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Newcastle University

A horizon scan of emerging quantum technologies for use in healthcare

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Date: 23rd July 2024

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Key findings

- We identified 116 quantum health technologies in development across 32 clinical trials, 565 published journal articles and 81 soft intelligence articles.

- Over half of these technologies are currently used or intended to be used clinically to assist in the diagnosis of health conditions.

- Activity has been steadily increasing in published literature and trial initiations for quantum health technologies over the last two decades.

- There are high levels of activity in quantum computing applications, particularly to facilitate drug discovery and design, and precision medicine implementation.

- Magnetoencephalography (MEG), quantum dots and superconducting quantum interference devices (SQUID) were the technologies that appeared the most during scanning.

Background

Quantum computing is an emerging field that has the potential to tremendously progress computation in fields of science and technology.[1,2] It stems from the principles of quantum mechanics, often explained through concepts of superposition, interference and entanglement, and uses a fundamentally different approach than classical computing.[2,3] For example, in quantum computing, superposition allows quantum bits, or qubits, to exist in multiple states simultaneously, unlike classical bits which can only be 0 or 1. This means a qubit can represent both 0 and 1 at the same time, exponentially increasing the potential computational power. Consequently, algorithms can process vast amounts of data more efficiently than traditional computers.[4] Quantum entanglement is a phenomenon where two or more qubits become interconnected in such a way that the state of one qubit instantly influences the state of the other, regardless of the distance between them. This interconnectedness allows for the transfer of information with unprecedented speed and security. It is one of the foundational principles that enable quantum computers to perform complex calculations more efficiently than classical computers.[5]

These concepts have enabled the development of applications in quantum computing and quantum sensing, which have shown the potential of processing large-scale data and solving other complex tasks, offering valuable applications to healthcare, medicine and biomedical research.[2,3] Research and development in technologies utilising quantum mechanics, particularly quantum computing, has rapidly progressed in recent years.[6] The significantly greater computational power offered by quantum computing may be applied to medical domains such as genomics, diagnostics and drug discovery and design.[6,7] However, integrating quantum computing into medical fields comes with significant challenges. These include the current instability of quantum systems, the need for specialised hardware and software, and the necessity of training medical professionals to understand and utilise this advanced technology. Overcoming these obstacles will be crucial for fully realising the potential of quantum computing in healthcare.

In 2023, the UK Government published the National Quantum Strategy, a ten-year plan consisting of funding, support and preparation for quantum technologies that are expected to revolutionise many aspects of life. Healthcare is highlighted as a key aspect where the impact of “quantum technology” is expected to be greatest. “Quantum technology” refers to a highly diverse set of technologies that leverage “quantum mechanics”, the physics of sub-atomic particles.[8] Of particular interest, Mission 3 of the National Quantum Strategy aims to provide quantum sensing-based solutions for all NHS trusts to improve patient outcomes by 2030.[9] The National Quantum Strategy has catalysed interest in understanding the emerging landscape of quantum technologies in health care.

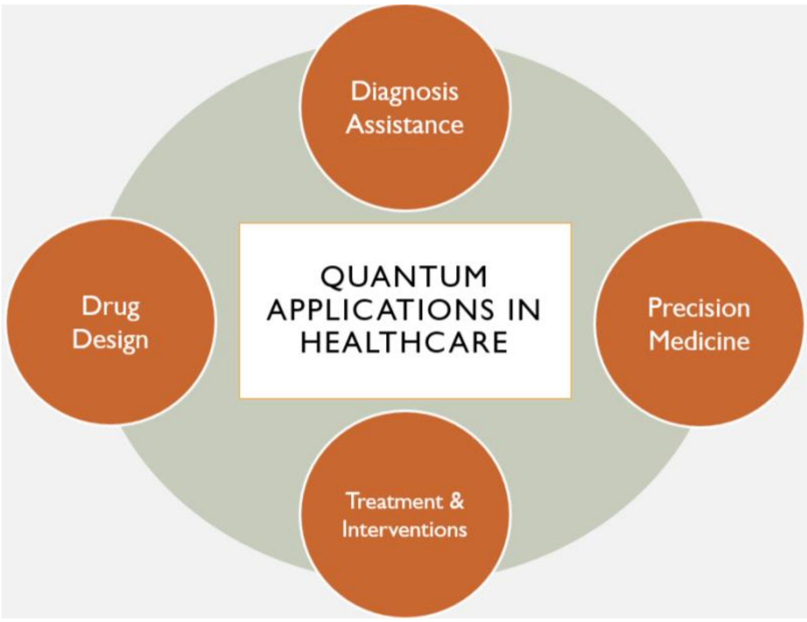

Figure 1 – Quantum applications in healthcare

Quantum applications in healthcare include drug discovery and design, diagnosis assistance, precision medicine, and treatment interventions, as shown in Figure 1.

Drug Discovery and Design

Quantum computing can significantly accelerate the drug discovery process by simulating complex molecular interactions with unprecedented accuracy. This allows researchers to identify potential drug candidates faster and more efficiently than traditional methods. Consequently, the development of new treatments for diseases could be expedited, potentially saving countless lives.[10] For instance, a quantum computing algorithm recently helped identify a promising compound for treating a rare genetic disorder called cystic fibrosis. By accurately modelling the behaviour of the defective protein involved, researchers were able to pinpoint a molecule that could effectively restore its function, paving the way for new therapeutic options.[11] Quantum technology excels at molecular simulations, predicting drug behaviour and properties, thus enhancing in-depth drug understanding and enabling drug design with more precision.[12]

Diagnosis Assistance

Quantum technology can analyse vast amounts of medical data with exceptional speed and accuracy, leading to earlier and more accurate diagnoses. For instance, quantum sensors may offer unprecedented sensitivity in diagnostic procedures, allowing for the detection of biomarkers at previously unattainable levels.[10] Quantum sensors have found an increasingly pivotal role within the healthcare landscape, demonstrating their prowess in the detection of biomarkers, monitoring cellular activities, and an array of diagnostic functions.[10] This capability enhances the ability of healthcare professionals to diagnose conditions such as cancers or neurological disorders at an earlier stage. Additionally, some studies have utilised quantum dots to trace specific proteins within cells, aiding in early disease detection and a better understanding of cellular processes.[10]

Precision medicine

With quantum applications, precision medicine can tailor treatments to the unique genetic makeup of each patient, leading to more effective and personalised therapies. This approach can significantly reduce adverse drug reactions and improve overall treatment outcomes. Additionally, quantum computing can analyse vast amounts of genetic data at unprecedented speeds, accelerating the development of new, targeted therapies. For instance, quantum machine learning (ML) and artificial intelligence (AI) algorithms are promising experimental technologies that can improve precision medicine applications by reducing the computational complexity of algorithms driven by big, unstructured, real-world data.[13]

Treatment and interventions

Quantum applications are also being utilised as direct interventions not only used for diagnosis, but also as treatment options. For instance, quantum molecular resonance (QMR) is a technique in which low-intensity, high-frequency electric currents are administered to a target biological tissue through contact electrodes. Studies have shown this technique to be an effective treatment option for indications such as dry eye disease.[14] These innovations often utilise core properties of quantum mechanics and are paving the way for novel therapy options to be introduced in patient care pathways going forward.

Aims

- Provide a comprehensive overview of emerging quantum technologies in all stages of development for use in the healthcare sector.
- Identify quantum technologies that could be utilised in the healthcare sector by reviewing clinical trials, published literature, and soft intelligence sources.
- Analyse the classifications, development status and activity levels of quantum technologies in development.

Methods

We conducted searches looking for quantum technologies in three distinct data sources: clinical trials, published literature and soft intelligence.

Clinical trials

Clinical trial searches were conducted on two registries: Clinicaltrials.gov[15] and the World Health Organisation's International Clinical Trials Registry Platform (ICTRP).[16] The following search terms were used on both registries: *(Quantum OR "quantum technology" OR "quantum technologies" OR "quantum medical technology" OR "quantum medical technologies" OR "quantum health technology" OR "quantum health technologies" OR "quantum application" OR "quantum applications" OR "quantum computing" OR "quantum computer" OR "quantum device" OR "quantum devices").*

Searches on Clinicaltrials.gov and ICTRP were conducted on 15th April 2024. The Clinicaltrials.gov search returned 260 trials and the ICTRP search returned 193 trials. The trials were deduplicated to create a single dataset for screening. The final screening dataset contained 284 clinical trials.

A pilot of ten clinical trials were screened by three individual researchers to ensure agreement in decisions. After agreement was confirmed, three researchers single-screened 284 clinical trials. Any clinical trial that was testing at least one quantum technology that is in early development, in clinical testing, or approved for the treatment, prevention or diagnosis of a health condition was eligible for inclusion.

The following information was extracted from the clinical trials for inclusion in our final dataset: *Trial identifier; Trial URL; Trial registry; Trial title; Technologies tested; Trial condition(s); Trial type; Trial design; Trial status; Trial start date; Trial primary completion date; Trial phase; Trial participants; Trial sponsor; Trial funder type; Trial locations (countries).*

Published literature

Published literature searches were conducted using two bibliographic databases: MEDLINE and Scopus. A detailed search strategy is available in Appendix A.

A search on Scopus was conducted on 8th May 2024, which returned 449 articles. A search on MEDLINE was conducted on 14th June 2024, which returned 1717 articles. These articles were deduplicated together to leave 2166 articles and uploaded to Rayyan, a web-based tool often utilised in systematic reviews.[17] Three screeners single-screened all articles. Any article that mentions in the title or abstract a quantum technology or technologies, or a technology or technologies that potentially utilise quantum mechanics were eligible for inclusion. Articles must also refer to technologies that are in early development, in clinical testing, or approved for the treatment, prevention or diagnosis of a health condition.

The following information was extracted from the published literature for inclusion in our final dataset: *Trial title; Abstract; Year; Authors; doi; Relevant technologies; Health conditions.*

Soft intelligence

We used the NIHR Innovation Observatory's in-house google news retrieval tool to retrieve news articles for 25 search queries, each time retrieving up to 100 articles published between 03/06/2023 and 03/06/2024. The following query search terms were used in the tool: *quantum technologies*, *quantum medical technology*, *quantum medical technologies*, *quantum health technology*, *quantum health technologies*, *quantum application*, *quantum applications*, *quantum computing*, *quantum computing applications*, *quantum computer*, *quantum device*, *quantum devices*, *quantum sensing* ,*quantum sensors*, *quantum machine learning*, *medical quantum solutions*, *healthcare quantum solutions*, *medical quantum applications*, *healthcare quantum applications*, *quantum algorithm*, *quantum algorithms*, *quantum computing software*, *quantum computing hardware*, *quantum artificial intelligence*, *quantum AI*.

The tool implements an unsupervised ranking algorithm that orders likely relevant articles to the top if they were retrieved by multiple queries and if they were among the first articles retrieved by each search. We retrieved 1,262 articles, which were single screened manually by a reviewer. During screening, we read titles and skimmed article full texts as retrieved by the tool, including 254 articles per the initial title and description screening, and a final dataset of 81 records that specifically met our inclusion criteria. In rare cases the tool was unable to retrieve the full text, then we followed article links to view the news articles online.

The following information was extracted from the soft intelligence news retrieval tool for inclusion in our final dataset: T*itle; Description; Media; URL link; Date of publication; Full text; Number of Appearances.*

Data collection

Following our three searches, data regarding the technologies identified in any one of clinical trial, published literature or soft intelligence, were added to a dataset of all technologies. Data was collected for technologies independently by three researchers from information sources including developer websites and soft intelligence articles. Based on observations from the published literature, we created a novel technology classification system for technology types.

The following information was extracted or collected for technologies: *Name of technology; Developer name; Developer website URL; Technology utility classification; Technology quantum application; Potential health conditions; Country of development; AI component?; Intended use/setting; Overall regulatory approval?; Number of clinical trials; Associated clinical trials; Number of journal articles; Associated journal articles; Number of soft intelligence articles; Associated soft intelligence articles; Total identifications of technology.*

Descriptive analyses were conducted for all data sets.

Results

Quantum technologies

Our scan identified 116 technologies utilising quantum mechanics that are currently used or have the potential to be used in healthcare (Table 1). The technologies were discovered through one of, or a combination of, clinical trials, published literature or soft intelligence articles.

Name of technology	Technology classification	Total identifications of technology
1. Magnetoencephalography (MEG)	Diagnosis assistance	362
2. Quantum dots	Diagnosis assistance	105
3. Superconducting quantum interference device (SQUID)	Diagnosis assistance	28
4. Quantum computing	Precision medicine	14
5. Quantum molecular resonance (QMR) device	Treatment and interventions	13
6. Rexon-Eye	Treatment and interventions	7
7. Quantum machine learning	Precision medicine	4
8. CdTe Quantum dot	Diagnosis assistance	3
9. Optically Pumped Magnetometer (OPM)	Diagnosis assistance	3
10. Cytotron	Treatment and interventions	3
11. Pulsed Electromagnetic Field Therapy	Treatment and interventions	3
12. Ag2S quantum dot	Diagnosis assistance	2
13. Carbon quantum dots	Diagnosis assistance	2
14. Fluorescence microscopy (quantum dots)	Diagnosis assistance	2
15. Magnetic Resonance Imaging (MRI)-based Quantitative Susceptibility Mapping (QSM)	Diagnosis assistance	2
16. Optical Pumping Magnetometer Sensors	Diagnosis assistance	2
17. Photonic quantum technologies	Diagnosis assistance	2
18. Quantum imaging	Diagnosis assistance	2
19.Quantum magnetic field sensor	Diagnosis assistance	2
20. Aurora	Drug design	2
21. Quanvolutional neural network	Precision medicine	2
22. Quantum neural network	Precision medicine	2
23. Quantum-Enhanced AI	Precision medicine	2
24. Quantum cascade laser	Treatment and interventions	2
25. Quantum hemotherapy	Treatment and interventions	2
26. Quantum light therapy	Treatment and interventions	2
27. Structured light imaging microscopy	Treatment and interventions	2
28. 7T MRI	Diagnosis assistance	1
29. 7Teslas NMR Spectroscopy	Diagnosis assistance	1
30.Ag2Se quantum dot	Diagnosis assistance	1
31. aZnO quantum dot	Diagnosis assistance	1
32. Black phosphorus quantum dot	Diagnosis assistance	1
33. CdS quantum dot	Diagnosis assistance	1
34.CdSe quantum dots	Diagnosis assistance	1
35. CdSe/ZnS-COOH quantum dot	Diagnosis assistance	1
36. Diamond magnetometry	Diagnosis assistance	1
37. DSPE-PEG-TPP-MoS2 quantum dot	Diagnosis assistance	1
38. Gold quantum dot	Diagnosis assistance	1
39. gp85-carbon quantum dot	Diagnosis assistance	1
40. Graphene quantum dots combined with Si nanowire photoelectrochemical immunosensor	Diagnosis assistance	1
41. InGaAs/GaAs quantum dots	Diagnosis assistance	1
42. MRI	Diagnosis assistance	1
43. Nanocrystal quantum dot	Diagnosis assistance	1
44. Nitrogen-doped graphene quantum dot	Diagnosis assistance	1
45. QI Model 1.0 Magentocardiogram	Diagnosis assistance	1
46. Quantum denoising	Diagnosis assistance	1

47. Quantum dot nanobeads	Diagnosis assistance	1
48. Quantum dot-DNA bioconjugate	Diagnosis assistance	1
49.Quantum molecular resonance (QMR) imaging	Diagnosis assistance	1
50. Quantum walks	Diagnosis assistance	1
51. Siemens Naeotom Alpha	Diagnosis assistance	1
52. Silicon nanowires	Diagnosis assistance	1
53. Superconducting biosusceptometry	Diagnosis assistance	1
54. VitalScan MCG	Diagnosis assistance	1
55. Zinc oxide quantum dots	Diagnosis assistance	1
56. ZnCdSe/ZnS quantum dot	Diagnosis assistance	1
57. Quantum optics	Diagnosis assistance	1
58. Quantum sensing	Diagnosis assistance	1
59. Quantum microscope	Diagnosis assistance	1
60. Quantum electromagnetic sensors	Diagnosis assistance	1
61. Quantum parallel processing	Diagnosis assistance	1
62.Optical nanotransducers	Diagnosis assistance	1
63. Quantum dot laser	Diagnosis assistance	1
64. Quantum diamond sensor	Diagnosis assistance	1
65. Optically pumped magnetic gradiometer (OPMG)	Diagnosis assistance	1
66. Entanglement-enhanced multiphoton fluorescence imaging	Diagnosis assistance	1
67, Integrated squeezed-light magneto-optical sensor	Diagnosis assistance	1
68. Nanodiamond quantum sensing	Diagnosis assistance	1
69. Quantum sensing with strongly nonclassical light based on third-order nonlinearities	Diagnosis assistance	1
70. Magnetic-Field Quantum Sensors	Diagnosis assistance	1
71. Quantum-Enhanced Diamond Molecular Tension Microscopy (QDMTM)	Diagnosis assistance	1
72. Quantum 3D imaging	Diagnosis assistance	1
73. Diamond quantum sensing	Diagnosis assistance	1
74. Nuclear magnetic resonance device	Diagnosis assistance	1
75. Diamond quantum sensors	Diagnosis assistance	1
76. Nvision Polariser	Diagnosis assistance	1
77. Diamond quantum sensor with NMR	Diagnosis assistance	1
78. 2C-QD	Diagnosis/Treatment	1
79. 5-FU@FACS-	Diagnosis/Treatment	1
80. Aspirin-based carbon dot	Diagnosis/Treatment	1
81. Quantum dots coated with veldoreotide	Diagnosis/Treatment	1
82. Q4Bio program	Drug design	1
83. Quantum communication	Drug design	1
84. IBM Quantum System One computer	Drug design	1
85. Electron paramagnetic resonance (EPR) spectroscopy	Drug design	1
86. Hybrid high performance computing-quantum computing (HPC-QC)	Drug design	1
87. Quantum software for drug discovery	Drug design	1
88. Hybrid quantum-classical machine learning	Drug design	1
89. Quantum enabled cell-centric therapeutics	Drug design	1
90. Quantum sensing platform for biomolecular analytics	Drug design	1
91. NVIDIA Quantum Cloud	Drug design	1
92. Quantum Refinement	Drug design	1
93. AQBioSim	Drug design	1
94. Hybrid Quantum-Classical Algorithm	Drug design	1
96. Molecular simulation quantum AI	Drug design	1
96. FATHOM	Drug design	1
97. QUEST-ADMET	Drug design	1
98. Measurement-device-independent quantum key distribution (MDI-QKD)	Precision medicine	1
99. Quantum computing and quantum machine learning	Precision medicine	1
100. Quantum algorithms and quantum computers	Precision medicine	1
101. Quantum Random Number Generator	Precision medicine	1
102. Quantum approximate optimization algorithms (QAOA)	Precision medicine	1
103. Quantum algorithm	Precision medicine	1
104. Quantum AI	Precision medicine	1
105. Shors algorithm	Precision medicine	1
106. Quantum annealing (QA)-based algorithm (D-wave quantum computing)	Precision medicine	1
107. PennyLane quantum programming software	Precision medicine	1
108. Bio-Qi	Treatment and interventions	1
109. D-xyl@ÎµPL carbon dots	Treatment and interventions	1

110. N-acetyl-l-cysteine (NAC)-derived red fluorescent carbonized polymer dots	Treatment and interventions	1
111. Quantum Code Technology TM	Treatment and interventions	1
112. Quantum molecular resonance	Treatment and interventions	1
113. Superparamagnetic chitosan nanoparticles (SPCIONPs)	Treatment and interventions	1
114. Vinblastine loaded graphene quantum dot	Treatment and interventions	1
115. Superconducting Technology for Heavy-ion Radiotherapy System	Treatment and interventions	1
116. Gold nanoparticles coated with redox-active molecules	Treatment and interventions	1

Table 1 - Selected characteristics for all identified quantum health technologies

Table 1 illustrates that, throughout the scanning process, magnetoencephalography (MEG), quantum dots, and superconducting quantum interference devices (SQUIDs) emerged as the most frequently used technologies. Magnetoencephalography (MEG) measures the magnetic fields produced by neural activity in the brain. This allows researchers to map brain function with high temporal resolution. It is particularly useful for identifying regions involved in sensory processing and motor planning.[18] Quantum dots are semiconductor particles that have unique electronic properties due to their nanoscale size. They are used in various applications, including medical imaging, solar cells, and quantum computing, due to their ability to emit light at specific wavelengths when excited. Their versatility and efficiency make them a crucial component in advancing nanotechnology and material science.[19] Superconducting quantum interference devices (SQUID) are highly sensitive magnetometers used to measure extremely subtle magnetic fields. By exploiting the principles of quantum mechanics, SQUIDs can detect changes in magnetic fields with extraordinary precision.[20] This makes them invaluable in medical imaging experiments.

Over half of the quantum health technologies identified were classified as diagnosis assistance interventions (n=63, 54%). Seventeen (15%) technologies were in use or being developed for drug design and a different seventeen (15%) technologies are used for treatment and intervention. Fifteen (13%) technologies were classified as precision medicine and four technology (3%) could be used for both diagnosis and treatment of health conditions (Figure 2).

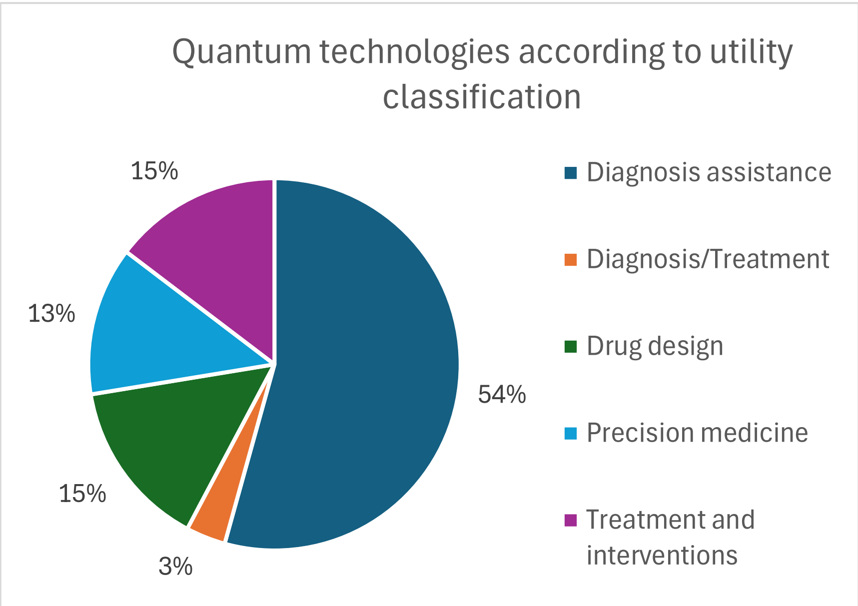

Figure 2 - Quantum health technologies by utility classification

The majority of technologies were in use or are likely to be used in a clinical setting. Sixty-one (53%) technologies were classified as clinical use only and a further forty-two (36%) technologies were considered as potentially useable in clinical and non-clinical settings. Only nine (8%) technologies were classified as non-clinical use only, with four (3%) of technologies having unknown potential use at this stage (Figure 2).

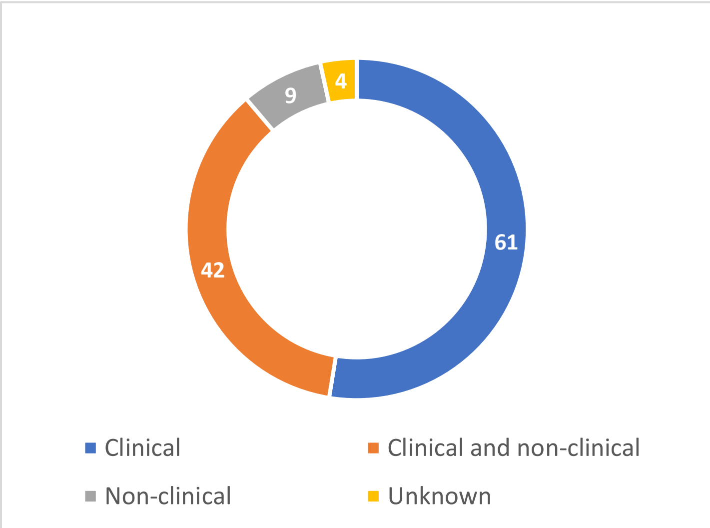

Figure 3 - Current or potential use setting for quantum health technologies

Of the 116 identified technologies, thirty-one (27%) were considered to potentially have a component of AI within their mechanism of action. This group mainly consists of technologies to facilitate personalised medicine and imaging diagnosis, such as quantum machine learning algorithms, and highly powered quantum computing applications to power drug discovery and design.

Quantum computing (n = 33, 28%) and quantum dots (n = 28, 24%) were found to be the most common quantum application type of the technologies in our scan. This was closely followed by quantum sensing (n = 20, 17%) and quantum imaging (n = 19, 16%). Only six technologies were considered to be utilising quantum resonance (n = 6, 5%) (Figure 4).

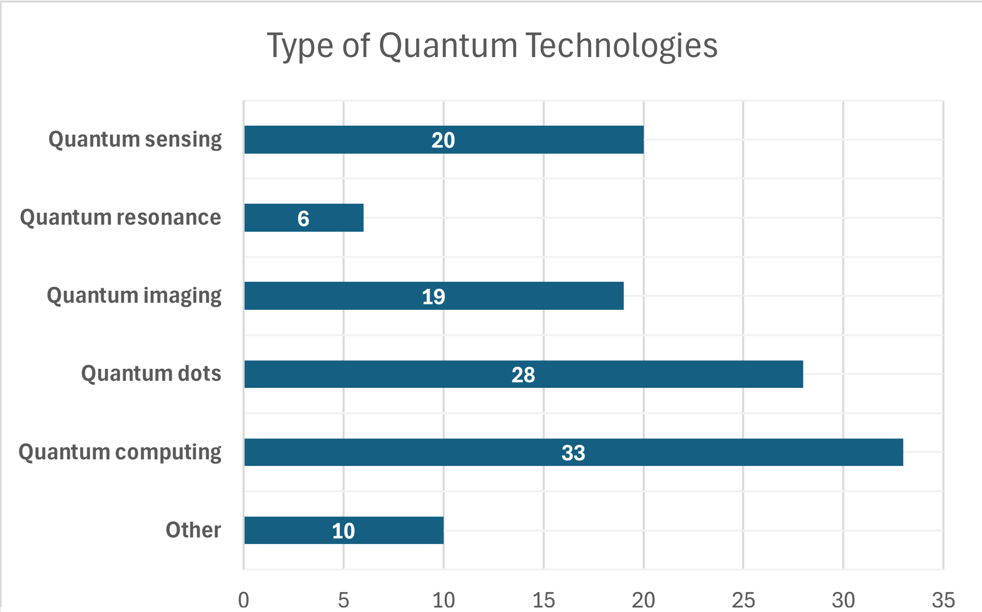

Figure 4 - Health technologies by quantum application type

Published literature

We included 565 published journal articles in our scan that referred to a quantum technology for use in healthcare. A clear increase in publishing activity was identified for quantum health technologies within the last two decades. Starting around the mid-2000's, there were yearly increases in publishing activity, peaking at forty-one (7%) articles in 2016, and remaining high to the present year (Figure 5). NeuroImage was the journal that had published the most articles (n= 42, 7%), with high publishing activity in PLoS ONE (n = 17, 3%), Clinical Neurophysiology (n = 13, 2%) and Human Brain Mapping (n = 12, 2%).

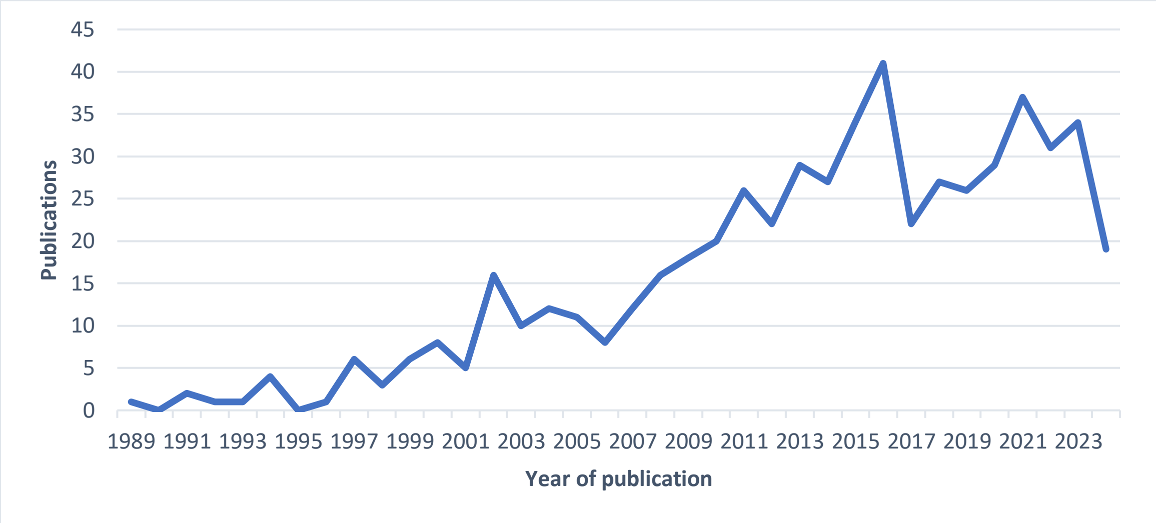

Figure 5 - Number of published articles referring to quantum health technologies by year

Clinical trials

Our scan identified thirty-two clinical trials testing potential quantum technologies for use in healthcare. Twenty-five unique technologies were to be or had been tested in the trials. Only four technologies appeared in more than one trial: Rexon-Eye (n = 5), Cytotron (n = 3), Pulsed electromagnetic field therapy (PEMF) (n = 3) and Optical Pumping Magnetometer (OPM) sensors (n = 2). Rexon-Eye is a non-invasive treatment designed to address dry eye syndrome using low-energy electric fields. It aims to stimulate the regeneration of damaged cells in the ocular surface, promoting natural healing without the need for drugs or surgery.[21] This technology has shown promising results in multiple clinical trials.

The majority of trials were identified on the Clinicaltrials.gov registry (n = 26, 81%), with the remaining trials posted on Chinese Clinical Trial Registry (ChiCTR) (n = 3, 9%), Clinical Trials Registry India (CTRI) (n = 2, 6%) and Australia New Zealand Clinical Trial Registry (ANZCTR) (n = 1, 3%). Twenty-six (81%) trials were of interventional design and six were observational trial designs (19%). Interventional trial designs involve actively applying a treatment or intervention to participants to assess its effects, often through controlled environments and randomisation. In contrast, observational trial designs do not involve any intervention; instead, researchers simply observe and collect data on participants' health outcomes without manipulating the study environment. This distinction is crucial for understanding the types of data and results each trial can produce.

Twenty-eight (88%) trials were run by non-commercial sponsors, while the remaining four (13%) trials had commercial sponsors. Non-commercial sponsorship typically involves academic institutions, government agencies, or non-profit organisations, which may focus more on the scientific and public health benefits rather than profit. Commercial sponsorship, on the other hand, often comes from pharmaceutical companies or medical device manufacturers that may have a vested interest in the commercial success of the technology. The predominance of non-commercial sponsors in these trials suggests a strong focus on advancing medical knowledge and patient care over immediate financial gain.

Most trials (n = 18, 56%) we identified were currently ongoing as of May 2024, with a further six trials (19%) having already completed. Current trial status was unknown for seven trials (22%) and a single trial (3%) was withdrawn prior to commencement (Figure 6). Three (9%) trials were being conducted at phase I and another three (9%) trials were being conducted at phase II. Many trials did not have an applicable phase of development reported on trial registries (n = 26, 81%).

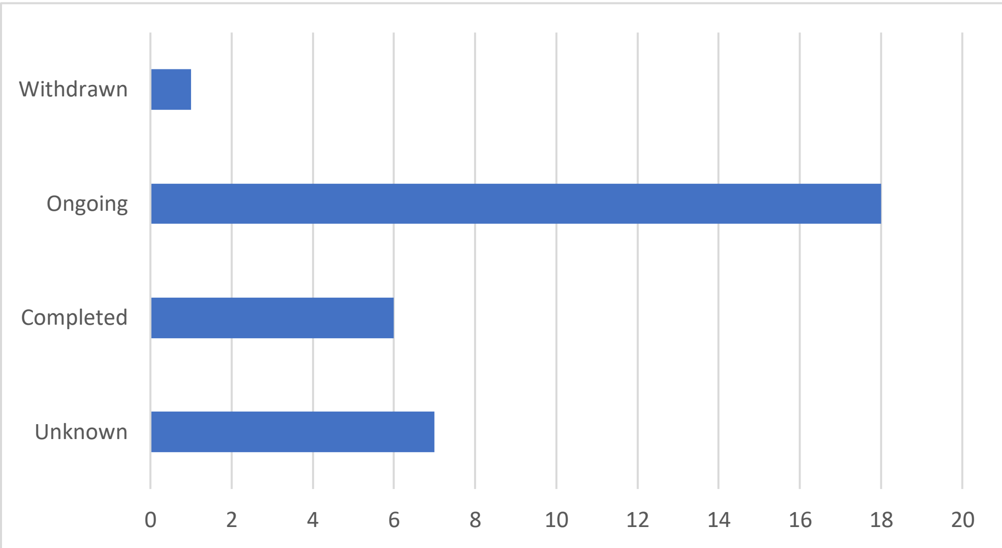

Figure 6 - Quantum technology clinical trial statuses

Our analysis identified a trend towards greater initiations of clinical trials in recent years. Three-quarters of all trials found had been initiated within the last four years (2021-2024), and only five (16%) trials were initiated prior to 2016. (Figure 7) This surge in clinical trials could be attributed to advancements in quantum computing and sensing technologies, which have made practical applications more feasible. Additionally, increased funding and interest from both public and private sectors have likely played a significant role. The growing recognition of the potential benefits of quantum technologies in improving diagnostic and treatment processes may also be driving this trend.

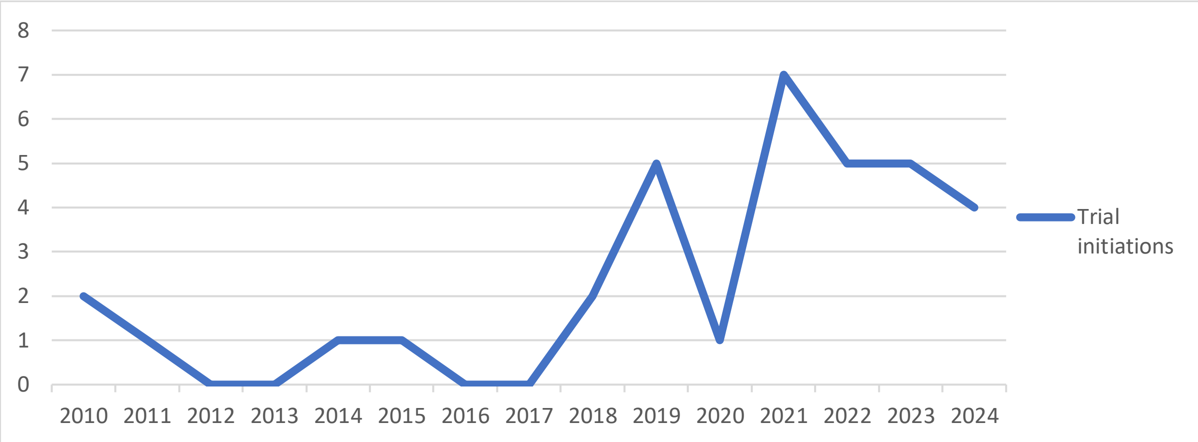

Figure 7 - Quantum technology clinical trials initiations by year

Soft intelligence

Our scan identified 81 soft intelligence articles from various news media sources, that referred to a quantum technology for use in healthcare. Many of the technologies identified in the soft intelligence articles were in early stages of development and had not yet entered any kind of clinical testing or use. Furthermore, we identified more novel proof-of-concept studies and technologies that are being privately developed by industry companies.

Discussion & Conclusions

Despite the relatively recent interest and emergence of quantum applications in healthcare, our scan was able to identify 116 quantum technologies in current use or in development worldwide. These technologies span a broad range of intervention types and therapeutic areas. Diagnostic applications and quantum computing applications for drug discovery and design such as platforms for molecular simulations and precision medicine implementation applications such as quantum ML algorithms were identified as two key areas generating the most development activity. While traditional healthcare technologies rely on classical computing and standard diagnostic methods, quantum technologies offer unprecedented accuracy and efficiency. For instance, quantum computing can process complex datasets at speeds unattainable by classical computers, potentially revolutionising drug discovery. Additionally, quantum-based diagnostics such as quantum sensors can detect diseases at much earlier stages compared to conventional techniques, leading to early interventions and better patient outcomes.

We identified a mixture of novel, emerging quantum technologies, such as quantum dots, quantum machine learning algorithms and artificial intelligence-powered quantum computers, and some more established uses of quantum technologies, such as MEG and SQUID imaging technologies. These classical uses of quantum technology appeared most often during scanning, whereas newer technologies appeared less often. However, integrating quantum technologies into healthcare poses significant challenges. These include the need for substantial investment in infrastructure and training for healthcare professionals to effectively use these advanced tools. Additionally, regulatory hurdles and ensuring data security in quantum systems are major concerns that need to be addressed for successful implementation.

The clinical trials revealed promising outcomes for several quantum technologies in healthcare. For instance, Rexon-eye showed significant potential in treating dry eye syndrome, with multiple trials demonstrating its effectiveness. Overall, the high proportion of non-commercially sponsored interventional trials suggests a strong interest in advancing these technologies for clinical use. A clear upward trend in the publication of literature and initiation of trials for quantum health technologies was identified over the last two decades, with peaks of activity in 2016 and 2021 respectively. Activity remains high in recent years, and we anticipate further increases as some of the quantum technologies identified in soft intelligence sources or proof-of-concept studies begin clinical trials and come to market. Health systems and regulators should prepare for the unique challenges that quantum health technologies will present in the coming years. Policymakers play a crucial role in facilitating the integration of quantum technologies into healthcare. They must create supportive regulatory frameworks that balance innovation with safety, ensuring that new technologies are rigorously tested before widespread adoption. Additionally, they should provide funding and incentives for research and development, as well as for the necessary training programs to equip healthcare professionals with the skills needed to utilise these advanced technologies effectively.

Appendix A – Published literature search strategy

Database:

Ovid MEDLINE(R) ALL <1946 to June 06, 2024>

#	Query
1	(quantum adj2 (health or medic* or tech* or applic* or comput* or device? or principle? or sens* or resonance or imag* or encrypt* or therap* or cryptograp* or sonotherap* or electrotherap* or electro*)).ab,ti,kw.
2	((Multimodal or structured light or fluorescence) adj (imaging or therap* or microscopy)).ti.
3	(quantum molecular resonance or QMR or QMRT).ti.
4	Quantum dot?.ti.
5	(semi?conductor adj (nanocrystals or particles)).ab,ti.
6	(Magnetoencephalogram or MEG or superconducting quantum interference or SQUID).ti.
7	(optically pumped Magnetometer or optically-pumped magnetometer or atomic magnetometers).ab,ti.
8	(Silicon Nanowire Biosensor or SiNW or Photoelectrical Immunosensor).ab,ti.
9	or/1-8
10	(Randomized Controlled Trial or Controlled Clinical Trial or Pragmatic Clinical Trial or Equivalence Trial or Clinical Trial, Phase III).pt.
11	Randomized Controlled Trial/
12	exp Randomized Controlled Trials as Topic/
13	"Randomized Controlled Trial (topic)"/

14	Controlled Clinical Trial/
15	exp Controlled Clinical Trials as Topic/
16	"Controlled Clinical Trial (topic)"/
17	Randomization/
18	Random Allocation/
19	Double-Blind Method/
20	Double Blind Procedure/
21	Double-Blind Studies/
22	Single-Blind Method/
23	Single Blind Procedure/
24	Single-Blind Studies/
25	Placebos/
26	Placebo/
27	Control Groups/
28	Control Group/
29	(random* or sham or placebo*).ti,ab,hw,kf.
30	((singl* or doubl*) adj (blind* or dumm* or mask*)).ti,ab,hw,kf.
31	((tripl* or trebl*) adj (blind* or dumm* or mask*)).ti,ab,hw,kf.
32	(control* adj3 (study or studies or trial* or group*)).ti,ab,kf.
33	(Nonrandom* or non random* or non-random* or quasi-random* or quasirandom*).ti,ab,hw,kf.
34	allocated.ti,ab,hw.
35	((open label or open-label) adj5 (study or studies or trial*)).ti,ab,hw,kf.
36	((equivalence or superiority or non-inferiority or noninferiority) adj3 (study or studies or trial*)).ti,ab,hw,kf.

37	(pragmatic study or pragmatic studies).ti,ab,hw,kf.
38	((pragmatic or practical) adj3 trial*).ti,ab,hw,kf.
39	((quasiexperimental or quasi-experimental) adj3 (study or studies or trial*)).ti,ab,hw,kf.
40	(phase adj3 (III or "3") adj3 (study or studies or trial*)).ti,hw,kf.
41	or/10-40
42	9 and 41

Results 1717

Scopus

#	Query
1	(TITLE-ABS KEY((multimodal OR structured AND light OR fluorescence) near/1 (imaging OR therap * OR microscopy)) OR
2	TITLE-ABS-KEY ("quantum molecular resonance" OR qmr OR qmrt) OR TITLE-ABS-KEY (quantum AND dot*) OR
3	TITLE-ABS-KEY ((semi-conductor OR semiconductor OR "semi conductor") near/1 (nanocrystals OR particles)) OR
4	TITLE-ABS-KEY (magnetoencephalogram OR meg OR "superconducting quantum interference" OR squid) OR
5	TITLE-ABS-KEY ("optically pumped magnetometer" OR "optically-pumped magnetometer" OR "atomic magnetometers") OR
6	TITLE-ABS-KEY ("Silicon Nanowire Biosensor" OR sinw OR "Photoelectrical Immunosensor")) AND

7	KEY ("Randomized Controlled Trial" OR "Controlled Clinical Trial" OR "Randomized Controlled Trials As Topic" OR "Pragmatic Clinical Trial" OR "Equivalence Trial" OR "Clinical Trial, Phase III" OR "Randomized Controlled Trial" OR "Randomized Controlled Trials as Topic" OR "Controlled Clinical Trial" OR "Controlled Clinical Trials as Topic" OR randomization OR "Random Allocation" OR "Double-Blind Method" OR "Double Blind Method" OR "Double Blind Procedure" OR "Double-Blind Studies" OR "Single-Blind Method" OR "Single Blind Procedure" OR "Single-Blind Studies" OR placebos OR placebo OR "Control Groups" OR "Control Group" OR nonrandom* OR non-random* OR quasi random* OR quasirandom* OR "quasiexperimental study" OR "quasiexperimental studies" OR "quasiexperimental trial" OR "quasiexperimental trials" OR "quasi-experimental study" OR "quasi-experimental studies" OR "quasi-experimental trial" OR "quasi-experimental trials")

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Acknowledgements and Disclaimers

This study/project is funded by the National Institute for Health Research (NIHR) [NIHRIO/project reference HSRIC-2016-10009]. The views expressed are those of the author(s) and not necessarily those of the NIHR or the Department of Health and Social Care.

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