2020 roadmap for quantum photonics, which predicts that commercial medical imaging applications using quantum sensing will become available between 2025 and 2029[13].

13. OSA Industry Development Associates, "OIDA QUANTUM PHOTONICS ROADMAP," 2020.

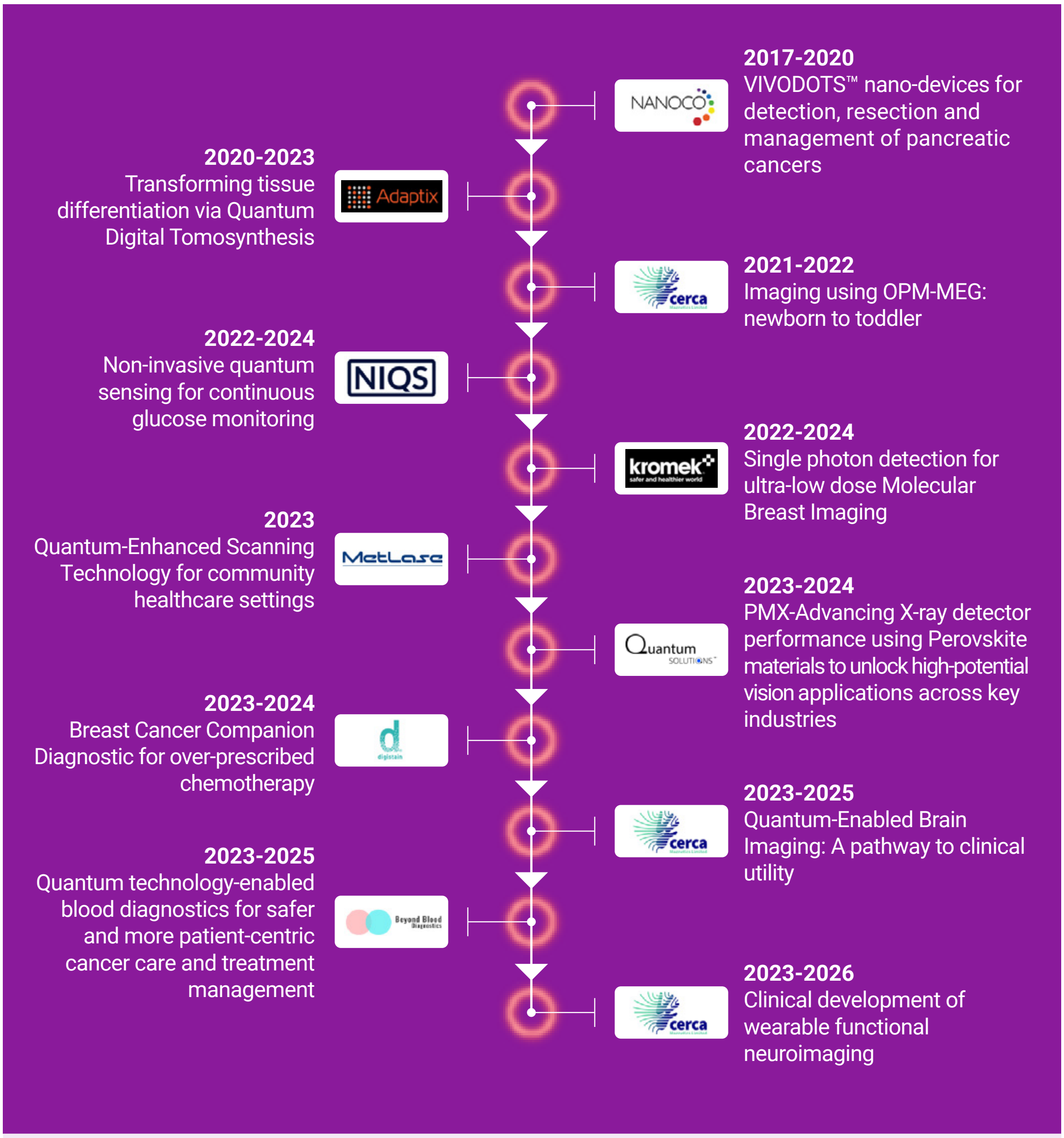

Figure 1: Quantum sensing for healthcare and life sciences projects funded by Innovate UK

Advantages of Quantum Sensing and Imaging for Life Sciences and Healthcare

For healthcare, quantum sensing can provide more sensitive measurements than current technologies, on finer spatial scales with smaller instrumentation. This means that better and faster monitoring can occur in smaller spaces, such as an ambulance, GP surgery or home, enabling constant monitoring and more accurate diagnosis of patients while saving clinicians' time.

Quantum sensing techniques can provide enough information to create images. As well as entirely new imaging techniques, quantum approaches to microscopy can improve current methods. Quantum enhanced microscopy could bring advantages, including real-time imaging, higher resolution images, and imaging biological material on a smaller scale than current applications.

Below are some of the specific technologies set to pioneer quantum sensing in life sciences and healthcare, and some examples of real-world applications already changing the landscape.

Technologies

There are numerous quantum sensors for healthcare applications at different technology readiness levels (TRLs). They can generally be broken down into three areas[14]: those based on photonics, on single atoms, and on diamond.

Photonic Sensors

Quantum technologies can manipulate single photons (the particles of the electromagnetic spectrum), across wavelengths spanning visible light, ultraviolet and infrared. Detecting single photons can provide high sensitivity and other desirable properties over conventional photodiodes.

The sensors used in such quantum photonic devices are usually either quantum dots or single photon detectors, such as single photon avalanche diodes (SPADs). These are not new technologies, but they have been improving in performance, with higher detection efficiencies and higher resolution when used for imaging, as well as being easier to manufacture. These improvements have enabled a plethora of new applications in the life sciences industry, with SPADs for example involved in many of the areas discussed below.

What are SPADs and quantum dots?

A SPAD is a type of semiconductor diode in which the arrival of a single photon can trigger an avalanche of electrons, producing a detectable electric current. Different types of SPAD are needed to detect photons of different wavelengths -- so one type might be used to detect photons of a green wavelength and another to detect photons of an orange wavelength. As well as visible light, they can detect radiation in the near infrared region.

Quantum dots have many applications. Their main property is to emit light of a specific wavelength when stimulated by a backing light. They can also be used as sensors and are being used within the life science sector for a multitude of applications such as cell tracking, in-vivo imaging and cell & tissue staining[15]*. As with SPADs, many types of quantum dots are used, giving different wavelengths and two different modes of sensing: fluorescence and electrochemical (where a small but detectable current is generated)*[16]*. The development of new quantum dots could improve the range of biophotonic sensing applications, providing quicker diagnoses of a greater variety of diseases.*

14. N. Aslam, H. Zhou, E. K. Urbach, M. J. Turner, R. L. Walsworth, M. D. Lukin and H. Park, "Quantum sensors for biomedical applications," Nature Reviews Physics, vol. 5, p. 157–169, 2023.

15. Thermo Fisher Scientific, "Qdot Probes," 2024. [Online]. Available: https://www.thermofisher.com/uk/en/home/brands/molecular-probes/key-molecular-probes-products/qdot.html.

16. J. Thirumalai, "7. Recent Advances in Quantum Dots-Based Biosensors," in Quantum Dots - Recent Advances, New Perspectives and Contemporary Applications, 2023.

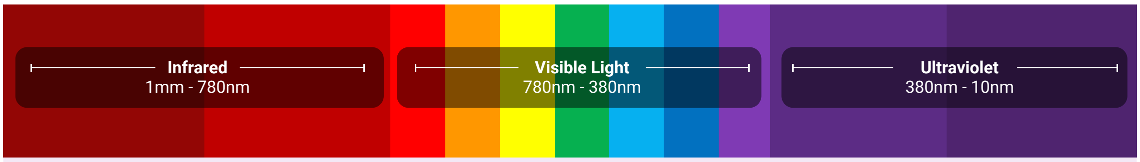

Figure 2: Light spectrum

Improving other photonic components can also enable new sensing and imaging devices, and make transformative improvements to existing devices. For example, photonic integrated circuits (PICs) can shrink the size of instruments by integrating optical components onto a single chip. Applying PICs to process single photons can allow for further imaging developments in this field.

Lastly, developments in the light source itself can improve overall performance. Advances in delivering the exact number of photons on demand, or better sources of squeezed states[17], can enable the creation of more efficient devices for medical and biological imaging.

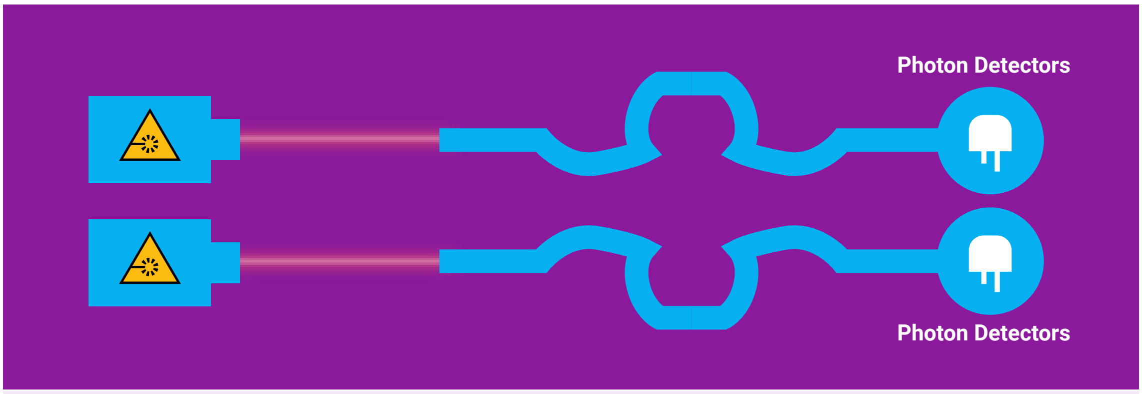

Figure 3: A graphical representation of a PIC demonstrating how photon sources and detectors can be integrated.

Atom-based Sensors

Atom-based technologies arguably form the next wave of deployable quantum sensors, with real-world applications already seen in clinical trials. For life science and healthcare applications, the most important technology is the optically pumped magnetometer (OPM)[18].

17. G. Atkinson, E. Allen, G. Ferranti, A. McMillan and J. Matthews, "Quantum Enhanced Precision Estimation of Transmission with Bright Squeezed Light," Phys. Rev. Applied 16,, vol. 16, no. 4, 2021.

18. I. K. Kominis, T. W. Kornack, J. C. Allred and M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer," Nature, vol. 422, p. 596–599, 2003.

OPMs can monitor very weak magnetic signals, and have been used for magnetoencephalography (MEG) – imaging the brain[19], heart[20] and nervous system[21] through the faint magnetic fields generated by biological tissue.

Although MEG was already possible using cryogenically cooled SQUIDs, those required bulky cryostats, whereas the new OPM based devices can be small and lightweight, and even wearable, without compromising sensitivity[22] [23] [24]. One advantage is the ability to record measurements even if the patient moves around, which is beneficial if there is involuntary shaking of the body.

Other quantum magnetometers are also being developed, such as radio-frequency atomic magnetometers. These devices operate on atomic vapour, and have lower sensitivities than OPMs but can work outside a shielded environment. A new generation of SQUIDs has also been developed[25].

What is an OPM?

OPMs are based on a vapour of atoms confined to a small cell. These atoms are effectively microscopic magnets, so they are affected by external magnetic fields, such as those from biological material. A laser beam is used to probe the effect of this interaction, passing through the atomic gas and measured using photon detectors[26].

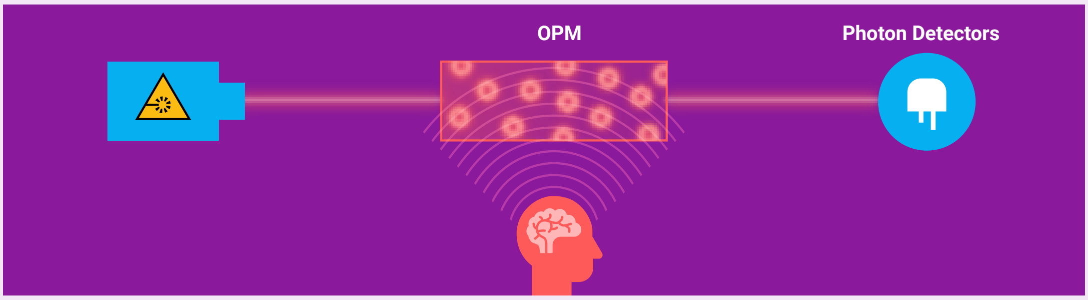

Figure 4: A graphical representation of an OPM detecting magnetic fields from biological material

19. E. Boto, R. Bowtell, P. Krüger, T. M. Fromhold, P. G. Morris, S. S. Meyer, G. R. Barnes and M. J. Brookes, "On the Potential of a New Generation of Magnetometers for MEG: A Beamformer Simulation Study," PLoS ONE , vol. 11, no. 8, 2016.

20. W. XIAO, C. SUN, L. SHEN, Y. FENG, M. LIU and Y. WU, "A movable unshielded magnetocardiography system," Sci. Adv., vol. 9, no. 13, 2023.

21. G. Z. Iwata, Y. Hu, A. Wickenbrock, T. Sander, M. Muthuraman, V. C. Chirumamilla, S. Groppa, Q. Liu and D. Budker, "Biomagnetic signals recorded during transcranial magnetic stimulation (TMS)-evoked peripheral muscular activity," Biomed Tech (Berl), vol. 67, no. 5, pp. 333-344, 2022.

22. M. J. Brookes, J. Leggett, M. Rea, R. M. Hill, N. Holmes, E. Boto and R. Bowtell, "Magnetoencephalography with optically pumped magnetometers (OPM-MEG): the next generation of functional neuroimaging," Trends in Neurosciences, vol. 45, no. 8, pp. 621-634, 2022.

23. R. M. Hill, E. Boto, M. Rea, N. Holmes, J. Leggett, L. A. Coles, M. Papastavrou, S. K. Everton, B. A. Hunt, D. Sims, J. Osborne, V. Shah, R. Bowtell and M. J. Brookes, "Multi-channel whole-head OPM-MEG: Helmet design and a comparison with a conventional system," NeuroImage, vol. 219, no. 116995, 2020.

24. A. Gialopsou, C. Abel, T. M. James, T. Coussens, M. Bason, R. Puddy and e. al., "Improved spatio-temporal measurements of visually evoked fields using optically-pumped magnetometers," Scientific Reports, vol. 11, no. 22412, 2021.

25. S. E. d. Graaf, S. T. Skacel, T. Hönigl-Decrinis, R. Shaikhaidarov, H. Rotzinger, S. Linzen, M. Ziegler, U. Hübner, H.-G. Meyer, V. Antonov, E. Il'ichev, A. V. Ustinov, A. Y. Tzalenchuk and O. V. Astafiev, "Charge quantum interference device," Nature Physics, vol. 14, pp. 590-594, 2018.

26. I. K. Kominis, T. W. Kornack, J. C. Allred and M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer," Nature, vol. 422, p. 596–599, 2003.

Diamond Sensors

Sensors based on specifically flawed diamonds can detect weak magnetic fields, pH and reactive oxygen species, and perform NMR. The most common artificially created flaw is the nitrogen-vacancy (NV) diamond sensor. These devices are split into two classes according to size: nanodiamonds, ranging in size from roughly 30nm-100nm, and larger crystals known as bulk NV diamonds.

What are NV diamond sensors?

In these sensors, diamonds are fabricated with deliberate inclusions of nitrogen atoms or other elements, each with a neighbouring vacancy in the diamond lattice where a carbon atom is missing. This arrangement can be further manipulated to leave an unbonded pair of electrons at the vacancy site, and together these act as the quantum sensor. This quantum state can be affected by magnetic fields, for example, and can be read out using a laser.

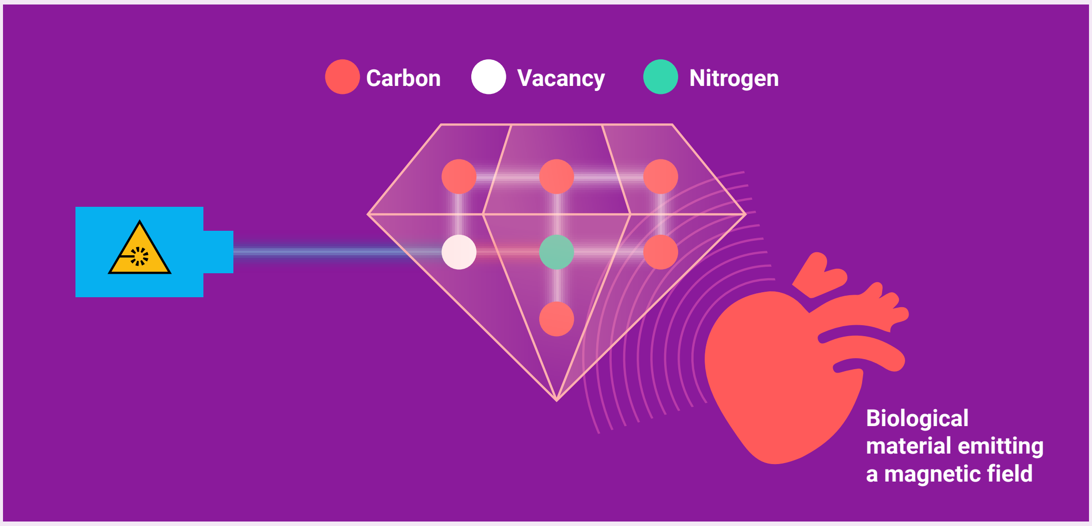

Figure 5: An NV diamond detecting magnetic fields from biological material

Bulk NV diamond magnetometers are the most developed spin-based sensors, with commercialised products available [27]. They can be adjusted for specific sensing applications too, such as next generation microscopy.

M Squared Lasers, a photonics company headquartered in Scotland, is a lead participant in building and testing an NV diamond quantum magnetometer [28]. The project is a collaboration with many other organisations, including the University of Saskatchewan, Dias Geophysical Ltd, and the University of Nottingham, as part of the UK-Canada Quantum Technologies Competition. It is due to be completed in 2024.

27. NQIT and Bruker, "Diamonds for Medical Applications NQIT Industry Partnership Case Study," 2017.
28. Innovate UK project 79437, "Diamond NV Sensors for Quantum-Limited Magnetic Field Measurements," 2021. [Online]. Available: https://gtr.ukri.org/projects?ref=79437.

More recent research is investigating nanodiamonds. This technology is less advanced than others, facing challenges such as isolating external noise and efficient reading of states [29]. Despite this, it has great potential for biosensing applications due to its biocompatibility and its potential to provide nanometre-scale resolution and higher sensitivity than atom-based sensors [30].

In 2023, the diamond quantum sensing group at the University of Nottingham was awarded a £2.5 million grant to develop NV diamond technologies, including applications for healthcare[31]. The group aims to push sensitivity, address scaling problems, make the technology more reliable, integrate it with other technologies such as photonic integrated circuits, and tailor it to address specific needs in healthcare. This and other research may address new applications, such as tracking magnetic implants to guide surgery.

Developments in other technologies can also enhance these quantum devices. For example, masers (microwave lasers) could lead to more efficient readout for NV diamond sensing[32] in current healthcare applications such as MRI [33] [34], and potentially provide new applications.

As well as nitrogen, germanium[35], silicon[36], hexagonal boron nitride [37] and silicon carbide[38] can also be used to make diamond-based quantum sensors. These could lead to alternative applications such as nanothermometry – measuring temperatures on the nanoscale [39]. For this application, hexagonal boron nitride appears to be superior to NV diamond, according to research at the University of Sydney[40].

29. F. Bruckmaier, K. Liu and K. Berghoff, "The future of industrial applications about diamond-based quantum sensing," QuantumDiamonds GmbH, 2023.

30. A. Kuwahata, T. Kitaizumi, K. Saichi, T. Sato, R. Igarashi, T. Ohshima, Y. Masuyama, T. Iwasaki, M. Hatano, F. Jelezko, M. Kusakabe, T. Yatsui and M. Sekino, "Magnetometer with nitrogen-vacancy center in a bulk diamond for detecting magnetic nanoparticles in biomedical applications," Scientific Reports, vol. 10, no. 2483, 2020.

31. D. Hall, "University of Notingham," 2023. [Online]. Available: https://www.nottingham.ac.uk/news/nottingham-researcher-awarded-prestigious-engineering-chair-to-create-next-generation-of-quantum-sensors.

32. I. Materials and I. C. London, "Research Insights: Dr Max Attwood on developing organic materials for quantum technologies," 2022. [Online]. Available: https://blogs.imperial.ac.uk/materials/2022/10/26/research-insights-dr-max-attwood-on-developing-organic-materials-for-quantum-technologies/.

33. Imperial Materials (Imperial College London), "Research Insights with Dr Max Attwood," 22 September 2023. [Online]. Available: https://blogs.imperial.ac.uk/imperialquest/2023/09/22/research-insights-with-dr-max-attwood/.

34. J. D. Breeze, E. Salvadori, J. Sathian, N. M. Alford and C. W. M. Kay, "Continuous-wave room-temperature diamond maser," Nature, vol. 555, p. 493–496, 2018.

35. J.-W. Fan, I. Cojocaru, J. Becker, M. H. A. A. Ilya V. Fedotov, A. Alajlan, S. Blakley, M. Rezaee, A. Lyamkina, Y. N. Palyanov, Y. M. Borzdov, Y.-P. Yang, A. Zheltikov, P. Hemmer and A, "Germanium-Vacancy Color Center in Diamond as a Temperature Sensor," ACS Photonics, vol. 5, no. 3, p. 765–770, 2018.

36. W. Liu, M. N. A. Alam, Y. Liu, V. N. Agafonov, H. Qi, K. Koynov, V. A. Davydov, R. Uzbekov, U. Kaiser, T. Lasser, F. Jelezko, A. Ermakova and T. Weil, "Silicon-Vacancy Nanodiamonds as High Performance Near-Infrared Emitters for Live-Cell Dual-Color Imaging and Thermometry," Nano Lett., vol. 22, no. 7, p. 2881–2888, 2022.

37. H. L. Stern, Q. Gu, J. Jarman, S. E. Barker, N. Mendelson, D. Chugh, S. Schott, H. H. Tan, H. Sirringhaus, I. Aharonovich and M. Atatüre, "Room-temperature optically detected magnetic resonance of single defects in hexagonal boron nitride," Nature Communications, vol. 13, no. 618, 2022.

38. S. Castelletto, A. Peruzzo, C. Bonato, B. C. Johnson, M. Radulaski, H. Ou, F. Kaiser and J. Wrachtrup, "Silicon Carbide Photonics Bridging Quantum Technology," ACS Photonics, vol. 9, no. 5, p. 1434–1457, 2022.

39. Y. Zhou, J. Wang, X. Zhang, K. Li, J. Cai and W. Gao, "Self-Protected Thermometry with Infrared Photons and Defect Spins in Silicon Carbide," Phys. Rev. Applied, vol. 8, no. 4, 2017.

40. Y. Chen, T. N. Tran, N. M. H. Duong, C. Li, M. Toth, C. Bradac, I. Aharonovich, A. Solntsev and T. T. Tran, "Optical Thermometry with Quantum Emitters in Hexagonal Boron Nitride," ACS Appl. Mater. Interfaces, vol. 12, no. 22, p. 25464–25470, 2020.

Applications

Lab Diagnostics

Detecting Breast Cancer

Current approaches can take a long time to provide a cancer diagnosis, and in some cases require the tumour to have reached a certain stage or size to be detectable. Quantum sensors and imagers can facilitate earlier detection.

One potential way to improve the accuracy of diagnosis is using infrared light, as cancerous cells strongly absorb light with wavelengths between 2.5 and 10 micrometres[41]. However, this can be difficult to detect, owing to background noise generated by objects emitting infrared. Furthermore, existing detectors in this waveband are inefficient and require cryostats.

One company addressing these issues is Digistain®, a photonic sensing company aiming to decrease the diagnosis time for breast cancer. The organisation has already developed a device based on infrared multi-spectral imaging, and is now developing a new product called EntangleCam, which uses quantum entanglement [42].

What is entanglement?

Entanglement means that the states of two or more subatomic particles are intertwined with each other. When one of two entangled particles is affected by something, such as a magnetic field, the other particle is also affected, no matter where it is. By using this technique with photons, it is possible to know whether one photon in an entangled pair has been absorbed by measuring the other photon.

EntangleCam generates entangled photons using a process called spontaneous parametric down-conversion (SPDC), which splits an incoming photon into two: one infrared, the other in the visible waveband. When the infrared photon is absorbed by a cancer cell, that can be revealed through a detection of the visible-light photon. This way, the technique can use a cheap, efficient visible light detector, which isn't overwhelmed by the infrared background noise.

41. Y. Ma, N. Gemmell, E. Pearce, R. Oulton and C. Phillips, "Eliminating thermal infrared background noise by imaging with undetected photons," PHYSICAL REVIEW A, vol. 108, no. 032613, 2023.

42. Innovate UK project 10040802, "Digistain - Breast Cancer Companion Diagnostic for over-prescribed chemotherapy," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10040802#/tabOverview.

This process can allow for a fast cancer diagnosis, before cells have built up into a substantial tumour, and also prevent samples from being damaged by the fluorescent dyes used in some current approaches. It should be noted that an oncologist is still needed to identify the area where they would use Digistain® to analyse and share the results. This research was first demonstrated in partnership with a group at Imperial College London[43].

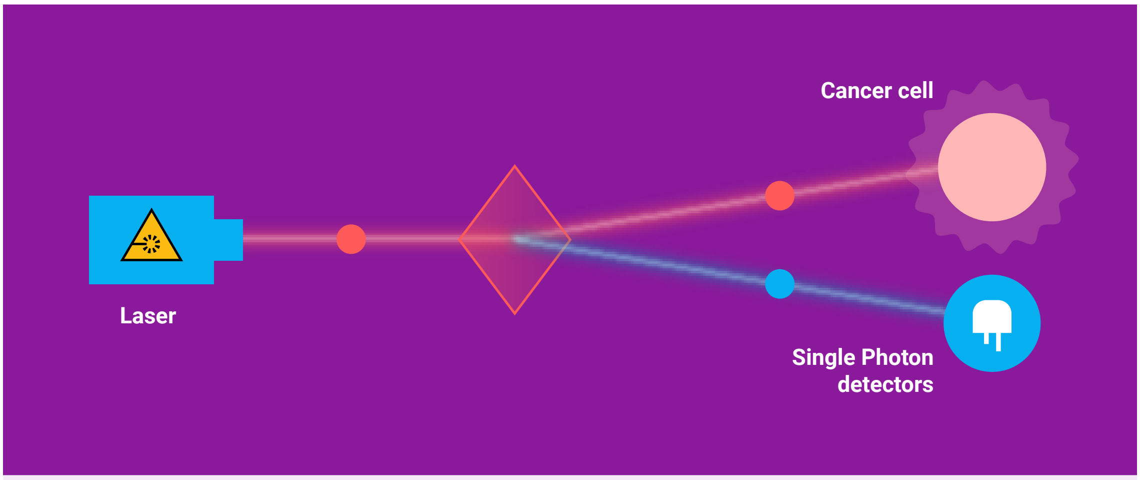

Figure 6: A graphical representation of SPDC being used to detect the presence of a cancerous cell

Another company, Kromek, is investigating molecular breast imaging (MBI) to detect cancer. This technique involves a radioactive tracer using single photon detectors to reveal differences in tissue density with a much lower dose of radiation. The project, a collaboration with Newcastle-upon-Tyne Hospitals NHS Foundation Trust, Newcastle University and University College London, has funding from the Innovate UK Industrial Strategy Challenge Fund and is scheduled to end in 2024[44].

In partnership with Adaptix and the University of Manchester, Kromek has also examined quantum digital tomosynthesis[45]. Tomosynthesis is an approach to mammography that can give surgeons more precise information about where the cancerous tissue is located, so it can be removed while more healthy tissue is left untouched.

The collaboration compared different photon detector systems to assess their individual benefits, such as the accuracy of the images, acquisition time, and compactness of the device. It is hoped that this could replace current cabinet-sized devices. The project finished in 2023[46].

43. Y. Ma, N. Gemmell, E. Pearce, R. Oulton and C. Phillips, "Eliminating thermal infrared background noise by imaging with undetected photons," PHYSICAL REVIEW A, vol. 108, no. 032613, 2023.

44. Innovate UK ISCF project: 10032607, "Single photon detection for ultra-low dose Molecular Breast Imaging," 2022. [Online]. Available: https://gtr.ukri.org/projects?ref=10032607#/tabOverview.

45. Innovate UK ISCF project: 106175, "Transforming Tissue Differentiation via Quantum Digital Tomosynthesis," 2020. [Online]. Available: https://gtr.ukri.org/projects?ref=106175.

46. Kromek, "Kromek attending the 6th Workshop on Medical Applications of Spectroscopic X-ray Detectors (SpecXray)," 24 August 2022. [Online]. Available: https://www.kromek.com/news/6th-workshop-medical-applications-spectroscopic-

Nanothermometry and Nanorheometry

Nanothermometry means measuring temperature on the nanoscale. This can help reveal information on cell biology, such as localised metabolic activity. It can also provide more information on how external temperature sources, such as radiation therapy, influence cells at this level. Nanorheometry measures the flow of a material at the nanoscale level, and can be used to understand how the structure of cells is affected by other forces or energy.

Existing approaches to nanothermometry are based on fluorescence, which requires a source of electromagnetic radiation to illuminate the sample. This approach cannot access *in-vivo* biological matter, such as cells, whereas NV nanodiamond thermometers don't suffer from this problem [47] [48].

In 2023, a group at Cambridge University published a paper detailing an early prototype NV nanodiamond sensor to be used for both nanothermometry and nanorheometry[49]. Nanorheometry can provide further information on cell function, such as how temperature changes the viscoelasticity.

To measure the precise location of the cell, the nanodiamonds were tracked, and the group found that it was possible to obtain both temperature and rheometry measurements from live cells, demonstrating that the target does not regulate its own temperature when external fluctuating temperatures are present. In the future, this could be combined with nanoscale imaging methods to obtain nanorheometry data

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x-ray-detectors/.

47. S. Belser, J. Hart, Q. Gu, L. Shanahan and H. S. Knowles, "Opportunities for diamond quantum metrology in biological systems," Appl. Phys. Lett., vol. 123, 2023.

48. Q. Gu, "Interfacing spin-based quantum sensors with complex systems," University of Cambridge, 2022.

49. Q. Gu, L. Shanahan, J. W. Hart, S. Belser, N. Shofer, M. Atature and H. S. Knowles, "Simultaneous nanorheometry and nanothermometry using intracellular diamond quantum sensors," ACS Nano, vol. 17, no. 20, pp. 20034-20042, 2023.

over a wider sample.

Body Imaging

Brain Imaging for Epilepsy, Parkinson's and Dementia

Magnetoencephalography (MEG) is a method of brain imaging based on detecting the magnetic fields produced by neurons. A team at the University of Nottingham first demonstrated the potential of optically pumped magnetometers (OPMs) for wearable MEG in 2018[50].

In 2020, they launched the spin-out Cerca Magnetics, which has since created wearable helmets containing these devices which allows for scanning of the human brain for adults, children, and infants[51]. The OPMs used in the creation of their device are sourced from QuSpin Inc.[52], while the helmets, system integration, magnetic field control systems and software are created by Cerca.

The company has demonstrated that this technology can be used to better understand epilepsy[53], and has the potential for further study into Parkinson's disease and dementia.

In 2021, Cerca Magnetics successfully delivered its first device to SickKids hospital in Toronto, to investigate the development of autistic spectrum disorders in children[54]. Later that year, a system was installed at Young Epilepsy in Surrey, a charity with a clinical facility affiliated with Great Ormond Street Hospital[55], with further devices to be installed at several more sites in North America and Europe[56]. These systems are being used to conduct research and provide images at least as high-quality as those from conventional, bulky SQUID-based devices.

Tests are currently performed in magnetically shielded rooms costing up to £700,000 to exclude external magnetic fields that would disrupt the measurements. The cost of Cerca Magnetics' OPM-based device, including the shielded room, is roughly half that of a conventional MEG device[57]. Shielded rooms are being further developed to make them easier to install in hospitals and other environments, such as by making the shielding thinner.

50. E. Boto, N. Holmes, J. Leggett, G. Roberts, V. Shah, S. S. Meyer, L. D. Muñoz, K. J. Mullinger, T. M. Tierney, S. Bestmann, G. R. Barnes, R. Bowtell and M. J. Brookes, "Moving magnetoencephalography towards real-world applications with a wearable system," Nature, vol. 555, p. 657–661, 2018.

51. Innovate UK ISCF project: 10003346, "Brain Imaging Using OPM-MEG: Newborn to Toddler," 2021. [Online]. Available: https://gtr.ukri.org/projects?ref=10003346.

52. QuSPIN, "QZFM Gen-3," 2021 . [Online]. Available: https://quspin.com/products-qzfm/.

53. U. Vivekananda, S. Mellor, T. M. Tierney, N. Holmes, E. Boto, J. Leggett, G. Roberts, R. M. Hill, V. Litvak, M. J. Brookes, R. Bowtell, G. R. Barnes and M. C. Walker, "Optically pumped magnetoencephalography in epilepsy," Annals of Clinical and Translational Neurology, vol. 7, no. 3, pp. 397-401, 2020.

54. University of Nottingham & Cerca Magnetics, "Wearable brain imaging system installed in Toronto for autism research," August 2021. [Online]. Available: https://www.nottingham.ac.uk/news/wearable-brain-imaging-system-installed-in-toronto-for-autism-research.

55. Cerca Magnetics, "Young Epilepsy System Installation," September 2021. [Online]. Available: https://www.cercamagnetics.com/cerca-young-epilepsy-system-installation.

56. N. Holmes, R. Bowtell, M. J. Brookes and S. Taulu, "An Iterative Implementation of the Signal Space Separation Method for Magnetoencephalography Systems with Low Channel Counts," Sensors (Basel), vol. 14, no. 6537, 2023.

57. The Institution of Engineering and Technology, "Quantum Engineering and Technologies for Healthcare," 11 October 2023. [Online]. Available: https://www.workcast.com/register?cpak=4948802036278026.

The company has been awarded three Innovate UK projects, with the second and third to bring its technology to market[58] [59]. This funding aims to obtain medical regulatory approval and catalyse widespread deployment of the system into clinical pathways. It is mainly focused on epilepsy monitoring, diagnosis and pre-surgical planning, but also looks ahead to broader studies of brain function.

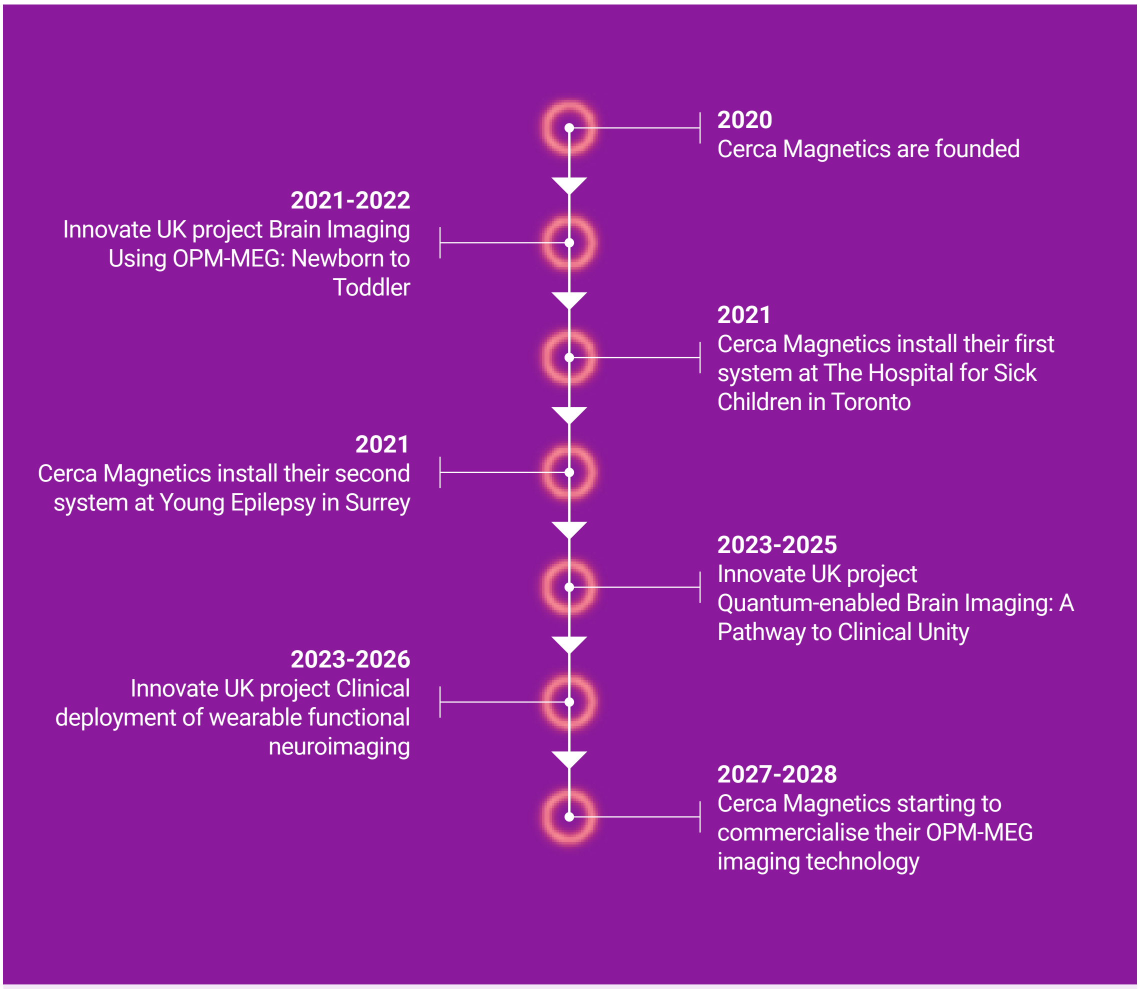

Figure 7: A timeline showing milestones in Cerca Magnetics development

In 2021, a University of Sussex team looked at using OPM technology to get more accurate timing of MEG signals. Preliminary results showed that by watching how the signal changes over time, rather than where the signals came from, it may be possible to diagnose conditions such as dementia[60] by comparing a patient's brainwaves over the course of time, to monitor the advancement of the disease. The research was conducted with a relatively small sample size, so further investigation is needed to confirm these results.

58. Innovate UK project: 10037425, "Clinical deployment of wearable functional neuroimaging," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10037425#/tabOverview.

59. Innovate UK project 10083773, "Quantum-Enabled Brain Imaging: A Pathway to Clinical Utility," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10083773.

60. A. Gialopsou, C. Abel, T. M. James, T. Coussens, M. Bason, R. Puddy and e. al., "Improved spatio-temporal measurements of visually evoked fields using optically-pumped magnetometers," Scientific Reports, vol. 11, no. 22412, 2021.

> "Current NHS waiting times from the point of referral to assessment is up to 6 weeks"

A Scanner for Community Healthcare

In 2023, METLASE began a project to develop a small, cheap medical scanner using OPMs, extending the idea of MEG to other parts of the body. In principle, such a scanner could be used in a variety of locations such as GP surgeries, rather than being limited to hospital departments with substantial resources[61]. This is a first-phase technical feasibility study, in partnership with The University of Sussex, Sheffield Hallam University, Sheffield Children's Hospital, Medilink, and Unipart Logistics.

Cheaper X-Ray Imaging

Quantum Solutions and AY Sensors are collaborating on a programme to use quantum dots for X-ray imaging[62]. The aim is to create a next-generation X-ray device that is cheaper to manufacture while maintaining high image quality, low radiation levels and rapid image acquisition. The project is due to end in October 2024.

Sensing of Strokes and Subdural Haematoma

Photonic technology may enable a new kind of brain imaging using light, which is currently impossible because light is scattered as it travels through the skull. Potential applications are to classify strokes, to identify whether a patient is having a subdural haematoma, and even to identify degenerative brain diseases. A group at the University of Glasgow have proposed to use SPAD based cameras[63] and other imaging techniques to overcome this problem, in a method known as diffuse optical imaging[64].

SPADs can give the arrival time of photons to less than a nanosecond[65], which means they can be used to detect the earliest traces of light after the brain is illuminated by a very brief laser pulse. Those earliest photons to arrive are the ones that have not been delayed much by scattering, so they reveal a sharper image.

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61. Innovate UK project 10085220, "QUESTS - QUantum Enhanced Scanning Technology for community healthcare Settings," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10085220.

62. Innovate UK project 10057107, "PMX - Advancing X-Ray detector performance using Perovskite Materials to unlock high potential vision applications across key industries," April 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10057107#/tabOverview.

63. Photon Force, "The PF32 Camera Range," 2024. [Online]. Available: https://www.photon-force.com/products/pf32-camera-range/.

64. J. Radford, A. Lyons, F. Tonolini and D. Faccio, "Role of late photons in diffuse optical imaging," Optics Express, vol. 28, no. 20, pp. 29486-29495, 2020.

65. E. P. McShane, H. K. Chandrasekharan, A. Kufcsák, N. Finlayson, A. T. Erdogan, R. K. Henderson, K. Dhaliwal, R. R. Thomson and M. G. Tanner, "High resolution TCSPC imaging of diffuse light with a one-dimensional SPAD array scanning system," Optics Express, vol. 30, no. 15, pp. 27926-27937, 2022.

In 2022, simulations showed that it was possible to image through about 12cm of human tissue[66]. Tests were then conducted using a wearable device, but the researchers could not confirm whether the detected near-infrared light had been transmitted through the head or was just background noise[67]. A major technical challenge at this stage is that near-infrared SPADs currently only have moderate efficacy at this wavelength.

If this issue can be solved, it could lead to a lightweight imager that facilitates quick diagnosis, eliminating the need for MRI scans in some cases and reducing the demand for MRI appointments for other conditions[68]. Current NHS waiting times from the point of referral to assessment is up to 6 weeks[69].

In 2023, the team at the University of Glasgow were awarded funding from the European Research Council to extend the work into imaging the brain. The new project, called Boson Sensing and Quantum Imaging for Complex Biological Systems, hopes to enable early detection of degenerative brain diseases.

Imaging to Guide *In-vivo* Devices

Devices such as endoscopes and nasogastric tubes inserted within the human body need to be properly guided to ensure they reach the intended area. Imaging for this purpose can be done with X-rays or other, more expensive, methods such as CT scans. Theoretically, this could be made cheaper and safer by using near-infrared light, except for the same problem that plagues brain imaging using infrared: light becomes widely scattered as it passes through the body.

66. J. Radford and D. Faccio, “Information transport and limits of optical imaging in the highly diffusive regime,” PHYSICAL REVIEW RESEARCH, vol. 5, 2023.

67. J. Radford, “Information limits of imaging through highly diffusive materials using spatiotemporal measurements of diffuse photons,” University of Glasgow, 2023.

68. Extreme Light Group, University of Glasgow in partnershiop with Quantic, “Imaging through body,” 3 June 2021. [Online]. Available: https://www.youtube.com/watch?v=UCPi-Fo7ZCE.

69. Department of Health & Social Care & Public Health England, “Handbook to the NHS Constitution for England,” 2023. [Online]. Available: https://www.gov.uk/government/publications/supplements-to-the-nhs-constitution-for-england/the-handbook-to-the-nhs-constitution-for-england. [Accessed 1 October 2023].

A collaboration between Heriot-Watt University and the University of Edinburgh has investigated a solution using SPAD-based imaging to detect the earliest photons to arrive after a flash of illumination. The project ended in 2023 after successful demonstration tests[70]. However, clinical application will require improvement in the illumination and accuracy of imaging.

Entangled PET Imaging

Positron emission tomography (PET) has long been used to provide detailed 3D imaging, via the gamma-ray photons emitted when a positron from a radioactive tracer meets an electron in the body. One challenge presented by this method is noise.

In 2021, the School of Physics, Engineering and Technology at the University of York investigated how to address this issue using the quantum properties of these photons[71]. When a positron and electron collide and annihilate one another, they emit two gamma-ray photons that are naturally entangled. In principle, correlations between the properties of these photons can be used to distinguish them from noise.

The project ended in 2022, with the group able to simulate and model entangled gamma propagation in matter[72] [73]. When applied to PET imaging, the software was able to distinguish between true PET events and noise.

Magnetocardiography

Magnetocardiography (MCG) is measuring magnetic signals emitted from the heart. MCG can enable better diagnosing of certain heart problems, such as arrhythmia, than the more commonly used electrocardiography (ECG). However, current MCG units have similar problems to SQUID-based MEG systems: they are bulky and very expensive, and not many exist worldwide [24].

Next-generation quantum approaches to magnetocardiography include the tunnel magnetoresistance sensor (TMS), which is based on quantum tunnelling. In this process, a particle can pass through a barrier that would be impenetrable according to classical physics. This sensor is being developed by Neuranics, a spin-out of the Universities of Glasgow and Edinburgh[74]. The device is set to launch as a development kit in 2024, allowing developers to create wearables that obtain measurements via a phone. In addition to the TMS, university groups are developing other quantum approaches to MCG.

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70. E. P. McShane, "Tracking medical devices using time-correlated single photon counting imaging," Heriot Watt University, 2023.

71. D. P. Watts, J. Bordes, J. R. Brown, A. Cherlin, R. Newton, J. Allison, M. Bashkanov, N. Efthimiou and N. A. Zachariou, "Photon quantum entanglement in the MeV regime and its application in PET imaging," Nature Communications, vol. 12, no. 2646, 2021.

72. R. Newton, "Entangled polarisation correlations of annihilation gamma and their applications to PET Imaging," University of York, 2022.

73. CERN, "Geant4," 2024. [Online]. Available: https://geant4.web.cern.ch/.

74. Neuranics, "Neuranics Unleashes 24/7 Heart Monitoring Revolution at CES 2024 with a Wearable Magnetocardiography (MCG) Development Platform," December 2023. [Online]. Available: https://neuranics.com/neuranics-unleashes-24-7-heart-monitoring-revolution-at-ces-2024-with-a-wearable-magnetocardiography-mcg-development-platform/.

A group at the University of Warwick have researched using NV diamonds to reduce the size and cost of MCG systems[75], potentially making more devices available in a wider range of clinical settings, enabling faster diagnosis and better monitoring[76]. In 2022, the group developed a magnetic gradiometer, which can distinguish the heart's signal from other interfering magnetic fields. However, further developments are needed for such a device to operate within unshielded environments[77].

At the University of Nottingham, researchers have used OPMs to detect magnetic signals emitted from the hearts of foetuses. This could complement sonography by providing richer information about heart function. The group performed a study with seven women at various stages of pregnancy and found that the signals recorded were clear enough to be promising for clinical use[78].

In 2020, a group at University College London investigated the use of radio frequency atomic magnetometers (RF-AMs) for electromagnetic induction imaging, a potential method to image the heart[79]. An oscillating magnetic field creates electrical currents in tissue, which generate their own magnetic fields, and a magnetometer detects these fields. The RF-AM provides increased sensitivity, and therefore sensing on a smaller scale. The group has investigated applying this technique to unshielded environments[80], addressed practical applications such as scanning in a clinical environment[81], and worked to enable the method to look deeper within the body[82].

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75. M. W. Dale and G. W. Morley, "Medical applications of diamond magnetometry: commercial viability," Applied Physics, 2017.

76. Innovate UK ISCF project 10003146, "Quantum diamond magnetometry for magnetocardiography," 2021. [Online]. Available: https://gtr.ukri.org/projects?ref=10003146#/tabOverview.

77. R. L. Patel, "High Sensitivity Fiber-coupled Magnetometry Using an Ensemble of Nitrogen-Vacancy Centers in Diamond," University of Warwick, 2022.

78. I. Gale, "MEG-UKI 2023 Conference Poster session 2 (1:00-2:30pm, Day 2)," 2023. [Online]. Available: https://meguk.ac.uk/meg-uki-2023-conference/poster-session-2/.

79. C. Deans, L. Marmugi and a. F. Renzoni, "Sub-Sm−1 electromagnetic induction imaging with an unshielded atomic magnetometer," Appl. Phys. Lett., vol. 116, no. 133501, 2020.

80. H. Yao, B. Maddox and F. Renzoni, "High-sensitivity operation of an unshielded single cell radio-frequency atomic magnetometer," Optics Express, vol. 30, no. 23, pp. 42015-42025, 2022.

81. B. Maddox, C. Deans, H. Yao, Y. Cohen and F. Renzoni, "Rapid Electromagnetic Induction Imaging with an Optically Raster-Scanned Atomic Magnetometer," IEEE Transactions on Instrumentation and Measurement, vol. 72, pp. 1-5, 2023.

82. B. Maddox and F. Renzoni, "Two-photon electromagnetic induction imaging with an atomic magnetometer," Applied Physics Letters, vol. 122, no. 14, 2023.

> "NV diamond magnetometry could provide real-time imaging and help us understand the body on a quantum level"

Brain Imaging on a Neuron Level

A group at the University of Strathclyde is studying the use of NV nanodiamonds to image brain activity on a neuron level. Their research involves implanting these diamonds within targeted areas of the brain. Each diamond focuses on a single neuron, recording the magnetic fields and potentially electric fields generated when the neuron is active[83]. While this has great potential, it is less advanced than other magnetometry techniques such as magnetoencephalography using OPMs.

Treatment for Glioblastoma using Quantum Tunnelling

The Bioelectronics Laboratory at the University of Nottingham is using quantum tunnelling to kill cancerous brain cells[84]. This process allows the precise delivery of electrons without direct contact. The group conducted an *in vitro* experiment, using nanoscale electrodes to deliver targeted electrons and induce apoptosis – programmed cell death. This was shown to kill glioblastoma cells while having no effect on healthy cells.

What is Quantum Biology?

Quantum biology is a field that investigates natural quantum mechanical phenomena in living systems, such as photosynthesis in plants, and how birds navigate using the Earth's magnetic field (known as magnetoreception). This area is not well developed and remains largely theoretical, but future quantum imaging could help develop it.

For example, NV diamond magnetometry could provide real-time imaging and sensing down to the angstrom scale – one-tenth of a nanometre. That could help us understand the body on a quantum level, such as by investigating how quantum tunnelling effects in DNA can cause mutations[85][86].

High-resolution NMR

Using NV diamonds for nuclear magnetic resonance (NMR) spectroscopy can enable much higher-resolution imaging. It can potentially reveal structures on the nanometre scale, such as protein molecules within the human body[87], which could advance medical discovery and healthcare. In 2019, a group at the University of Cambridge investigated imaging in cellular samples using high-grade NV nanodiamonds[88]. The team were able to successfully sense different nuclear species, but improvements are needed to the readout efficiency and quality of the diamonds[89].

83. B. Patton, "Nanobiophotonics Group," 2024. [Online]. Available: https://pols.phys.strath.ac.uk/research/nanobiophotonics/nanodiamond-for-biological-imaging/.

84. A. Jain, J. Gosling, S. Liu, H. Wang, E. M. Stone, S. Chakraborty, P.-S. Jayaraman, S. Smith, D. B. Amabilino, M. Fromhold, Y.-T. Long, L. Pérez-García, L. Turyanska, R. Rahman and Rawso, "Wireless electrical–molecular quantum signalling for cancer cell apoptosis," Nature Nanotechnology, 2023.

85. Y. Kim, F. Bertagna, E. D'Souza, D. Heyes, L. Johannissen, E. Nery, A. Pantelias, A. Sanchez-Pedreño Jimenez, L. Slocombe, M. Spencer and e. al., "Quantum Biology: An Update and Perspective," Quantum Rep, vol. 3, pp. 80-126, 2021.

86. Leverhulme Quantum Biology Doctoral Training Centre (QB-DTC) University of Surrey, "Quantum Tunnelling in DNA," 2024. [Online]. Available: https://www.surrey.ac.uk/leverhulme-quantum-biology-doctoral-training-centre/research/quantum-tunnelling-dna.

87. J. W. Hart and H. S. Knowles, "Multimodal quantum metrology in living systems using nitrogen-vacancy centres in diamond nanocrystals," Frontiers in Quantum Science and Technology, vol. 2, 2023.

88. J. Holzgrafe, Q. Gu, J. Beitner, D. M. Kara, H. S. Knowles and M. Atatüre, "Nanoscale NMR Spectroscopy Using Nanodiamond Quantum Sensors," Phys. Rev. Applied, vol. 13, no. 4, 2020.

89. Q. Gu, "Interfacing spin-based quantum sensors with complex systems," University of Cambridge, 2022.

Consumer Medical Monitoring and Wearable Healthcare

Glucose Monitoring

NIQS Tech, a spin-out from the University of Leeds, is developing a highly accurate, non-invasive glucose sensor that is equally effective for different skin tones[90 91]. Existing devices for monitoring blood glucose levels, such as those used by people with diabetes, can be painful, invasive and expensive. Commonly used light-based approaches also tend to be less effective for patients with darker skin.

In the device developed by NIQS Tech, the user touches a doped silica platform, which enables quantum interference effects. When this is illuminated with laser light, it fluoresces, and the lifetime of the fluorescence depends on the amount of glucose in the user's blood, regardless of skin tone. NIQS has already demonstrated proof of concept with lab-based testing, and is now working to reduce the size of the technology, so it can be a wearable device which monitors glucose levels continuously[92].

Blood Oxygen Meter

Quantum technology may be useful in detecting blood oxygen levels, again being indiscriminate to skin tone. In 2021, the Institute for Integrated Micro and Nano Systems at the University of Edinburgh, in partnership with semiconductor manufacturer Elmos, investigated a method that involved shining a laser through biological material and then detecting the received light with SPADs.

The group built two test devices and found that it was possible to determine the change in specific wavelength absorption levels, which can reveal blood oxygen levels. Unlike existing oxygen monitors, this is equally effective for any skin tone, and could provide very accurate readings when compared to traditional pulse oximeters. The devices could be miniaturised to become wearable, but real-world devices will require reduced noise and a stronger signal[93].

90. N. Furtak-Wells, "Long-range atomic interactions for novel quantum technologies," University of Leeds, 2019.

91. B. Dawson, "Remote photoluminescence effects mediated by asymmetric semi-transparent mirrors and their potential application for non-invasive biosensingRemote photoluminescence effects mediated by asymmetric semi-transparent mirrors and their potential application fo," University of Leeds, 2023.

92. Innovate UK Project 10031417, "Non-invasive quantum sensing for continuous glucose monitoring," 2022. [Online]. Available: https://gtr.ukri.org/projects?ref=10031417#/tabOverview.

93. Y. Hua, K. Bantounos, A. V. N. Jalajakumari, A. Turpin, I. Underwood and D. Chitnis, "A pulse oximeter based on time-of-flight histograms," Proc. SPIE Photonic Instrumentation Engineering VIII, vol. 11693, 2021.

Brain-Computer Interfaces and Neuroscience

Brain-computer interfaces link neuronal activity with external devices, so they can be controlled directly. US company Meta Reality Labs uses a spectroscopy technique[94] to do this, measuring oxygen levels in the brain to track changes in blood flow[95] and therefore neuronal activity. In 2020, Meta Reality Labs used a SPAD-based camera developed by UK-based Photon Force [57] to improve this technique and provide a clearer signal. This may have applications in brain monitoring for healthcare.

In 2021, a collaboration between the University of Nottingham and KU Leuven in Belgium investigated the creation of a brain-controlled keyboard[96] based on magnetoencephalography (MEG) using optically pumped magnetometers (OPMs). MEG has been shown to provide higher-quality information than other methods of non-invasive neural interfaces, such as scalp-mounted electroencephalography (EEG)[97].

The group tested their platform by asking subjects to spell out words by moving a cursor on a screen. These tests were performed with an average accuracy of 97.7%. At present this technology requires a specially shielded room, as these OPMs are sensitive to background magnetic fields.

A group at the University of Birmingham is focusing on other ways to improve OPMs for MEG applications[98] such as reducing response time and so increasing the speed of brain-computer interfaces[99]. Another line of research involves combining OPM-based MEG with transcranial magnetic stimulation, which allows the excitation of one part of the brain and the measurement of the response in another part with great precision.

From this result, it is possible to tell if other regions in the brain contribute to the analysed area. It is hoped that this could help neuroscientists explore connectivity in the brain, and help clinicians diagnose mild traumatic brain injury.

94. Photon Force, "Brain/Computer Interface Using Photon Force Technology," 2020 [Online]. Available: https://www.photon-force.com/applications/brain-computer-interface/?_gl=1*fdh122*_up*MQ..*_ga*MTk1MTE5MTMzMC4xNjg3NTIzMTQ3*_ga_DB7SQ6GCT1*MTY4NzUyMzE0Ni4xLjAuMTY4NzUyMzE0Ni4wLjAuMA...

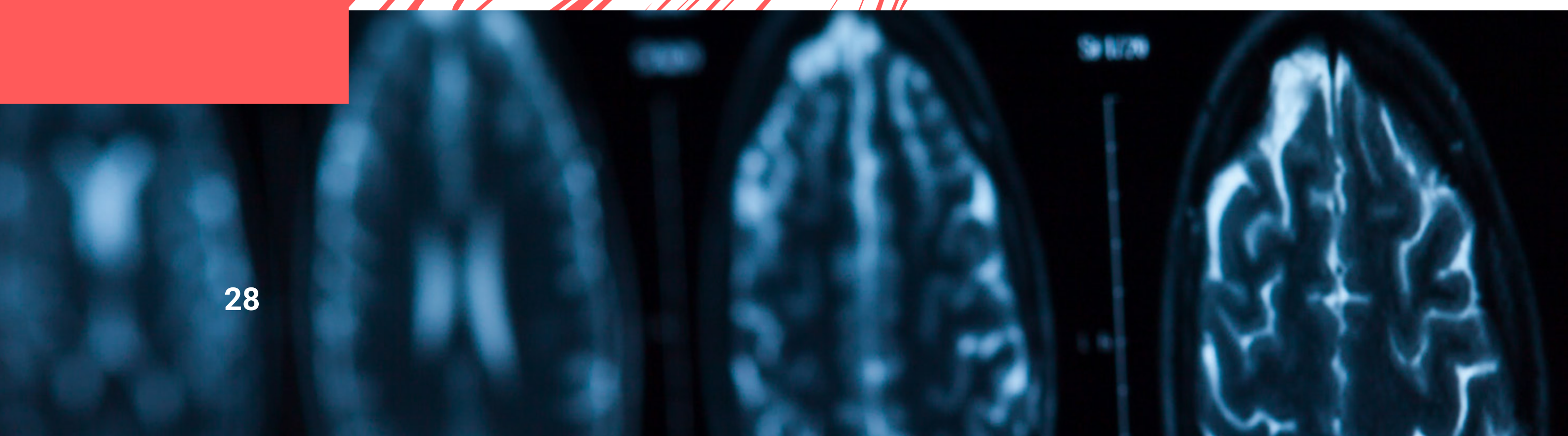
95. E. J. Sie, H. Chen, E.-F. Saung, R. Catoen, T. Tiecke, M. A. Chevillet and F. Marsili, "High-sensitivity multispeckle diffuse correlation spectroscopy," Neurophotonics, vol. 7, no. 3, 2020.

96. B. Wittevrongel, N. Holmes, E. Boto, R. Hill, M. Rea, A. Libert, E. Khachatryan, M. M. V. Hulle, R. Bowtell and M. J. Brookes, "Practical real-time MEG-based neural interfacing with optically pumped magnetometers," BMC Biology, vol. 19, no. 158, 2021.

97. F. L. d. Silva, "EEG and MEG: Relevance to Neuroscience," Neuron, vol. 80, no. 5, p. 1112–1118, 2013.

98. Y. Bezsudnova, L. M. Koponen, G. Barontini, O. Jensen and A. U. Kowalczyk, "Optimising the sensing volume of OPM sensors for MEG source reconstruction," NeuroImage, vol. 264, no. 119747, 2022.

99. M. Brickwedde, Y. Bezsudnova, A. Kowalczyk, O. Jensen and A. Zhigalov, "Application of rapid invisible frequency tagging for brain computer interfaces," Journal of Neuroscience Methods, vol. 382, no. 0165-0270, 2022.



Point of Care Diagnostics

Detecting Biomarkers with Quantum Dots

A potential future application for quantum dots is detecting biomarkers. This could provide a cheaper and faster method for diagnosing diseases, and reduce waste from single-use diagnosis kits such as lateral flow tests.

Beyond Blood Diagnostics, a spin-out from Imperial College London, is hoping to improve cancer diagnostics in partnership with the University of Calgary and Applied Quantum Materials. The company uses quantum dots to detect and identify traces of cancer within blood. An antibody is attached to each quantum dot that will latch on to a specific type of cancer cell. The quantum dots are then added to a blood sample taken from the patient, and fluoresce when illuminated with a laser if attached to a cancer cell. This project is due to end in 2025[100].

If successful, it could enable the use of specific drugs to target the type of cancer identified.

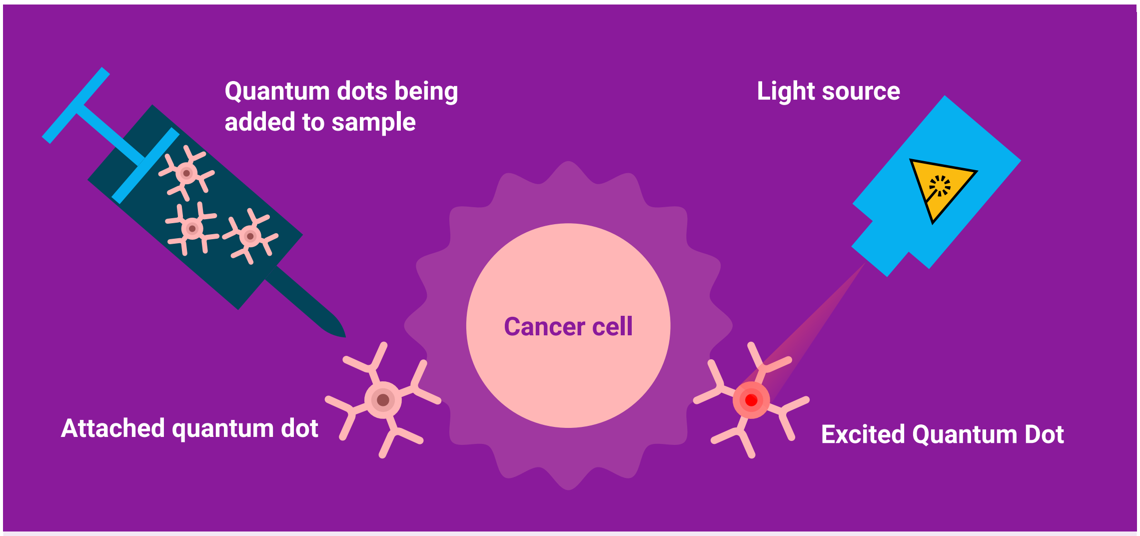


Figure 8: A graphical representation of quantum dots detecting cancerous cells

A partnership between the University of Strathclyde and the Fraunhofer Centre for Applied Photonics has investigated cadmium selenide colloidal quantum dots for biomedical applications[101] [102]. Using these quantum dots attached to antibodies, the aim was to detect pathogens and protein biomarkers in extracted samples.

100. Innovate UK project 10075392 , "Quantum technology enabled blood diagnostics for safer and more patient centric cancer care & treatment management," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10075392

101. EPSRC Project 2125310, "Hybrid UV LED/elastomeric bio-instrumentation," 2018. [Online]. Available: https://gtr.ukri.org/projects?ref=studentship-2125310.

102. N. Bruce, F. Farrell and N. Laurand, "Temperature Stability of Elastomeric Colloidal Quantum Dot Colour Converter," IEEE British and Irish Conference on Optics and Photonics (BICOP), pp. 1-4, 2019.

The partnership aimed to speed up the detection process currently performed with enzyme-linked immunosorbent assays and reduce the size of the detection equipment. The prototype, using a smartphone camera and filter, enabled accurate detection of the dots with a compact device[103 104].

Similar research is being conducted at Cardiff University, where a group is investigating how to detect biomarkers using miniature lasers based on quantum dots, alongside photonic crystals[105]. Photonic crystals are periodic arrays of material that can filter specific wavelengths of light. These components are combined on a single chip to reduce the size of the device, and the group aims to incorporate this technology into a wearable device to allow for continuous monitoring[106 107].

Detecting Biomarkers with Diamonds

NV diamonds can also detect biomarkers. Two companies, Element Six in the UK and QDTI in the USA[108], have developed a product to rapidly detect biomarkers in a range of samples, including blood plasma and cerebrospinal fluid. The device can detect the magnetic fields emitted from certain proteins, which can reveal some diseases in their early stages, including many cancers and degenerative brain diseases such as Alzheimer's. It can also detect nucleic acids and identify different types of cells. This device is already available to buy, and a future goal of the partnership is to reduce diagnosis time by introducing device improvements[109].

A group at UCL, in partnership with the i-sense interdisciplinary research collaboration, have investigated *in vitro* diagnosis of HIV-1 using NV nanodiamonds to trace biomarkers within lateral flow tests. They were able to detect concentrations up to 100,000 times lower than is possible using gold nanoparticles, as in conventional lateral flow tests[110].

This result was obtained from a small set of thirteen samples, and the researchers state that further testing with clinical samples is required to fully understand the clinical sensitivity of this approach. This approach could also be applied to other diseases, including virus-based illnesses such as Covid-19[111].

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103. Institute of Physics, "PHOTON 2020 Session: Waveguide sensors," 2020. [Online]. Available: https://www.youtube.com/watch?v=fKguewoKnZ4.

104. N. Bruce, F. Farrell, E. Xie, M. G. Scullion, A.-M. Haughey, E. Gu, M. D. Dawson and N. Laurand, "MicroLED biosensor with colloidal quantum dots and smartphone detection," Biomedical Optics Express, vol. 14, no. 3, pp. 1107-1118, 2023.

105. F. Masia, N. Monim and W. Langbein, "Wavelength agile quantum dot laser for lab-on-chip optical biosensors," IEEE Photonics Conference (IPC), pp. 1-2, 2022.

106. EPSRC project: 2834700, "EPSRC PhD Studentship in Integrated sensing technology for point-of-care diagnostics," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=studentship-2834700#/tabOverview.

107. Cardiff School of Biosciences, "EPSRC PhD Studentship in Integrated sensing technology for point-of-care diagnostics," 2022. [Online]. Available: https://www.findaphd.com/phds/project/epsrc-phd-studentship-in-integrated-sensing-technology-for-point-of-care-diagnostics/?p143422.

108. Element Six Ltd (UK); Quantum Diamond Technologies Inc, "Quantum diamond biomarker detection," PhotonicsViews, vol. 19, pp. 48-50., 2022.

109. Element Six Ltd (UK); Quantum Diamond Technologies Inc, "Quantum diamond biomarker detection," PhotonicsViews, vol. 19, pp. 48-50., 2022.

110. B. S. Miller, L. Bezinge, H. D. Gliddon, D. Huang, G. Dold, E. R. Gray, J. Heaney, P. J. Dobson, E. Nastouli, J. J. L. Morton and R. A. McKendry, "Spin-enhanced nanodiamond biosensing for ultrasensitive diagnostics," Nature, vol. 587, p. 588–593, 2020.

111. Mark Greaves, University College London, "Quantum nanodiamonds may help detect disease earlier," 25 November 2020. [Online]. Available: https://www.ucl.ac.uk/news/2020/nov/quantum-nanodiamonds-may-help-detect-disease-earlier.

Tracing Pancreatic and Skin Cancer

Nanoco Technologies Limited, which manufactures quantum dots, has investigated the ability of their VIVODOTS® product to trace cancer cells[112]. The company looked at injecting the dots to provide accurate and immediate detection of cancerous tissues, and preclinical studies *in vitro* and *in vivo* showed promising results[113].

This approach could help to reduce the unnecessary removal of healthy tissue, and help to ensure that no residual cancer tissue remains after surgery for pancreatic cancer [105]. In addition, it was determined that the VIVODOTS® could provide a simplified diagnosis method for skin cancer[114].

112. Innovate UK Project 103357, "VIVODOTS™ nano-devices for detection, resection and management of pancreatic cancers," 2017. [Online]. Available: https://gtr.ukri.org/projects?ref=103357.

113. Nanoco, "Cutting-edge nanomedicine," 24 October 2019. [Online]. Available: https://www.nanocotechnologies.com/case-studies/cutting-edge-nanomedicine/.

114. Nanoco Technologies, "Nanoco: developing new techniques to detect and treat cancer," 8 7 2019. [Online]. Available: https://www.nanocotechnologies.com/media/nanoco-developing-new-techniques-to-detect-and-treat-cancer/.

Microscopy

Entangled Microscopy

In 2020, the optics group at the University of Glasgow looked at how to enhance microscopy using quantum entanglement – a process known as ghost imaging. One photon in each entangled pair interacts with a sample, and the image is built up by detecting the effect on the other member of each entangled pair. An image can then be created without the detected light interacting with the sample[115], helping to negate much of the noise encountered when imaging with low levels of light.

In 2021, the group built a demonstration device and trialled incorporating it inside a microscope to enhance medical imaging of photosensitive samples[116 117]using an Oxford Instruments camera[118] as the detector. Further technological improvements are needed for this to become a practical imaging approach[119].

Improving Multiphoton Microscopy

Quantum approaches could enhance multiphoton microscopy. In this technique, a fluorescent dye absorbs two or more photons, then emits visible light. Multiphoton microscopy can provide 3D images, as the illuminating lasers are scanned through a sample, and has applications in imaging a vast range of biological materials such as the brain and eye. However, it requires powerful lasers which could damage the sample.

115. T. Gregory, P.-A. Moreau, E. Toninelli and M. J. Padgett, "Imaging through noise with quantum illumination," SCIENCE ADVANCES, vol. 6, no. 6, 2020.

116. M. J. Padgett, "Microscopy using quantum sources of illumination," Proc. SPIE Photonics for Quantum 2020;, vol. 11918, no. 1191808, 2021.

117. T. Gregory, P.-A. Moreau, S. Mekhail, O. Wolley and M. J. Padgett, "Noise rejection through an improved quantum illumination protocol," Scientific Reports, vol. 11, no. 21841, 2021.

118. Oxford Instruments, "Quantum Optics & Imaging," 2024. [Online]. Available: https://www.oxinst.com/applications/quantum-optics-and-imaging.

119. T. Gregory, "Quantum Enhanced Imaging," University of Glasgow, 2022.

In 2020, a collaboration between the University of Strathclyde and the Fraunhofer CAP[120] looked at quantum-enhanced multiphoton microscopy. The team calculated that using entangled photons would increase the probability of exciting fluorescence, and enable the technique to work with much lower-intensity light. It would also reduce noise and enable deeper imaging of a sample[121]. If successful, the project could benefit neuroscience by providing images deep within the brain, which may be important for studying Alzheimer's disease[122].

Another issue with multiphoton microscopy is after-bleaching, in which dyes stop fluorescing over time. To address this, another group at the University of Strathclyde looked at replacing the dye with fluorescent NV nanodiamonds in 2019[123]. This completely removed the after-bleaching effect and thus enabled continual imaging of the sample. The nanodiamonds also helped enable higher resolution. The results suggested that NV nanodiamonds could be used in other fluorescence-based techniques.

A Scanless 3D Microscope

A quantum-enhanced microscope could provide real-time 3D imaging on the nanometre scale. A group at the University of Glasgow has used a form of interferometry combined with a SPAD-based camera to gain depth information[124]. This removes the need to scan the sample, cutting acquisition time[125] and potentially allowing real-time 3D imaging. The results were positive, providing a 3D image red blood cell with depth resolution down to 100 nm[126].

Real-time Fluorescence Lifetime Imaging Microscopy

In fluorescence-lifetime imaging microscopy (FLIM), fluorescent dyes emit light of different colours depending on the time it takes for the dye to decay, revealing characteristics such as pH and chemical concentration at a cellular level. However, FLIM is too slow to acquire an image in real time, preventing adoption in hospitals and other clinical settings.

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120. EPSRC project 2332160, "Quantum-enhanced multiphoton fluorescence microscopy," 2020. [Online]. Available: https://gtr.ukri.org/projects?ref=studentship-2332160.

121. QUANTIC, "Revolutionising Biomedical Imaging," 22 July 2021. [Online]. Available: https://quantic.ac.uk/technologies/healthcare/headline_802773_en.html.

122. University of Strathclyde, "Quantum physics project with microscopy application receives €2 million grant," 23 November 2023. [Online]. Available: https://www.strath.ac.uk/whystrathclyde/news/2023/quantumphysicsprojectwithmicroscopyapplicationreceives2milliongrant/.

123. G. E. Johnstone, G. S. Cairns and B. R. Patton, "Nanodiamonds enable adaptive-optics enhanced, super-resolution, twophoton excitation microscopy," R. Soc. open sci, vol. 6, no. 190589, 2019.

124. B. Ndagano, H. Defienne, D. Branford, Y. D. Shah, A. Lyons, N. Westerberg, E. M. Gauger and D. Faccio, "Quantum microscopy based on Hong–Ou–Mandel interference," Nature Photonics, vol. 16, p. 384–389, 2022.

125. A. Lyons, G. C. Knee, E. Bolduc, T. Roger, J. Leach, E. M. Gauger and D. Faccio, "Attosecond-Resolution Hong-Ou-Mandel Interferometry," SCIENCE ADVANCES, vol. 4, no. 5, 2018.

126. The Institution of Engineering and Technology, "Quantum Engineering and Technologies for Healthcare," 11 October 2023. [Online]. Available: https://www.workcast.com/register?cpak=4948802036278026.

In 2023, a group at the University of Glasgow researched how to improve FLIM by combining a low-spectral-resolution image from a CCD camera with a high-spectral-resolution image from a SPAD-based camera called FILMera, developed by Horiba and the University of Edinburgh[127]. This approach can provide up to 20 frames per second and could enable a better understanding of biological information on the nanometre scale[128].

The same year, a group at the University of Edinburgh also investigated using SPADs for FLIM[129]. One issue they encountered was a bottleneck in information processing: detecting vast numbers of photons and quickly translating that information into a storable electronic format can be a challenge. The team were able to solve this using a method called on-chip histogramming, and built a test device that acquired many thousands of photons per second, enabling high-quality FLIM images to be obtained.

NV Diamond Microscopy

NV diamond microscopy can analyse and image samples down to a scale of tens of nanometres at room temperature[130]. An NV diamond probe obtains exact values of the magnetic field and is scanned across a sample to build up an image. In 2022, science consultancy company Cambridge Consultants helped Swiss company QNAMI to further develop its NV scanning microscopy system, the ProteusQ[131], and investigate how it could be used for biomagnetic imaging applications[132].

In 2019, a group at the University of Nottingham conducted experiments using NV diamonds to detect paramagnetic species such as free radicals and paramagnetic metalloproteins. These species are involved in key processes such as metabolism, cell signalling and immune response[133]. All current approaches can only detect paramagnetic species *in vitro*, but using NV diamonds, the group built a prototype microscope that can detect them in living systems. This could be further developed to allow observation of metabolism within cells.

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127. Horiba, "FLASH-FLIM measurements with the FLIMera TCSPC Camera," June 2023. [Online]. Available: https://static.horiba.com/fileadmin/Horiba/Application/Health_Care/Biotechnology/FLASH-FLIM_measurements_with_the_FLIMera_TCSPC_Camera.pdf.

128. V. Kapitany, V. Zickusa, A. Fatimaa, G. Carlesa and D. Faccioa, "Single-shot time-folded fluorescence lifetime imaging," PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, vol. 120, no. 16, 2023.

129. H. Mai, A. Jarman, A. T. Erdogan, C. Treacy, N. Finlayson, R. K. Henderson and S. P. Poland, "Development of a high-speed line-scanning fluorescence lifetime imaging microscope for biological imaging," Optics Letters, vol. 48, no. 8, pp. 2042-2045, 2023.

130. Qnami, "Qnami White Paper NV Magnetometry," 3 July 2020. [Online]. Available: https://qnami.ch/wp-content/uploads/2020/07/Qnami_WhitePaper1_NV_magnetometry-5.pdf.

131. P. Maletinsky, S. Hong, M. S. Grinolds, B. Hausmann, M. D. Lukin, R. L. Walsworth, M. Loncar and A. Yacoby, "A robust scanning diamond sensor for nanoscale imaging with single nitrogen-vacancy centres," Nature Nanotechnology, vol. 7, p. 320–324, 2012.

132. E. Owen, "Cambridge Consultants: Quantum sensing technology for the life sciences – exploring the potential," 24 January 2023. [Online]. Available: https://www.cambridgeconsultants.com/insights/opinion/quantum-sensing-for-life-sciences.

133. V. Radu, J. C. Price, S. J. Levett, K. K. Narayanasamy, T. D. Bateman-Price, P. B. Wilson and M. L. Mather, "Dynamic Quantum Sensing of Paramagnetic Species Using Nitrogen-Vacancy Centers in Diamond," ACS Sens, vol. 5, no. 3, pp. 703-710, 2020.

Quantum Computing

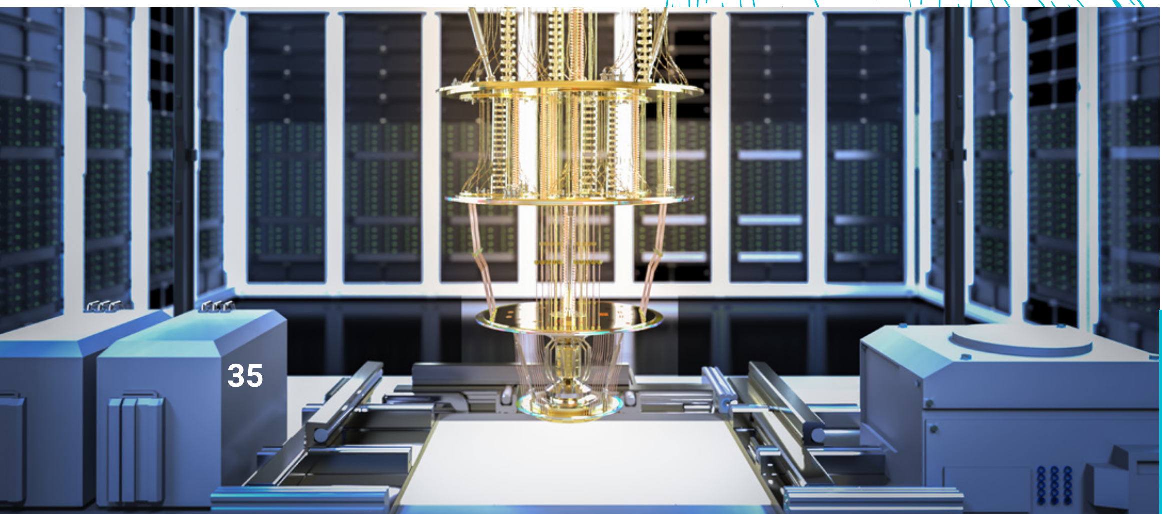
Quantum computing promises to transform many industries, including healthcare. Research by Ernst & Young and the National Quantum Computing Centre[134] identified that by 2035, quantum computing is likely to play a significant role in health and life sciences.

There may be some applications before 2035, highlighted by current Innovate UK projects, using small-scale machines known as noisy intermediate scale quantum (NISQ) computers. Others may use high-performance computing related to quantum technology, such as D-Wave's quantum annealing approach[135], and Fujitsu's quantum-inspired digital annealer, which can reduce the time to simulate the behaviour of novel molecules from 15 months to 7 weeks[136].

134. (EY), Catriona Campbell; Piers Clinton-Tarestad Partner, technology risk (EY); (EY), Harvey Lewis; (EY), Laura Henchoz; (NQCC), Simon Plant; (NQCC), Geoff Barnes, "How can you prepare now for the quantum computing future? EY Quantum Readiness Survey 2022," June 2022. [Online]. Available: https://assets.ey.com/content/dam/ey-sites/ey-com/en_uk/topics/emerging-technology/quantum/ey-quantum-readiness-survey-2022.pdf.

135. N. H. Prickett, "GlaxoSmithKline Marks Quantum Progress with D-Wave - The Next Platform," February 2021. [Online]. Available: https://www.nextplatform.com/2021/02/24/glaxosmithkline-marks-quantum-progress-with-d-wave/.

136. Fujitsu UK, "Accelerating Drug Discovery," 2024. [Online]. Available: https://www.fujitsu.com/uk/services/business-services/digital-annealer/accelerating-drug-discovery/.



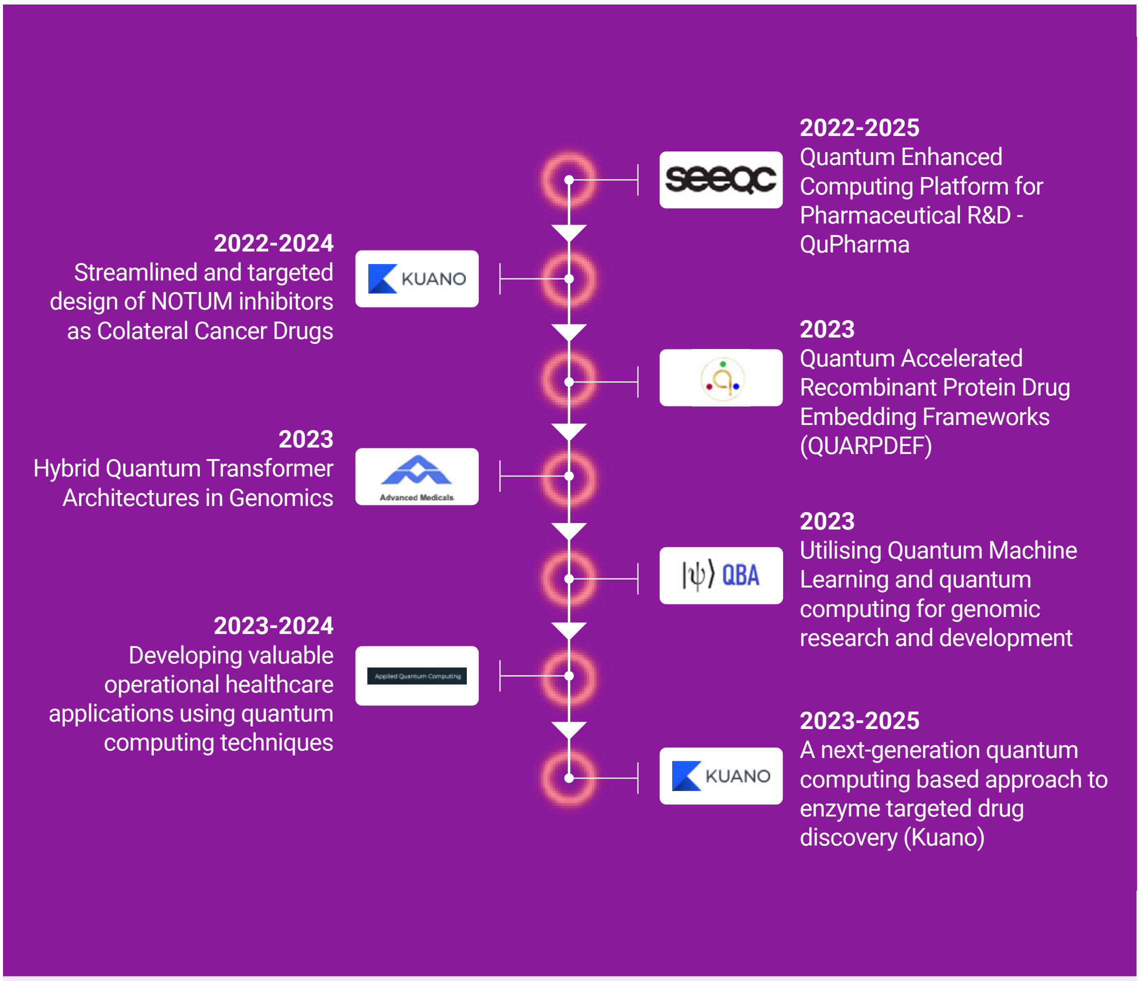


Figure 9: Quantum Computing for healthcare and life sciences projects funded by Innovate UK

However, the most compelling applications, such as advanced molecular modelling for drug discovery, would need a fully-functioning fault-tolerant quantum computer. This would be able to perform some types of calculations far faster than any possible classical computer, but the technology remains some years away.

Stubborn challenges include reducing noise, error correction and scaling up the hardware to implement a large number of logical qubits (quantum bits – see box). Many institutions around the world are researching this problem and trying to achieve quantum advantage, where a useful real-world application that can be run on a quantum computer outcompetes classical computing.

The first National Quantum Strategy Mission, announced in 2023[137], aims to overcome many of these issues to help the UK compete globally. It states that "by 2035, there will be accessible, UK-based quantum computers capable of running 1 trillion operations and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy".

What is a Qubit?

Ordinary, classical computers process bits of information. One bit represents a signal that can be in either of two states – often labelled as 0 and 1, and usually encoded in electrical form.

By contrast, a quantum computer processes quantum bits, or qubits. These are encoded in the states of a simple quantum system with two levels. That could be two energy levels of an atom or ion, for example. Quantum systems display a phenomenon called superposition, in which they can be in a combination of states – an atom can be both high and low energy, for example.

This means that a qubit can have values involving any combination of 0 and 1: for example, representing a 25% probability of 0 and a 75% probability of 1. As qubits are combined, the potential complexity of their states grows exponentially, which is the basis of the quantum computer's power.

The flipside is that quantum states are delicate, so environmental noise can cause errors. Reducing and removing those errors is required to make a fault-tolerant quantum computer. Many physical qubits may be needed to perform the error-correction needed for a single logical qubit.

There are many approaches to making physical qubits, including superconducting circuits, trapped ions, neutral atoms, spins in silicon, photons and NV diamond. Some showing higher levels of progress, but it is still too early to determine which will provide the best paths to quantum advantage. The UK hosts companies working on all six of these qubit architectures.

137. Department for Science, Innovation & Technology, "National Quantum Strategy Missions," 22 November 2023. [Online]. Available: https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions.

National Quantum Strategy Mission 1: By 2035, there will be accessible, UK-based quantum computers capable of running one trillion operations.

Advantages of Quantum Computing for Life Sciences and Healthcare

Optimisation is one area that will be important to healthcare. Quantum optimisation algorithms could improve monitoring and delivery of treatment, for example, as well as the transport infrastructure that delivers vital equipment.

Quantum simulation is another promising approach. Perhaps unsurprisingly, quantum computers will be good at simulating inherently quantum phenomena such as protein folding and other chemical processes. Existing approaches using classical computers are either low in accuracy or take a long time to simulate only a small number of atoms[138]. Quantum computing promises to provide more rapid and larger-scale simulations. Especially when combined with AI, this could enable the discovery of new drugs and materials to be discovered. In turn, new materials could enhance quantum sensing. For example, new superconducting materials could allow single photon detectors with high detection efficiency to operate outside bulky cryostat systems, giving better imaging than existing devices.

138. N. S. Blunt, J. Camps, O. Crawford, R. Izsák, S. Leontica, A. Mirani, A. E. Moylett, S. A. Scivier, C. Sünderhauf, P. Schopf, J. M. Taylor and N. Holzmann, "Perspective on the Current State-of-the-Art of Quantum Computing for Drug Discovery Applications," J. Chem. Theory Comput, vol. 18, no. 12, p. 7001–7023, 2022.

Figure 10: Quantum computing hardware companies operating in the UK

Superconducting

- Rigetti
- IBM Quantum
- SEEQC
- Oxford Quantum Circus

NV Diamond

- Quantum Brilliance

Trapped Ion

- Quantinuum
- Universal Quantum
- Oxford Ionics

Photon

- Psi Quantum
- Orca Computing

Silicon Spins

- Hitachti
- Quantum Motion Technologies

Neutral atoms

- QuEra
- M Squared Lasers
- Infleqtion
- Pasqal UK

Applications

Quantum computing has many potential applications in healthcare and life sciences. Future applications are being researched using either existing quantum computers or quantum simulators – programmes run on classical computers that simulate small-scale quantum machines.

The majority of research so far is on drug design and discovery, but there are several other application areas that could prove important. Quantum computers could analyse insurance claims by detecting similarities in previously identified false claims[139], therefore reducing fraud, which currently costs the NHS £1.27 billion a year [128]. They could also be used for rapid diagnostics and medical imaging.

Quantum sensing and computing could also combine for precision medicine, tailoring drugs and other treatments to an individual. Sensing could provide a detailed understanding of an individual's biology, then a quantum computer could simulate drug responses, increasing drug effectiveness and decreasing the risk of adverse reactions.

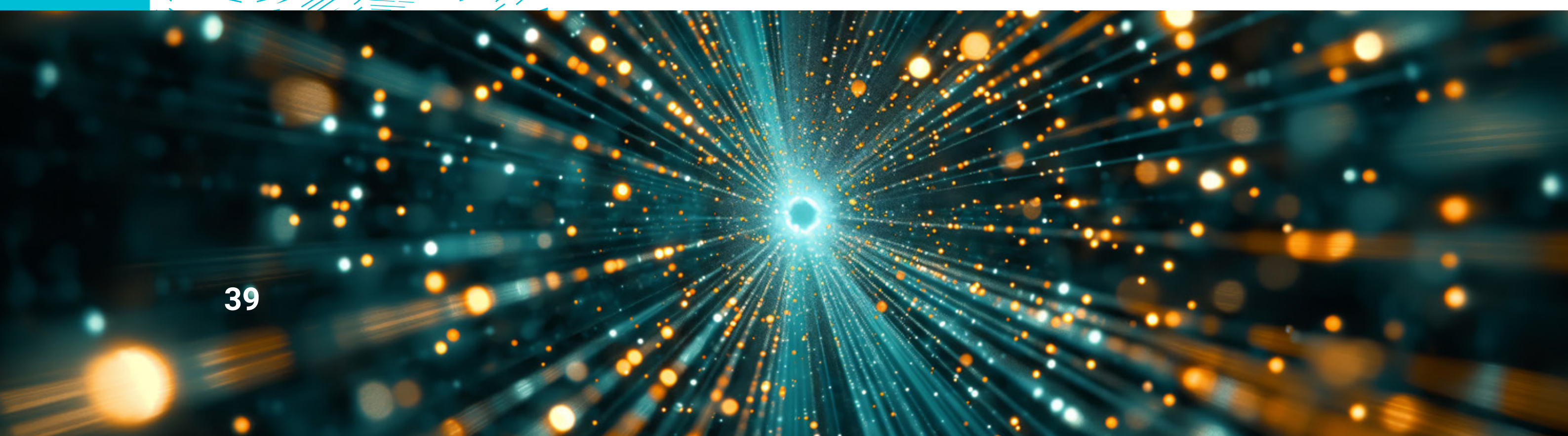
Optimisation in Healthcare Environments

Quantum computers will be able to solve complex optimisation problems that are intractable for classical computers. This could have many applications in healthcare, but so far there have only been a few investigations into its potential.

In partnership with the NHS and the NQCC, Applied Quantum Computing has investigated quantum optimisation algorithms within hospital environments. This included a small-scale demonstration on the use of quantum computing to optimise theatre and operation allocation[140].

139. R. Ur Rasool, H. Ahmad, W. Rafique, A. Qayyum, J. Qadir and Z. Anwar, "Quantum Computing for Healthcare: A Review," Future Internet, vol. 15, no. 94, 2023.

140. NQCC, "Investigating the application of near-term quantum computing techniques to addressing operational healthcare use cases important to NHS health and care provision," 2023. [Online]. Available: https://www.nqcc.ac.uk/investigating-the-application-of-near-term-quantum-computing-techniques-to-addressing-operational-healthcare-use-



In 2023, this research was continued under an Innovate UK project[141], which also investigates optimisation for other problems including urgent care triage and community nurse visiting schedules. The project examined these applications on a range of different quantum devices to determine the best approach in the near term, before fully fault-tolerant machines exist.

Radiotherapy

Radiotherapy involves delivering ionising radiation, such as x-rays or high-energy protons, through many angles so that a tumour receives a much higher dose than surrounding tissue. Quantum computing could improve this delivery of radiation by enabling more precise positioning and dose management[142].

Professional services company Jacobs has teamed up with the NQCC, National Nuclear Laboratory, Sellafield Ltd and the University of Cambridge, to investigate the feasibility of using quantum computing to model radiation transport[143]. As well as helping to inform radiotherapy, this could have applications in shielding and medical isotope production.

Drug Design and Discovery

The rate of new drug discovery has slowed since the turn of the century, and this is predicted to continue, following a trend known as Eroom's law. The process of discovery is taking longer and costing more, with one source stating that, on average, discovering a single drug takes 12 to 15 years and costs £1-2 billion[144].

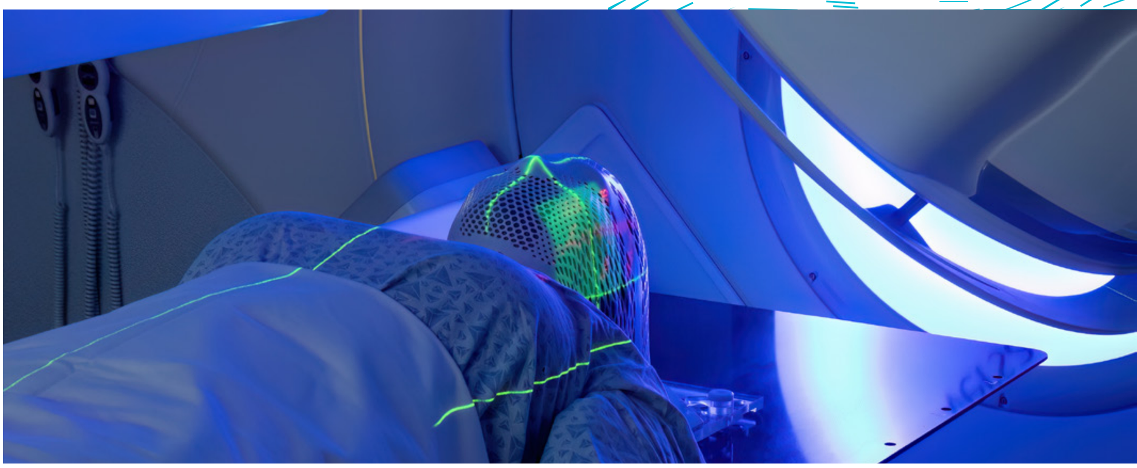
cases-important-to-nhs-health-and-care-provision/.

141. Innovate UK project 10072653, "Developing valuable operational healthcare applications using quantum computing techniques," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10072653#/tabOverview.

142. R. Ur Rasool, H. Ahmad, W. Rafique, A. Qayyum, J. Qadir and Z. Anwar, "Quantum Computing for Healthcare: A Review," Future Internet, vol. 15, no. 94, 2023.

143. NQCC, "Quantum Monte Carlo radiation transport simulation," 2023. [Online]. Available: https://www.nqcc.ac.uk/quantum-monte-carlo-radiation-transport-simulation/.

144. Association of the British Pharmaceutical Industry, "Time to Flourish - Inside Innovation: The Medicine



Quantum computing promises rapid simulation of the effects of new drugs through biomolecular modelling. It can also support current methods such as structure-based virtual screening and ligand-based virtual screening. The latter uses computational approaches, such as machine learning, to simulate drug reactions to different ligands. Quantum computing could allow simulation of more complex structures in less time.

Scientists can now use quantum computing to run feasibility studies into approaches for drug discovery. These do not aim to achieve immediate quantum advantage, but instead to explore suitable approaches, such as determining the right algorithm. This can provide helpful insights such as benchmarking performances against classical computing methods. Within the UK, these feasibility studies are mostly centred around protein folding and genomic simulation.

Hardware Compatibility for Drug Design

Different types of quantum computing hardware have differing compatibility with algorithms for drug design and discovery. In an early attempt to address this issue, IBM has installed a superconducting-circuit quantum computer, dedicated to biomedical research, at the Cleveland Clinic in the USA[145].

The collaborative, Innovate UK-funded Quantum Enhanced Computing Platform for Pharmaceutical (QuPharma) project, which began in 2022, aims to build a quantum computer to address the needs of the pharmaceutical industry[146]. It will combine specific quantum algorithms with high-performance computers whilst identifying use cases and their feasibility. It brings together Riverlane, NQCC, BASF, Merck, Oxford Instruments, Medicines Discovery Catapult, University of Oxford and the STFC's Hartree Centre; along with SEEQC, the main participant. The project finishes in 2025, and the consortium reports it could speed up the drug discovery process tenfold.

Scientists at Imperial College London, in collaboration with USTC in China, have built a quantum computer based on photons[147] that has run algorithms to simulate molecular docking and RNA folding. This device does not yet provide a quantum advantage over classical computers, due to photon loss, but it may provide a path to hardware that can perform more complex tasks.

Development Process," 2012. [Online]. Available: https://www.abpi.org.uk/media/h40bcxrq/medicine-development-process.pdf.

145. IBM, "Cleveland Clinic and IBM Unveil First Quantum Computer Dedicated to Healthcare Research," 20 March 2023. [Online]. Available: https://newsroom.ibm.com/2023-03-20-Cleveland-Clinic-and-IBM-Unveil-First-Quantum-Computer-Dedicated-to-Healthcare-Research#:~:text=The%20IBM%20Quantum%20System%20One,Cleveland%20Clinic%20accelerate%20biomedical%20discoveries.

146. Innovate UK ISCF project 10005792, "Quantum Enhanced Computing Platform for Pharmaceutical R&D - QuPharma," 2022. [Online]. Available: https://gtr.ukri.org/projects?ref=10005792#/tabOverview.

147. S. Yu, Z.-P. Zhong, Y. Fang, R. B. Patel, Q.-P. Li, W. Liu, Z. Li, L. Xu, S. Sagona-Stophel, E. Mer, S. E. Thomas, Y. Meng, Z.-P. Li, Y.-Z. Yang, Z.-A. Wang, N.-J. Guo, W.-H. Zhang and G. Tranmer, "A universal programmable Gaussian Boson Sampler for drug discovery," arXiv, 2023.

> “It is thought that a more accurate understanding of the chemical reactions that drive biological processes could lead to valuable innovations in drug discovery.”

Software for Drug Design and Discovery

It is thought that a more accurate understanding of the chemical reactions that drive biological processes could lead to valuable innovations in drug discovery. This can be achieved within a software package that simulates orbitals of atoms – the prediction of an electron’s position and wave-particle behaviour in regard to its corresponding atom – such as Density Functional Theory (DFT).

However, these approaches tend to only provide approximations, sacrificing accuracy for tangible results. More accurate approaches do exist but are limited by current computing processing power – sometimes meaning the simulation of only a small number of atoms is possible – but still takes a vast amount of time[148].

Quantum chemistry software enables more accurate simulations to run on a quantum computer. While simulating whole biological systems using these devices is likely to remain some years away, it is hoped that insights into the exact behaviour of smaller subsystems could accelerate or improve overall workflows.

Many quantum chemistry software platforms already exist. For example, Qiskit Nature, created by IBM, allows researchers to investigate protein folding and drug discovery[149]. The chemistry platform InQuanto, developed by the quantum computing company Quantinuum, enables researchers to explore the capabilities of today’s quantum computers and how they could accelerate the simulation of complex molecules, drugs and materials in the future[150].

148. N. S. Blunt, J. Camps, O. Crawford, R. Izsák, S. Leontica, A. Mirani, A. E. Moylett, S. A. Scivier, C. Sünderhauf, P. Schopf, J. M. Taylor and N. Holzmann, “Perspective on the Current State-of-the-Art of Quantum Computing for Drug Discovery Applications,” J. Chem. Theory Comput, vol. 18, no. 12, p. 7001–7023, 2022.

149. IBM Qiskit, “Qiskit Nature,” 2024. [Online]. Available: https://qiskit.org/ecosystem/nature/.

150. Quantinuum, “InQuanto,” 2022. [Online]. Available: https://www.quantinuum.com/computationalchemistry/inquanto.

A further example is the platform Qubec, developed by Qu&Co. In 2021, Qu&Co teamed up with Janssen Pharmaceuticals to develop and test quantum computational methods for pharma applications. They used Qubec to perform chemistry algorithms and investigate drug development[151]. In 2022, Qu&Co merged with PASQAL, a France-based company specialising in neutral atom quantum computing. Their current focus in quantum healthcare includes drug discovery as well as plasma treatment and structure-activity relationship analysis[152].

Error Correction

Error correction is an overarching problem for quantum computing, but it works best if tailored to a particular application. In 2021, Riverlane partnered with Astex and Rigetti, a company developing superconducting quantum computers, to examine quantum algorithms calculating exact positions of electron orbitals in drug molecules[153].

Previous attempts to do this suffered from noise, making simulations run very slowly. The partnership developed error correction software which, according to their calculations, will reduce the time to simulate 50 orbitals from roughly a thousand years to a few days[154].

Machine Learning and Quantum Machine Learning for Drug Design

Machine learning models are already being implemented to improve many stages of the drug discovery process. Quantum machine learning takes this process a step further, by combining machine learning with quantum algorithms. In this process, a machine learning algorithm is run on a classical computer and manages the input and/or the output to the quantum computer. This enables greater precision in analysis, faster training of models and continuous testing without human involvement, significantly speeding up the process of drug design.

Kuano Ltd was founded in 2020 with a vision to combine AI and quantum computing to accelerate and de-risk the design of effective drugs, specifically those targeting enzymes. The company's platform blends machine learning with quantum simulations of different enzymes, allowing the design of drugs that bind with greater efficiency and with fewer off-target effects.

In partnership with UCL, the company is now investigating drugs to target metalloenzymes using a variety of quantum algorithms[155]. This research is also in partnership with the National Quantum Computing Centre, which provides quantum computing resources and quantum computing algorithm development.

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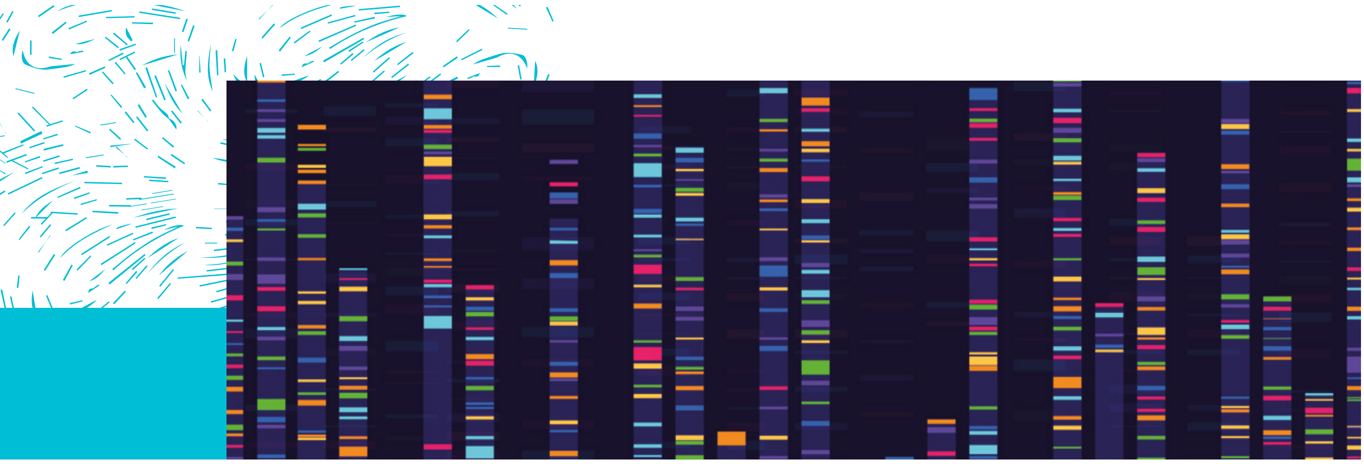
151. PASQAL, "Platform," 2024. [Online]. Available: https://www.pasqal.com/solutions/platform.

152. PASQAL, "Healthcare," 2024. [Online]. Available: https://www.pasqal.com/industry/healthcare/drug-discovery.

153. Riverlane, "Riverlane and Astex Pharmaceuticals join forces with Rigetti Computing to drive drug discovery forward," 13 July 2021. [Online]. Available: https://www.riverlane.com/press-release/riverlane-and-astex-pharmaceuticals-join-forces-with-rigetti-computing-to-drive-drug-discovery-forward.

154. N. S. Blunt, J. Camps, O. Crawford, R. Izsák, S. Leontica, A. Mirani, A. E. Moylett, S. A. Scivier, C. Sünderhauf, P. Schopf, J. M. Taylor and N. Holzmann, "Perspective on the Current State-of-the-Art of Quantum Computing for Drug Discovery Applications," J. Chem. Theory Comput, vol. 18, no. 12, p. 7001–7023, 2022.

155. Innovate UK project 10075020, "A next-generation quantum computing based approach to enzyme targeted drug discovery," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10075020.



In 2023, the STFC Hartree Centre in partnership with IBM Quantum Zurich used quantum machine learning for virtual screening of ligand-based interactions[156]. The results were run on IBM's Montreal and Guadalupe computers. This provided a slight advantage over classical approaches when screening a small sample, suggesting that a future device could manage the large samples required in practical screening.

Rahko, another spin-out from UCL, developed a quantum machine learning platform called Hyrax, a chemical simulation platform that allows multiple quantum algorithms to be run on a variety of devices. The company also partnered with UCL to investigate improving quantum algorithms' performance on current devices[157 158].

In 2022, Rahko was acquired by Odyssey Therapeutics, a US company specialising in precision medicine[159]. Odyssey Therapeutics has used this technology to investigate 'undruggable' proteins, whose structure means they cannot be targeted by conventional medicines. This could help in the development of new drugs, including cancer treatments.

In 2023, Capgemini partnered with the NQCC and GlaxoSmithKline to explore quantum machine learning for enhanced prediction of chemical reactions[160]. Tests were run on a quantum simulator, as well as IBM's Montreal quantum computer, to simulate reactions with sulfonyl fluoride covalent warheads. The team determined that this algorithm would work at scale on future quantum computing hardware[161].

156. S. Mensa, E. Sahin, F. Tacchino, P. K. Barkoutsos and I. Tavernelli, "Quantum machine learning framework for virtual screening in drug discovery: a prospective quantum advantage," Machine Learning: Science and Technology, vol. 4, no. 1, 2023.

157. EPSRC projcet - 2252518, "Quantum Simulations for Real Problems," 2019. [Online]. Available: https://gtr.ukri.org/projects?ref=studentship-2252518#/tabOverview.

158. EPSRC project - 2468302, "Exploring complexity and scalability of Near-term Quantum Computing algorithms for Quantum Chemistry," 2020. [Online]. Available: https://gtr.ukri.org/projects?ref=studentship-2468302#/tabOverview.

159. O. Therapeutics, "Odyssey Therapeutics Acquires Rahko, a Quantum Machine Learning Company," 2022. [Online]. Available: https://odysseytx.com/odyssey-therapeutics-acquires-rahko-a-quantum-machine-learning-company/.

160. Capgemini UK PLC, GSK, National Quantum Computing Centre (NQCC), "Data-driven reactivity prediction using computed quantum features for drug discovery," 2023. [Online]. Available: https://www.nqcc.ac.uk/data-driven-warhead-reactivity-prediction-using-computed-quantum-features-for-drug-discovery/.

161. T. W. A. Montgomery, P. Pogány, A. Purdy, M. Harris, M. Kowalik, A. Ferraro, H. Hasan, D. V. S. Green and S. Genway, "Data-driven reactivity prediction of targeted covalent inhibitors using computed quantum features for drug discovery," https://doi.org/10.48550/arXiv.2307.09671, 2023.

Protein Folding

Understanding how proteins fold can help scientists better understand some diseases – notably Alzheimer's – and provide better drug delivery. Advances have been made with AI prediction-based approaches such as AlphaFold[162], but challenges remain, including the limited variety of proteins that can be simulated and the financial cost of the computing power needed to train the algorithm[163]. Quantum computing could overcome these challenges and speed up the process of simulating protein folding.

In 2021, Quantinuum teamed up with Roche to investigate quantum computational techniques for simulating protein-ligand interactions[164]. Using the company's chemistry platform InQuanto[165], it was determined that a small-scale simulation was possible using existing quantum computers. Although this does not enable quantum advantage over existing methods, the paper suggests that InQuanto would be able to support scale-up of this process to a fault-tolerant quantum computer.

In 2023, Quantinuum looked at peptide binding to major histocompatibility complex molecules in partnership with Amgen[166]. This is an important process in immune response, and further understanding of this could unlock novel therapeutics.

162. J. Jumper, R. Evans, A. Pritzel and e. al., "Highly accurate protein structure prediction with AlphaFold," Nature, vol. 596, p. 583–589, 2021.

163. S. Boulebnane, X. Lucas, A. Meyder and S. A. a. A. Montanaro, "Peptide conformational sampling using the Quantum Approximate Optimization Algorithm," npj Quantum Information, vol. 9, no. 70, 2023.

164. J. J. M. Kirsopp, C. D. Paola, D. Z. Manrique, M. Krompiec, G. Greene-Diniz, W. Guba, A. Meyder, D. Wolf, M. Strahm and D. M. Ramo, "Quantum Computational Quantification of Protein-Ligand Interactions," International Journal of Quantum Chemistry, vol. 122, no. 22, 2022.

165. Quantinuum, "InQuanto," 2022. [Online]. Available: https://www.quantinuum.com/computationalchemistry/inquanto.

166. C. London, D. Brown, W. Xu, S. Vatansever, C. J. Langmead, D. Kartsaklis and S. Clark, "Peptide Binding Classification on Quantum Computers," https://doi.org/10.48550/arXiv.2311.15696, 2023.

"Potential applications include vaccine design and transplants, assisting in the understanding of autoimmunity and cancer development."

The team compared quantum and classical models in a classification task relevant to the design of therapeutic peptides. They determined that their simulation could run on their own H1-1 quantum computer, based on trapped ions, with comparable performance to classical simulations. The team says that this proof of concept could scale in the future, with potential applications to aid vaccine design and transplants whilst assisting in the understanding of autoimmunity and cancer development.

In 2023, Vorsus was awarded funding by Innovate UK to help develop quantum computational toolkits that will accelerate protein drug discovery[167]. They have addressed the technical feasibility of developing specific and highly efficient quantum computational methods and algorithms for predicting key protein properties.

Genomic Simulation

It is thought that only 2% of DNA is responsible for coding proteins[168]; the remainder is non-coding DNA. Mutations in some of its sequences are linked to cancer, so understanding this portion of DNA could open a new route for cancer drug discovery. However, the simulation of non-coding DNA is a relatively new field. Advances have been made with AI programmes such as DNA Bert[169], but quantum computing could provide more accurate simulations.

Advanced Medicals is a company hoping to create more efficient ways for quantum computers to simulate processes connected to non-coding DNA[170]. It is investigating hybrid quantum transformer architectures, and plans to compare the results to classical simulations to determine whether there is a quantum advantage.

Quantum Base Alpha, in collaboration with the Medicines Discovery Catapult, is looking at future pathogenic epidemics, which the World Health Organisation calls Disease X. The project uses the University of Edinburgh's computing facility, which includes the UK's largest supercomputer, to simulate a quantum computer[171]. It is hoped that this approach could identify regions of non-coding DNA as good targets for drug development.

A group at the University of Cambridge was awarded funding under the Quantum for Bio competition run by Wellcome Leap. This 30-month competition involves investigating human and pathogen quantum pangenomics[172]. The Cambridge project looks at applying quantum algorithms to simulate genome assembly and sequence alignment, which are to be run on quantum computers expected to be available between 2026 and 2028.

167. Innovate UK project 10082522, "Quantum-Accelerated Recombinant Protein Drug Embedding Frameworks (QARPDEF)," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10082522.

168. The ENCODE Project Consortium., "An integrated encyclopedia of DNA elements in the human genome," Nature, vol. 489, p. 57–74, 2012.

169. Y. Ji, Z. Zhou, H. Liu and R. V. Davuluri, "DNABERT: pre-trained Bidirectional Encoder Representations from Transformers model for DNA-language in genome," Bioinformatics, vol. 37, no. 15, p. 2112–2120, 2021.

170. Innovate UK project 10075813, "Hybrid Quantum Transformer Architectures in Genomics," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10075813.

171. Innovate UK project 10083188, "Utilising Quantum Machine Learning and quantum computing for genomic research and development," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10083188.

172. Welcome Leap, "Quantum for Bio," 2023. [Online]. Available: https://wellcomeleap.org/q4bio/program/#:~:text=The%20Wellcome%20Leap%20Quantum%20for,address%20pressing%20human%20health%20challenges.

Scaling for Specific Drug Discovery

Some projects are investigating how to use existing quantum computers for specific drug discovery applications.

Another winner of the Quantum for Bio competition is a project run by the University of Nottingham, in partnership with QuEra and Phasecraft, a spin-out of University College London and the University of Bristol. The project is investigating new drugs for people suffering from myotonic dystrophy[173 174], and aims to develop quantum algorithms suitable for the simulation of such a drug. The collaboration with QuEra allows access to the company's quantum computing hardware; in the latter half of 2023, it announced a device with 48 logical qubits[175].

Kuano has been awarded funding to discover potential drug candidates to treat metastatic bowel cancer[176]. It has deployed a hybrid quantum simulation/AI platform to model the Notum enzyme, a recently identified target for bowel cancer therapies, and used the results to design inhibitory compounds that have proved effective in both cellular and early *in vivo* studies. It is hoped that this can provide a shortlist of candidates that could be used in future trials.

173. Phasecraft, "Phasecraft partners with University of Nottingham and QuEra to accelerate applications of quantum computing to human health," 28th September 2023. [Online]. Available: https://www.phasecraft.io/news/phasecraft-nottingham-quera-wellcome.

174. Welcome Leap, "Quantum for Bio," 2023. [Online]. Available: https://wellcomeleap.org/q4bio/program/#:~:text=The%20Wellcome%20Leap%20Quantum%20for,address%20pressing%20human%20health%20challenges.

175. D. Bluvstein, S. Evered, A. Geim and e. al., "Logical quantum processor based on reconfigurable atom arrays," Nature, 2023.

176. Innovate UK project: 10038464, "Streamlined and Targeted Design of NOTUM Inhibitors as Colorectal Cancer Drugs," 2022. [Online]. Available: https://gtr.ukri.org/projects?ref=10038464.

Quantum Communication and Security

Cyber attacks can be highly disruptive to the UK health service, as the virus WannaCry demonstrated in 2017. Attacks similar to WannaCry, which exploited vulnerabilities in Microsoft's operating systems, can be prevented with sufficient user training and malware protection, but it is becoming harder to protect against other cyber threats including the safe transmission and storage of data.

Quantum technology can provide a form of ultra-secure communication. Quantum networking, where two or more devices are linked together via quantum mechanics, creates the foundations of quantum communication. This can benefit the healthcare industry through protocols such as quantum key distribution (QKD) and quantum-secure algorithms known as post-quantum cryptography, to protect patient information by preventing data from being leaked or decrypted.

Compared with the other two quantum technology areas already covered, quantum networking is likely to have a less direct impact on the healthcare industry, but it will become more important as other technologies develop. For example, the development of quantum computers could see them able to crack RSA encryption, which is commonly used today.

What is QKD?

Quantum key distribution (QKD) can distribute cryptographic keys securely, in a way that an eavesdropper cannot intercept without revealing their presence. This is achieved by exploiting entanglement between pairs of photons, meaning when a photon is intercepted, this can be detected via the other. Once the attack has been identified, a new channel can be established.

Quantum networks can also help hospitals and medical facilities to access quantum computers through an approach called distributed quantum computing which connects many devices, increasing their computational power. This could enable diagnostic devices to exploit the power of quantum computers to perform computationally demanding tasks. As well as enhancing existing approaches such as radiotherapy, this could lead to entirely new types of medical devices.

Protecting Sensitive Training Data for Quantum Machine Learning

In machine learning, it is necessary to share training data to ensure highly accurate algorithms. However, the sensitive nature of some data, especially in a healthcare environment, could prevent machine learning applications from being developed.

In 2023, Zaiku Group worked with the NQCC to investigate this problem under the project Quantum Machine Learning for Genomics Data[177]. A cloud-based proof of concept was created to train quantum machine learning algorithms without revealing sensitive data.

This work has continued under the 'Feasibility Studies in Quantum Computing Applications' competition run by Innovate UK[178]. This project aims to integrate the current work with fully homomorphic encryption and quantum machine learning, which could also help health organisations to save money by preventing data breaches[179]. It is due to finish in 2024.

Protecting Patient Information

Qubitl, an India-based company with an office in the UK, is working on a platform to securely store patient information using quantum communication and quantum cryptographic methods[180], aiming to prevent fraud in the healthcare sector.

177. Zaiku Group Ltd, North East Yorkshire Genomics Lab Hub, National Quantum Computing Centre (NQCC), "Federated quantum machine learning for genomics data," 2023. [Online]. Available: https://www.nqcc.ac.uk/federated-quantum-machine-learning-for-genomics-data/.

178. Innovate UK project 10072286, "Security-first Federated Quantum Machine Learning for Genomics," 2023. [Online]. Available: https://gtr.ukri.org/projects?ref=10072286.

179. ISCF Project: 10002147, "Sakurai: A Quantum Error Mitigation Platform-as-a-Service for Privacy-Preserving Genomics Data Analysis," 2021. [Online]. Available: https://gtr.ukri.org/projects?ref=10002147.

180. Qubitl, "HealthCetra - our Quantum Cryptographic Medical Info-DAPP," 2024. [Online]. Available: https://www.qubitl.com/implementation.

> "The sensitive nature of some data, especially in a healthcare environment, could prevent machine learning applications from being developed."

Conclusion

Companies are pushing towards the commercialisation of quantum applications in healthcare and life sciences, from wearable brain scanners to algorithms that simulate novel drugs for myotonic dystrophy and bowel cancer. Meanwhile, education institutions are investigating long-term solutions, imaging through the body with light and biomonitoring on the nanoscale.

Quantum computing for drug design is growing at a rapid pace, thanks to major advances in hardware and error correction. Funding from the National Quantum Technology Programme will help more applications develop to the point of commercialisation and support further research from spin-out companies and established organisations.

Three companies mentioned in the quantum computing section have either been acquired or gone through mergers. This could allow for greater access to resources and international collaboration; however, in the case of acquisitions, this also means the loss of IP within the UK.

Quantum sensing for healthcare applications has seen an explosion of research since 2020. Promising solutions include the identification of cancer, namely breast, but also detecting traces of various cancers within the blood, indiscriminate glucose monitoring and monitoring epilepsy. The technologies providing these solutions are projected to be available in the latter half of this decade.

But despite the promising signs of near-term deployment and world-leading research in the UK, this industry has a large amount of untapped potential, and a long and perilous road to commercialisation ahead. A few relatively simple initiatives could support the adoption of quantum technologies beyond these select few examples, benefitting both healthcare and quantum companies.

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