



2023

Emerging technologies and scientific innovations:

A global public health perspective

WHO global health foresight series



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Foreword

Advances in science and technology hold great promise and hope for new, improved ways to address global health challenges and ensure healthier populations worldwide. Science and technology are advancing rapidly, and WHO strives to remain abreast of the latest developments in relevant areas of scientific research and technology to identify, anticipate and prepare for issues that hold potential for global health.

The WHO Global Health Foresight function was established to assist Member States in building “futures-thinking” into strategic health planning. WHO Global Health Foresight actively monitors scientific and technological advances to support Member States in ensuring better anticipation of risks, better preparation for governance, and more timely adoption and scale-up of scientific advances with significant potential for global health.

This document presents the findings of a global horizon scan of advances that deserve focus and could be harnessed to improve global public health. While this report does not provide a definitive or exhaustive list of emerging technologies, it is intended to serve as a starting-point for optimizing the benefits, identifying critical enablers, and mitigating the risks associated with some of the most promising emerging technological and scientific innovations.

While the Foresight function is not a crystal ball designed to predict the future, it offers a set of tools by which possible futures can be imagined via a structured and inclusive approach, to create opportunities for deliberate discussions to inform decision-making.

By adopting a futures-thinking mindset, WHO and Member States can inform actions today to shape the optimal development and governance of scientific advances, in hopes of providing timely and equitable access to new treatments, diagnostics, vaccines and health-related innovations to populations worldwide.



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Abbreviations and acronyms

3D	three-dimensional
AI	artificial Intelligence
CRISPR/Cas	clustered regularly interspaced short palindromic repeats with Cas enzyme
EPS	Emerging Technologies, Research Prioritization and Support (WHO unit)
IG	innovation group
LMIC	low- and middle-income countries
mAbs	monoclonal antibodies
ML	machine learning
mRNA	messenger RNA
R&D	research and development
WHO	World Health Organization



Glossary

The following terms and explanations of their meanings are those used in the context of this document. They may have different meanings or formal definitions in other contexts.

3D-printing	Construction of a three-dimensional (3D) object from a computer-aided design model or a digital 3D model by a process in which material is deposited, joined or solidified under computer control, material being added, usually layer by layer.
Artificial intelligence	The ability of computers to demonstrate intelligence and perform acts usually associated with intelligent beings.
Augmented reality	Augmentation of the user's reality and surroundings by digital means; can be used in health care to train health-care professionals in diagnosis and treatment.
Big Data	Very large sets of data that, when analysed on a computer, can reveal patterns, trends and associations.
Biobank	Collection, storage of biological material for use in research.
Bioprinting	Use of 3D-printing-like techniques with biomaterials to fabricate body parts, often with the aim of imitating natural tissue characteristics.
Biosensor	An analytical device used for the detection of a chemical substance that combines a biological component with a physicochemical detector; typically consists of a bio-receptor (enzyme, antibody, cell, nucleic acid or aptamer), a transducer component (semi-conducting material or nanomaterial), and an electronic system that includes a signal amplifier, processor and display.
Blockchain	A distributed ledger with growing lists of records (called blocks) that are securely linked.
Body on a chip	Multi-organ system, often designed to study disease mechanisms and emulate human physiological response to drugs.
Cloud	"The cloud" refers to servers that are accessed on the Internet and to the software and databases that run on those servers.
CRISPR/Cas	Clustered, regularly interspaced short palindromic repeats with CRISPR-associated enzyme.
Cryonics	Low-temperature freezing and storage of human remains.
Delphi	An anonymous survey method with iterative structured feedback for pooling expert opinion on potential future events and their comparative probabilities.
Digital health	Field of knowledge and practice associated with the development and use of digital technologies to improve health.
Digital twin	A digital representation of an intended or actual physical product, system or process that serves as its effectively indistinguishable digital counterpart for practical purposes, such as simulation, integration, testing, monitoring and maintenance.
Foresight	A systematic, participatory, multi-disciplinary approach to explore trends, emerging changes, systemic impacts and mid- to long-term alternative futures that might evolve from those changes.
Gamification	Strategic use of game mechanisms and elements to enhance systems, services, organizations and activities in order to motivate and engage users.

Genomics	Study of the total or part of the genetic or epigenetic sequence information of organisms to understand the structure and function of those sequences and of downstream biological products, including the interplay of molecular information, health interventions and environmental factors in disease.
Horizon scanning	A set of systematic methods for monitoring evolving change by collecting data on trends and identifying weak signals of change that may impact futures.
Internet of things	A network of devices that contain sensors, processing ability, software and other elements that connect and exchange information through communication networks.
Lab on a chip	A platform for integration and automation of several laboratory functions onto an integrated circuit measuring millimetres to a few square centimetres.
Machine learning	A field of inquiry for understanding and building methods that “learn” by using data to improve performance in a set of tasks; machine learning algorithms typically build a model from a set of sample data (referred to as “training data”) and make predictions or decisions without explicit programming; part of artificial intelligence.
Metagenomics	The study of genetic material recovered from environmental or clinical samples by sequencing.
Metaverse	A deep augmented virtual reality; a mixture of social media and a massive online video game.
Nanomedicine	Application of nanotechnology for medical purposes, such as diagnosis, prevention and treatment of diseases and conditions.
Nutrigenomics	Study of the relations and interactions between the human genome, nutrition and health.
Polypill	A single pill containing multiple medications.
Proteomics	Study of all proteins in a living organism or a biological system.
Regenerative medicine	Field of medicine in which damaged tissues or organs are replaced or regenerated to restore normal function.
Sio-membrane	A thin layer of silicon oxide consisting of a microporous structure with a pore size distribution of 0.3 nm, which enables small molecules to pass through its channels.
Telehealth	Use of electronic information and telecommunication technology in long-distance clinical health care, for health education of patients and professionals, and for public health and health administration.
Tissue engineering	A discipline of biomedical engineering in which functional constructs are produced from cells, scaffolds and biologically active molecules to restore, maintain, improve or replace damaged tissues or organs.
Virtual reality	An immersive experience that allows the user to experience an alternative simulated reality.
Wearable	“Smart” electronic devices worn close to a person that can monitor and transmit information about the wearer.

Executive summary

Aim

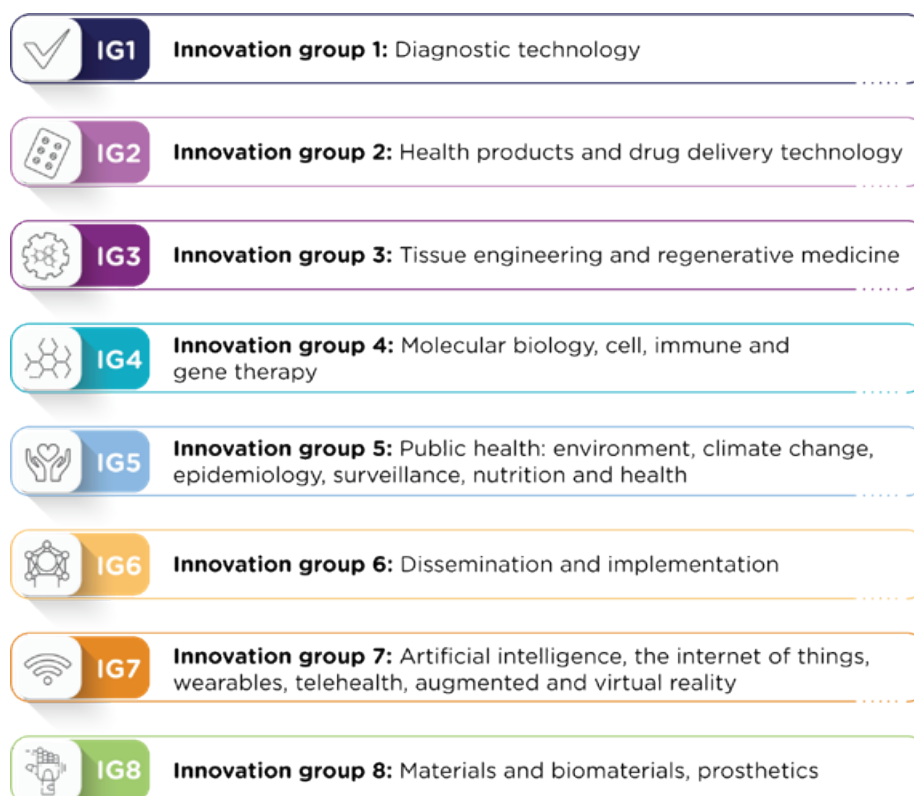
In 2022, the WHO Science Division initiated a horizon scan to identify innovations in science and technology that could improve global health, including to address health needs that are frequently neglected or not addressed adequately or rapidly enough. The exercise is part of the discipline of “foresight”, which is the exploration, anticipation and shaping of the future, to build and use collective intelligence in a structured, systemic way to anticipate developments.

The objective of the exercise was to identify innovations in areas of research and emerging technologies and their potential uses and opportunities to obtain useful insights for strategic planning, policy-making and preparedness. The horizon scan was not designed to predict the future but rather to identify areas that deserve focus and could be harnessed to be better prepared and to catalyse equitable access and innovation for global public health.

Methods

The exercise comprised a literature review, a broad call to identify innovations and consultation with a group of international experts, balanced in terms of gender and geographical distribution. The horizon scan was conducted online with the Delphi method, with roundtables for discussion among experts. Some key informant interviews were conducted.

Eight innovation groups (IGs) with over 100 innovations were defined:



In each of two Delphi rounds, the experts were asked to rate the innovations according to their potential impact for global health, their chance of adoption (and wide use) and the associated time horizon. The experts were also asked to rank the most promising innovations in each group and the top five overall. In roundtables between the two Delphi rounds, the experts discussed the findings of the first round. New innovations and enablers were added for the second Delphi round, while those that the experts considered less relevant were discarded.

The exercise also included classification of up to 40 enablers according to their relevance for facilitating and optimizing development or adoption of the innovations. The enablers were grouped into technological; skill- or capacity-building; structural, legal and political; and cultural enablers. In the second Delphi round, the experts were also asked to identify risks related to the innovations that might have important implications for global health.

Outcomes

The outcomes of the exercise were ranking of the innovations and enablers from a global public health perspective and identification of risks.

Innovations

Overall ranking

The following five innovations were considered, according to the experts' votes in the second Delphi round, to be the most promising overall:

- application of genomics for early diagnosis and pre-diagnosis of diseases, starting from universal genomic prenatal screening to identify metabolic and other congenital disorders pre-symptomatically to enable a precise diagnosis and to guide management and treatment;
- better coordinated, more effective systems of vaccine production and global distribution;
- low-cost viral diagnostics. Rapidly design and construct cost-effective point-of-care diagnostics for HIV and hepatitis B virus load testing with CRISPR/Cas techniques;
- broad-spectrum antimicrobial drugs that do not cause resistance or tolerance, that, for example, adapt their conformation to target structural changes and mutations; and
- rapid remote diagnostics through cell phones, watches and other devices (such as smart implants, prostheses and wearable sensors) that can provide information on markers and link health information in real-time for clinicians and other (public) health entities, supporting individual health promotion, disease prevention and disease (self) management and also providing real-world data for public health management and health economics.

Potential impact and chance of adoption

A cross-analysis was performed to map potential impact against the chances of adoption within each group. The experts' responses indicated 36 innovations as having a high or very high potential impact and a high chance of adoption (Table 1). Full descriptions of the innovations considered are given in Annex 1.



Table 1. Innovations considered to have a high or very high potential impact and a high chance of adoption









Innovation group (IG)	Innovations
IG1 Diagnostic technology 	IG1-7 Low-cost viral diagnostics. Rapidly design and construct cost-effective point-of-care diagnostics for HIV and hepatitis B virus load testing with CRISPR/Cas techniques
	IG1-11 Open-source diagnostic toolkits. Free, open-source toolkits that would allow laboratories in developing countries to produce their own tools (e.g. for COVID-19 research and diagnosis), reducing their dependence on the global supply chain
	IG1-12 Rapid remote diagnostics. Connect people through cell phones, watches and other devices (such as smart implants, prostheses and wearable sensors) that can provide information on key markers and link health information in real time for clinicians, people and other (public) health entities, supporting individual health promotion, disease prevention and disease (self) management and also providing real-world data for public health management and health economics.
	IG1-6 “Lab on a chip” to diagnose several diseases with small easy-to-use devices, based, for example, on the CRISPR enzyme Cas12 or micro-electro-mechanical systems-based dual axes confocal microendoscopy
	IG1-9 Home “laboratory” tests and direct-to-consumer genetic tests
IG2 Health products and drug delivery technology 	IG2-7 Better coordinated, more effective systems of vaccine production and global distribution
	IG2-2 Broad-spectrum antimicrobial drugs that do not cause resistance or tolerance, that for example, adapt their conformation to target structural changes and mutations
	IG2-1 Potent monoclonal antibodies against infectious diseases
IG3 Tissue engineering and regenerative medicine 	IG3-8 Stem-cell technology for replacement of muscles, organs (eyes, ears) and bone or teeth, and, later, heart, brain and neural tissues. An example is transplantation of retinal cells to treat blindness.
	IG3-6 Regenerative medicine with therapies involving proliferation and transplantation of cells to improve the functioning of tissues or organs, potentially to treat diseases such as diabetes, nervous system disorders and cardiovascular disorders
	IG3-2 Bio-adhesives for tissue adhesion, haemostatic agents and membrane transplantation
IG4 Molecular biology: cell, immune and gene therapy 	IG4-5 Biobanks for discovery of biomarkers and for monitoring, surveillance, testing, diagnostics and improving response to pandemics
	IG4-19 mRNA vaccine platforms as a new way of programming for antigenic stimulation, developing potential new vaccines for tuberculosis, HIV, syphilis, hepatitis B, cancer and other diseases
	IG4-2 Adaptive platform trials in which multiple interventions are studied continuously
	IG4-11 Microbiome analytical tools for research, clinical prevention and treatments
IG5 Public health: environment, climate change, epidemiology and surveillance, nutrition, and health 	IG5-6 Global early warning systems and solutions to monitor conditions related to development of global infections and for disease monitoring, worldwide genomic surveillance of pathogens to identify potential zoonoses with information technology
	IG5-5 Global capacity for rapid response to infectious disease outbreaks by real-time pathogen sequencing for surveillance, with equitable sharing and distribution of countermeasures
	IG5-8 Machine learning-powered surveillance tools with symptom data, interpretation of basic tests (e.g. imaging, electrocardiograms), with algorithms for selecting further laboratory testing
	IG5-14 Use of digital technologies to automate the collection and analysis of data at the intersection of health and environment to better predict, prevent and reduce environmental risks to health, such as enhanced widely deployed aerosol and wastewater surveillance technologies
	IG5-10 Monitoring and predicting new or recurrent pandemics from analysis of, for example, medical records, mobile phone traffic, social media
	IG5-15 Water storage for clean water in countries prone to flooding (heavy rain catchment areas)
	IG5-9 Making plastics without harmful chemicals or contaminants
	IG5-4 Use of mobile phones (and other wearable technology) to improve human health, specifically with sensors, data and analytics

Table 1. *continued*

IG6 Dissemination and implementation 	IG6-9	Innovations to make new scientific and technological advances available and affordable for low- and middle-income countries
	IG6-13	Technology to prevent and reduce the prevalence of post-partum haemorrhage that is understood and can be applied by women and adolescent girls in hard-to-reach communities in low- and middle-income countries
	IG6-8	Digital tools, especially mobile apps, that enable provider-to-provider communication and provide community health workers, clinical officers and other front-line generalist health workers with support from specialists in real time, bringing expertise on medical and surgical specialties to where patients live and seek care
	IG6-3	An innovative implementation science model for use in major global health issues, such as the health consequences of climate change and mental health, to improve the reach, effectiveness, adoption and impact of innovations at population level and to implement (and sustain) best practices
	IG6-7	Digital health tools for public health research and for development of new clinical preventive measures, treatments and vaccines
	IG6-11	Medical devices to improve evidence generation in trials, replacing previous end-points, ensure that clinical studies truly address patient-relevant outcomes, and, when used on treatment, increase compliance with treatment
IG7 Artificial intelligence, the Internet of things, wearables, telehealth, augmented and virtual reality 	IG7-4	Big Data, artificial intelligence and machine learning to evaluate large amounts of patient data and other information and create tailored algorithms, to support physicians in personalized medicine, possible diagnoses, medications and treatment plans
	IG7-2	Artificial Intelligence prediction of the 3D structures of proteins and for drug development
	IG7-12	Artificial Intelligence-based decision-support systems based for (public) health surveillance and public health promotion, creating risk models for noncommunicable and communicable diseases in order to predict the risk of an individual in 5 or 10 years
	IG7-1	Artificial Intelligence-aided diagnostics from databases of medical images to ensure earlier, more accurate detection of various pathologies
IG8 Materials and biomaterials, prosthetics 	IG8-4	New materials and prosthetics, such as artificial hearts (heart valves) made of aluminium, exoskeletons for spinal cord injuries, prosthetic fingers, arms, knee joint replacements, wide-range hearing aids, bionic eyes, electronic olfaction
	IG8-2	Minimally invasive surgery or minimally invasive procedures that replace surgery altogether
	IG8-1	Diagnosis and monitoring with intelligent materials that continuously sense, respond and adapt

Enablers

The most relevant enablers for facilitating and optimizing development or adoption of the innovations are listed in Table 2. These enablers obtained more than 75% of experts' votes.

Table 2. Enablers that were considered most relevant for facilitating and optimizing development and adoption of the innovations

Technological enablers	<ul style="list-style-type: none"> • Big Data • Cloud • Building and sustaining broad health infrastructure 	<ul style="list-style-type: none"> • Artificial intelligence and machine learning • Availability of data and better data capture at source • Open-source platforms
Skills- and capacity-building enablers	<ul style="list-style-type: none"> • Skilled health professionals and technicians • Leadership and good governance • Data analysis 	<ul style="list-style-type: none"> • Skilled communities and people • Best practices for synthesizing and diffusing evidence
Structural, legal and political enablers	<ul style="list-style-type: none"> • Regulatory and policy framework • High-quality Internet access and power supply • Investment and access to funding • Use of globally accepted ethical and legal guidelines • Public–private partnerships for research and development 	<ul style="list-style-type: none"> • Regulations on data privacy and trust • Universal primary health care • Establishment of regional networks for high-cost research • Intellectual property management
Cultural enablers	<ul style="list-style-type: none"> • Building trust in science, disabling spread of misinformation • Accountability and cooperation • Communication of science (various platforms) 	<ul style="list-style-type: none"> • Proactive approach and attitude • Health and digital literacy • Empowered patients

Risks

Although emerging technologies and scientific innovations provide many opportunities, they may also be associated with certain risks. Some of the risks identified by the experts are common to all innovations, others are common to groups of innovations, and others are specific to certain innovations.

The risks that were considered common to all innovations are:

- potential to accentuate gaps in health equity;
- dependence of reliability and accuracy on the quality of inputs (such as data) and of processes and the ability to make good use of results;
- cost for both development of the desired quality, accuracy and reliability and for commercialization and scaling up; and
- data privacy.

Conclusion

A horizon scan is a first step in a foresight approach. It invites readers to consider innovations from a public health perspective: What innovations are being made? How can they be made available for the benefit of all in the near future? The subsequent steps may include scenario planning to build plausible scenarios for the future, deep dives into the most promising innovations, and defining means to improve adoption for the ultimate benefit of populations. The most promising innovations should be monitored to follow their evolution and adoption.



Introduction

1

WHO strives to remain abreast of the current and future developments in relevant areas of research, science and technology to proactively identify, anticipate and prepare for issues that could improve global health. In 2020, the WHO Science Division established a “global health foresight function” to assist Member States in building futures thinking and including horizon scanning in their strategic health planning so that they can both better anticipate and prepare for a changing world and accelerate acquisition of the gains offered by emerging technologies.

To monitor emerging technologies and trends, the Emerging Technologies, Research Prioritization and Support (EPS) unit initiated a new project to scan the horizon for innovations in science and technology, including those that could be used to address health needs that are frequently neglected or not addressed adequately or in a timely manner.

This horizon scan was not designed to predict the future but rather to identify areas that deserve focused attention and could be harnessed for better preparation and to catalyse innovation for global public health. A group of international experts was approached to identify, discuss new and emerging science and technology relevant to global public health and consider enablers that could increase the chances of adoption of the innovations by maximizing the benefits globally while mitigating risks. The project was conducted between June 2022 and January 2023.

Foresight is a systematic, participatory, multi-disciplinary approach to exploring trends, emerging changes, systemic impacts and mid- to long-term alternative futures that might evolve from those changes (1). Various methods are available, and WHO has published a document providing guidance on foresight approaches in global public health (1). Foresight can start with a horizon scan to identify trends and to analyse their promise (Fig. 1).

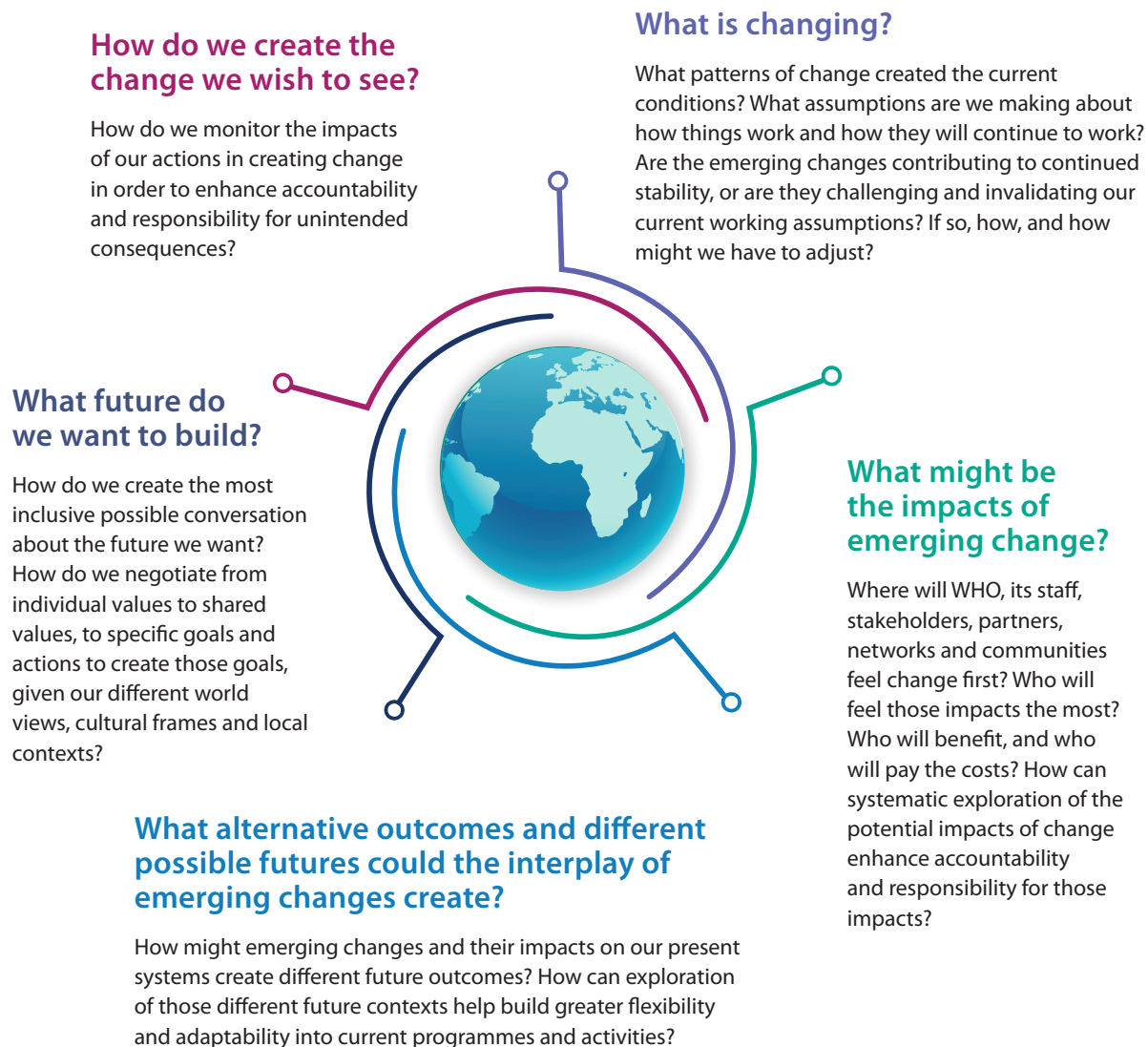


Fig. 1. Areas for consideration in a preliminary foresight exercise

Source: WHO (1).

Today's world is volatile, uncertain, complex and ambiguous, including the fast pace of technological and scientific advances. Horizon scanning is therefore critical to ensure better preparation for the future. Various time horizons can be considered in scanning future trends (2) (Fig.2):

- 0–5 years, the known horizon, which concerns science and technological innovations that are starting to be used but have not yet been scaled up;
- 5–10 years, the medium-term horizon, for innovations and trends that have already begun to affect health care but for which it is not yet known how they will develop or play a role in health; and
- ≥ 10 years, a more distant horizon, for which trends and drivers of change are difficult to see. Those identified are very early innovations or signals that point in certain directions and will then be monitored.

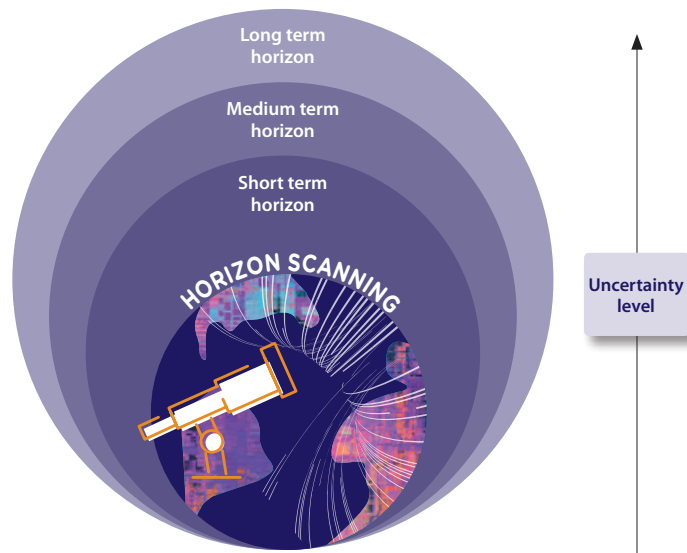


Fig. 2. Time horizons of technological advances

Horizon scanning is not a one-off exercise. Information updates, monitoring of signals of change and work on various plausible scenarios are necessary to understand how the global health landscape could change if some of the identified technologies and science became widely used (3) (Fig. 3).

This report presents the conclusions of the horizon scan exercise with a group of international experts. It presents the methods used, the innovations identified during the exercise, consolidated views on their potential impact and their chance of adoption, with the corresponding timeframes, and enablers that might increase, optimize or accelerate scaling up of the most promising innovations.

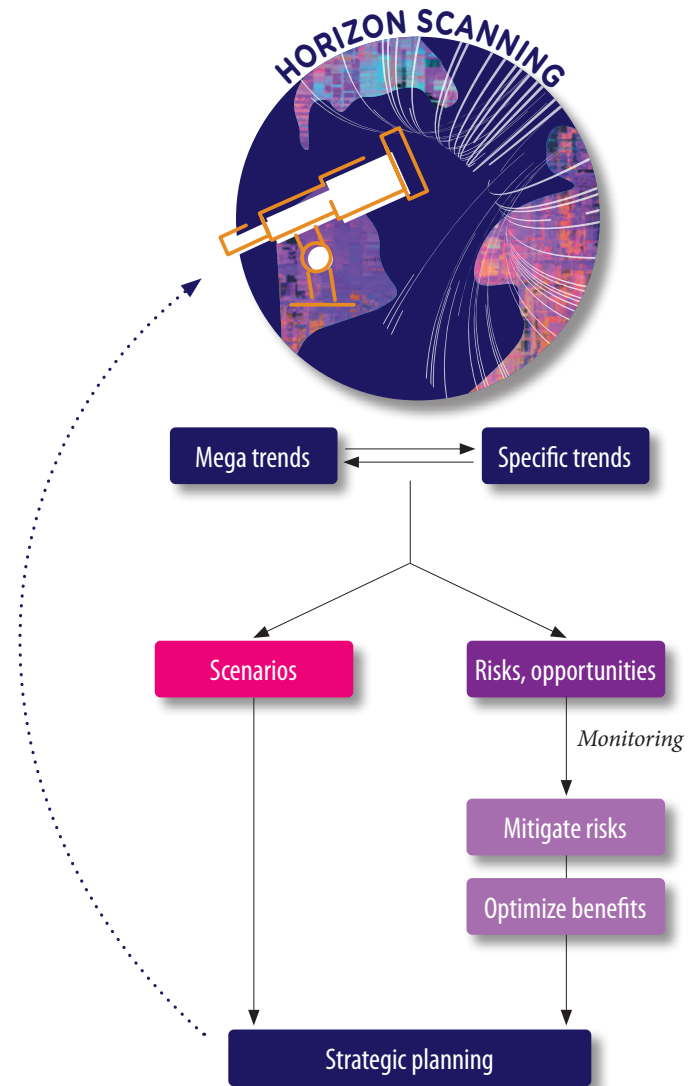


Fig. 3. Horizon scanning cycle

Methods

2

2.1 Overview

The horizon scanning exercise comprised a literature review and consultations with experts. In this multi-stage, multi-layered approach, a preliminary step was a call for ideas. The exercise was then conducted online with the Delphi method, rounds of discussion and interviews with experts. Some adaptations were made to the original Delphi exercise (4,5) for wide participation of a diverse group of experts and to identify as many promising innovations as possible. Consensus was analysed and discussed but was not considered the ultimate goal. The number of Delphi rounds was limited to two, and roundtables were used to discuss innovations and to determine the reasons for lack of consensus. Experts were invited to participate in at least one roundtable. The aim was to obtain as many views and opinions as possible in an organized format, and experts were given the possibility to meet virtually. At each step, the list of innovations was refined and processed. The work flow is shown in Fig. 4.

The project was granted an exemption from review by the WHO Research Ethics Review Committee. Consent was obtained for participation, and declarations of interests were collected from experts who participated in the horizon scan exercise. After WHO review of the declarations, the participation of experts in the horizon scan was adapted when deemed appropriate, in particular with regard to participation in online scoring of innovations.

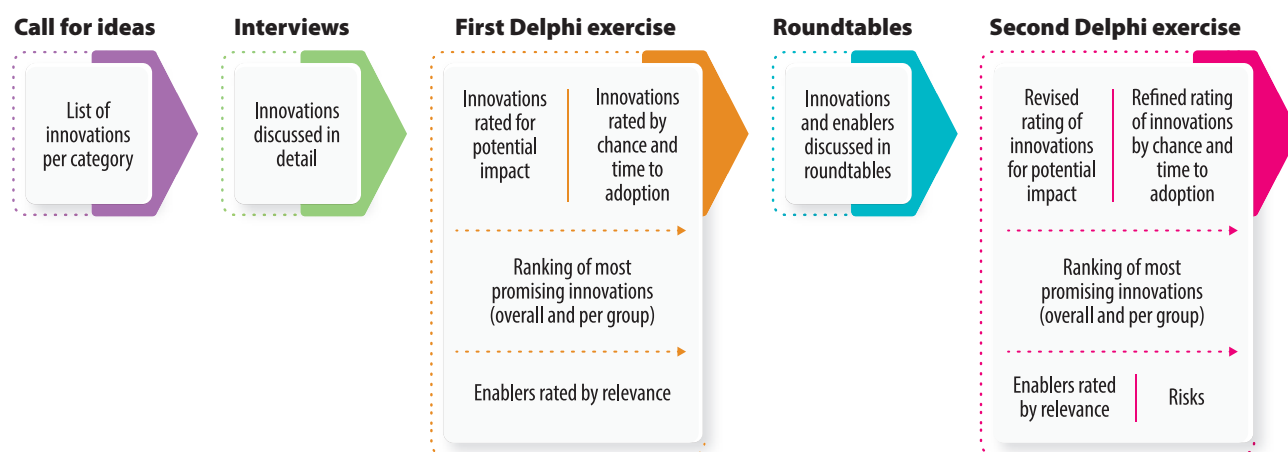


Fig. 4. Work flow

2.2 Desk research, literature review and identification of experts

The purpose of the literature review was to identify categories of innovations that hold promise and, for innovations within those categories, to identify general areas of promising innovation for the expert consultations.

The review was also used to identify experts to be consulted, on the basis of their professional experience in emerging technologies, science and global public health.

2.3 Preliminary call for ideas

A preliminary call for ideas was conducted online with open-ended questions, summarized as follows:

- What innovations in science and technology could have the greatest impact for global public health? (Indicate specific examples and estimated time to adoption.)
- What are the barriers to uptake of and access to these innovations?
- What are the five most promising areas in the following list: artificial intelligence, Internet of things and wearables; virtual and augmented reality; telehealth; diagnostic technology; drug delivery technology; tissue engineering; nanomedicine; molecular biology, cell, immune and gene therapy; phage therapy; materials and biomaterials, prosthetics; cryonics; application of data in decision-making; epidemiology and surveillance; environment, climate change and health; nutrition and health; production and distribution of health products; proof of scientific evidence (misinformation and disinformation); dissemination and implementation; other.

Links, citations and other information that would support the project were requested.

The call was sent to more than 200 professionals identified in the desk research and literature review, with attention to ensuring a fair balance with respect to gender and geographical distribution. About 45 responses were considered. Of those who responded, 27% were aged < 40 years, and 60% were ≥ 40 years; 63% had ≥ 15 years of experience in their field. Each WHO region was represented. The fields of expertise of the respondents included medicine and health sciences, life sciences, social sciences, computer and information sciences, engineering and technology, and education.

2.4 Horizon scan

2.4.1 Key informant interviews

In order to obtain a more informed view and diverse perspectives on the innovations, 13 in-depth interviews were conducted.

2.4.2 Consultation with the international group of experts

A group of more than 50 international experts was constituted for the Delphi exercise, with balanced representation in terms of gender and geographical distribution. An average of 68% participated in the Delphi rounds.

2.4.3 First Delphi round

Over 100 innovations were identified for the first Delphi round. The innovations were organized into eight groups:

- IG1: Diagnostic technology
- IG2: Health products and drug delivery technology
- IG3: Tissue engineering and regenerative medicine
- IG4: Molecular biology, cell, immune and gene therapy
- IG5: Public health: Environment, climate change, epidemiology and surveillance, nutrition and health
- IG6: Dissemination and implementation
- IG7: Artificial intelligence, Internet of things, wearables, telehealth, augmented and virtual reality
- IG8: Materials and biomaterials, prosthetics

These innovations were assessed for their potential impact, chance of adoption and time horizon. The most important enablers for adoption and improvement of the innovations were also assessed and the outcomes scored online.

Scoring

The experts were asked to:

- rank the importance of innovations for solving global health challenges on a scale of 1 to 4, where 1 is no significant potential impact and 4 is very high potential impact;
- rank the chance of adoption and wide use of each innovation on a scale of 1 to 4, where 1 is little chance and 4 is a high chance;
- classify the innovations by the time horizon for adoption: ≤ 5 years, 5–10 years and > 10 years;
- rank the list of enablers for their relevance in supporting adoption of innovations on a scale of 1 to 4, where 1 is no significant relevance and 4 is very high relevance;
- rank the first five most promising innovations, from the most to the least promising;
- rank the first five most important innovations per innovation group, from those with the most to the least potential impact; and
- add any other innovations or enablers.

Responding to every question was not mandatory. A four-point scale, with no middle value, was chosen to avoid the central tendency bias (6) and to ensure an adequate number of options for reliable results.

Analysis of results

Individual responses for innovations and for enablers were aggregated and analysed. The innovations were ranked from one to five, five points being the highest and one the lowest.

2.4.4 Discussions in roundtables

Three roundtables were organized to discuss the findings of the first Delphi exercise and to align the understanding of the experts. About 30 experts attended at least one online roundtable. The meetings consisted of main sessions for discussing key findings and breakout rooms for group discussions of innovations of a similar nature.

The roundtable discussions resulted in revision of the list of innovations, with exclusion of some with a lower impact and less chance of adoption and addition of new innovations considered to be relevant. Furthermore, the impact and chance of adoption were discussed for each innovation, leading to some changes in the analysis. Special attention was paid to innovations for which there was a low level of agreement, with discussion of the possible reasons and a wider view of perspectives that could not be captured in the Delphi exercise.

The list of enablers was also revised, with changes in wording, additions and deletions. The final list of enablers comprised 40 for building technological, skills and capacity, and regulatory and cultural enablers.

2.4.5 Second Delphi exercise

Scoring

In the second Delphi round, each expert was asked to rank each innovation again for potential impact, chance of adoption and associated horizon time. Experts were also asked to indicate any risk(s) associated with each innovation that might have implications for global health (including risks to safety and security due to accidents and inadvertent or deliberate misuse).

The experts were then asked to classify the revised list of enablers according to their relevance for enabling the adoption of innovations; to rank the five most promising innovations overall; and to rank the three most promising innovations in each innovation group.

Analysis of results

The results were analysed with the approach used in the first round. Consensus among participants was analysed on box-and-whisker plots to illustrate variations (Annex 2).

Descriptive information on risks was collected and reviewed and is summarized in section 5.



Innovations for the future of global health

3

The innovations identified were categorized and grouped. The results presented here reflect the participants' opinions and compiled responses. When useful or relevant to the context, additional information has been provided from the literature review and comments from experts in the roundtables or the interviews. The innovations are presented by group (Fig. 5).

The results presented are from the second Delphi round. Annex 1 provides complete descriptions of the innovations considered.

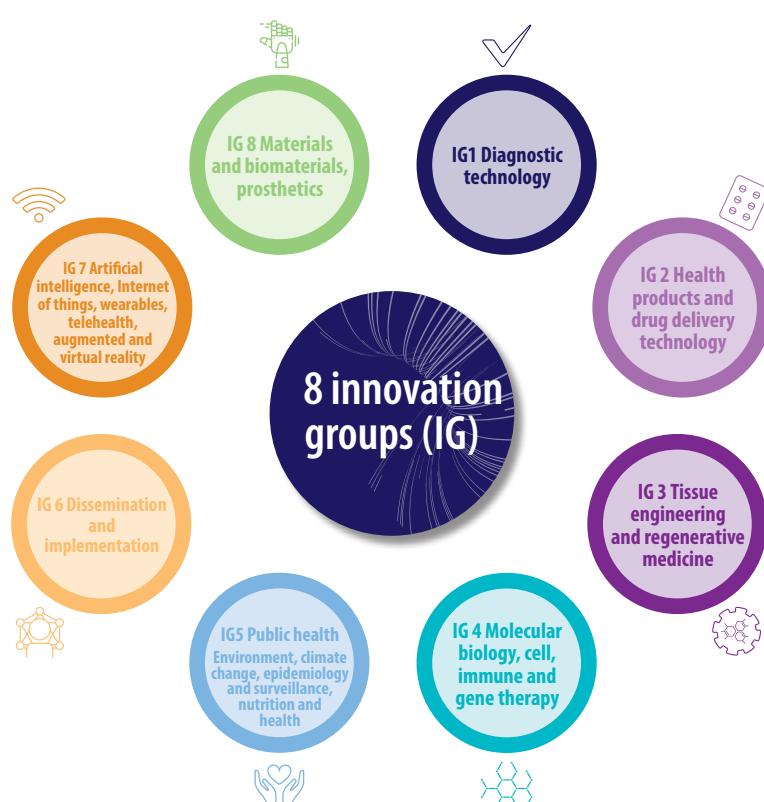


Fig. 5. Innovation groups for the horizon scan exercise

3.1 Overall ranking

After overall ranking analysis, the five innovations determined to be the most promising were those listed in Table 4.

Table 4. The five most promising innovations

Rank	Innovation	Innovation group
1	Application of genomics for early diagnosis and pre-diagnosis of diseases, starting from universal genomic prenatal screening to identify metabolic and other congenital disorders pre-symptomatically to enable a precise diagnosis and to guide management and treatment (IG1-3)	IG1: Diagnostic technology
2	Better coordinated, more effective systems of vaccine production and global distribution (IG2-7)	IG2: Health products and drug delivery technology
3	Low-cost viral diagnostics. Rapidly design and construct cost-effective point-of-care diagnostics for HIV and hepatitis B virus load testing, with CRISPR/Cas techniques (IG1-7)	IG1: Diagnostic technology
4	Broad-spectrum antimicrobial drugs that do not cause resistance or tolerance; e.g. adapt their conformation to structural changes or mutations in the target (IG2-2)	IG2: Health products and drug delivery technology
5	Rapid remote diagnostics: connect people through cell phones, watches and other devices (such as smart implants, prostheses and wearable sensors) that can provide information on key markers and link health information in real-time to clinicians, people and other (public) health entities, supporting individual health promotion, disease prevention and disease (self) management and also provide real-world data for public health management and health economics (IG1-12)	IG1: Diagnostic technology

All five of the most promising innovations were in either IG1, Diagnostic technology, or IG2, Health products and drug delivery technology.

Participants also ranked the top three promising innovations in each group (Table 5).

Table 5. The three most promising innovations in each innovation group

Innovation group	Rank and innovation
IG1 Diagnostic technology	<ol style="list-style-type: none"> 1. Application of genomics for early diagnosis and pre-diagnosis of disease (IG1-3) 2. Molecular multiplex point-of-care testing with low-cost, accurate, easy-to-use platforms (IG1-10) 3. Rapid remote diagnostics to connect people through cell phones, watches and other devices (IG1-12)
IG2 Health products and drug delivery technology	<ol style="list-style-type: none"> 1. Broad-spectrum drugs (IG2-2) 2. Better coordinated, more effective systems of vaccine production and global distribution (IG2-7) 3. Potent monoclonal antibodies against infectious diseases (IG2-1)
IG3 Tissue engineering and regenerative medicine	<ol style="list-style-type: none"> 1. Regenerative medicine (IG3-6) 2. Stem-cell technology (IG3-8) 3. 3D printing of tissues and body parts (IG3-1)
IG4 Molecular biology; cell, immune and gene therapy	<ol style="list-style-type: none"> 1. Biobanks for discovery of biomarkers and for monitoring and surveillance (IG4-5) 2. mRNA vaccine platforms (IG4-19) 3. Adaptive platforms trials (IG4-2)
IG5 Public health	<ol style="list-style-type: none"> 1. Real-time pathogen sequencing (IG5-5) 2. Global early warning systems and solutions for global infections (IG5-6) 3. Mobile phones and wearables (IG5-4)
IG6 Dissemination and implementation	<ol style="list-style-type: none"> 1. Co-design and co-implement innovations in poor rural settings in low- and middle-income countries (IG6-4) 2. Make scientific and technological innovations available and affordable for low- and middle-income countries (IG6-9) 3. An innovative model for implementation science to improve reach, effectiveness, adoption and impact of innovations (IG6-3)
IG7 Artificial intelligence, Internet of things, wearables, telehealth, augmented and virtual reality	<ol style="list-style-type: none"> 1. Big Data, artificial intelligence and machine learning to evaluate large amounts of patient data and other information, and create tailored algorithms (IG7-4) 2. Artificial intelligence-aided diagnostics from databases of medical images (IG7-1) 3. Artificial intelligence decision support systems for (public) health surveillance and promotion (IG7-12)

Table 5. continued

IG8 Materials and biomaterials, prosthetics	1. Minimally invasive surgery or procedures to replace surgery altogether (IG8-2)
	2. New materials and prosthetics, such as artificial hearts, exoskeletons for spinal cord injuries, prosthetic fingers, arms, knee joint replacements, wide-range hearing aids, bionic eyes, electronic olfaction (IG8-4)
	3. Diagnosis and monitoring with intelligent materials that continually sense, respond and adapt (IG8-1)

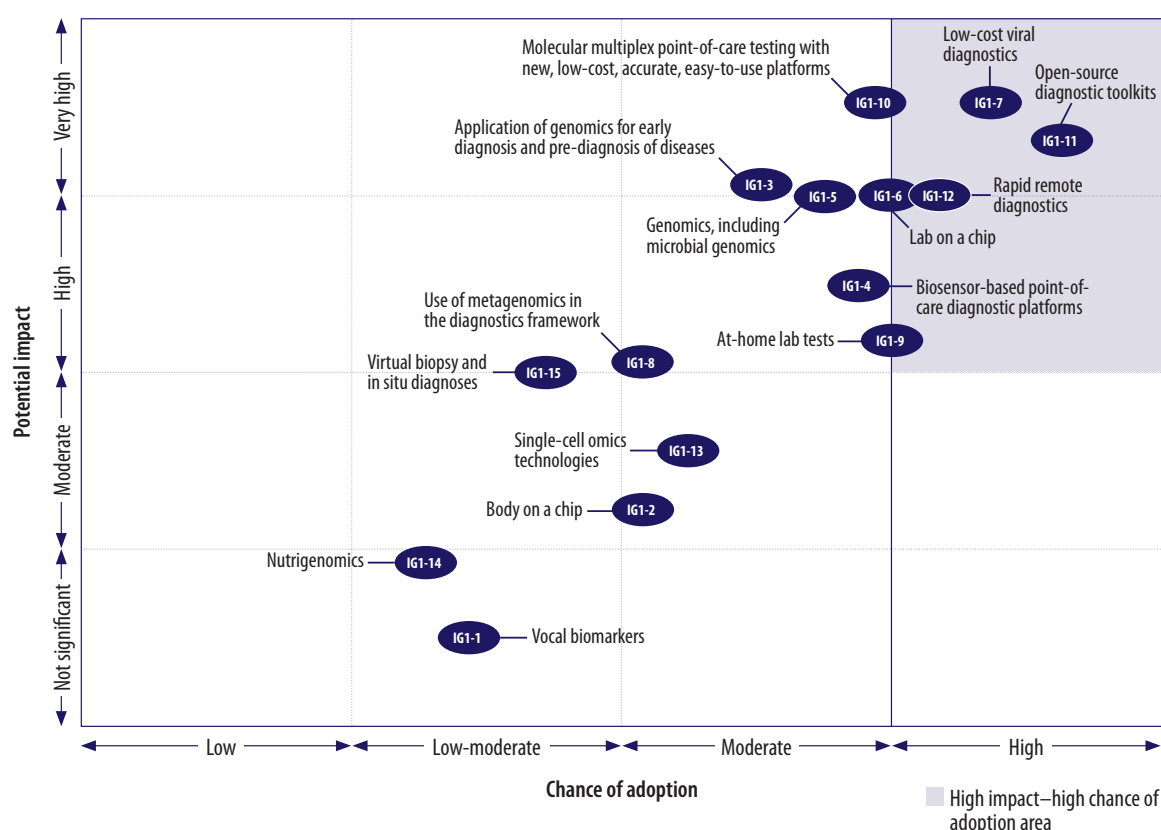
As expected, most of the innovations in the global top five were also top in their innovation group. In the diagnostic technology group, low-cost viral diagnostics was ranked fourth. Several innovations in this group were assessed as having a high potential impact, as described in section 3.2.1.

3.2 Rating of innovations according to their potential impact, chance of adoption and time to adoption

Participants also rated the innovations in each group according to the criteria of impact, plausibility (chance of adoption) and horizon time. (All of the most promising innovations listed in Table 5 are associated with a high or very high potential impact. For some, the chance of adoption provides complementary information). Innovations with a good chance of adoption appear more likely to reach their full potential for global health.

3.2.1 Innovation group 1: Diagnostic technology

Fig. 6 represents the experts' evaluation of innovations in diagnostic technology in terms of potential impact and chance of adoption. Full descriptions of each innovation are provided in Annex 1.



Note: IG1-2: Body-on-a-chip was not ranked for its chances of adoption; the opinions expressed during the roundtables were used to rank the chances of adoption of this innovation on the matrix.

Fig. 6. Innovation group 1: potential impact vs chance of adoption

Five innovations were analysed as having a high or very high potential impact and a high chance of adoption:

- Low-cost viral diagnostics. Rapidly design and construct cost-effective point-of-care diagnostics for HIV and hepatitis B virus load testing, with CRISPR/Cas techniques
- Open-source diagnostic toolkits. Free, open-source toolkits that would allow laboratories in developing countries to produce their own tools (e.g. for COVID-19 research and diagnosis), reducing their dependence on the global supply chain
- Rapid remote diagnostics. Connect people through cell phones, watches and other devices (such as smart implants, prostheses and wearable sensors) that can provide information on markers and link health information in real-time for clinicians and other (public) health entities, supporting individual health promotion, disease prevention and disease (self) management and also providing real-world data for public health management and health economics
- “Lab-on-a-chip” to diagnose several diseases with small, easy-to-use devices, based for example on the CRISPR enzyme Cas12 or micro-electro-mechanical systems-based dual axes confocal microendoscopy
- Home “laboratory” tests and direct-to-consumer genetics tests

The time horizon (Fig. 7) for adoption of most of these innovations is short, within the next 5 years, probably because the technology and science in those areas are already developed, and, in some cases, there is some limited experience in their use.

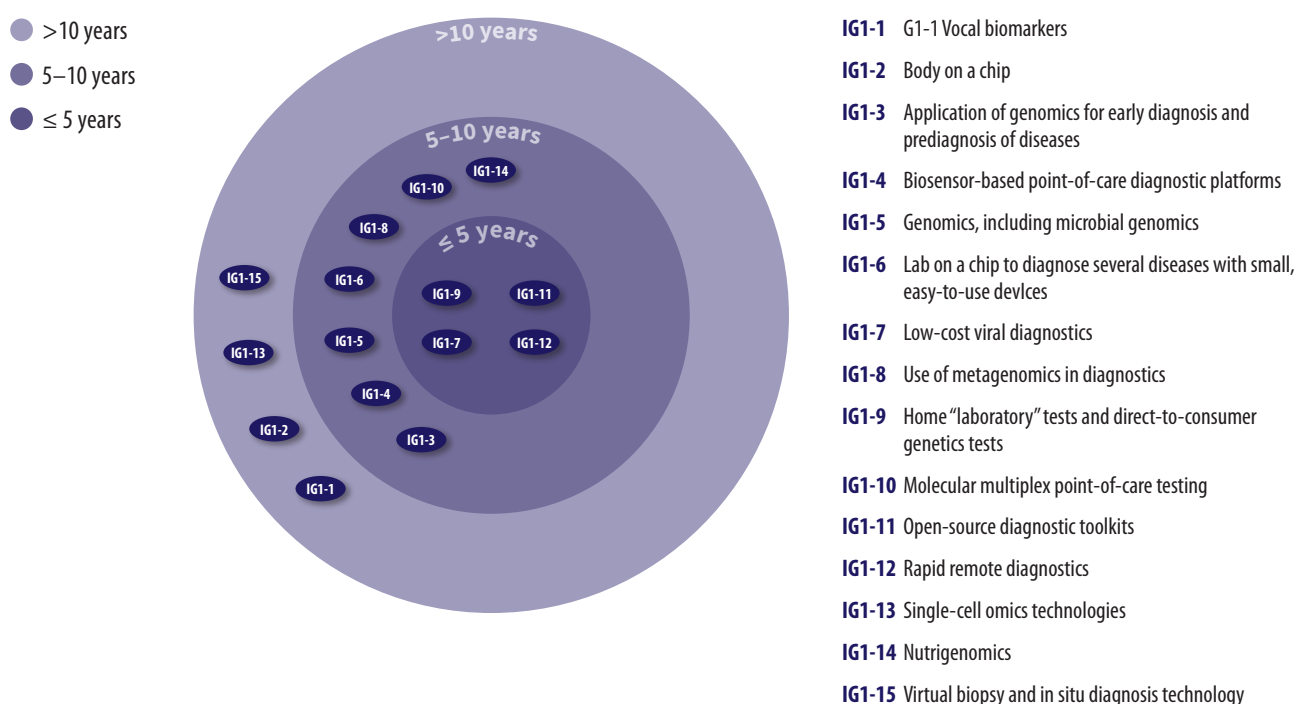


Fig. 7. Innovation group 1: time horizon for adoption

For each innovation considered to have a very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

Low-cost viral diagnostics (IG1-7)

Rapid design and construction of cost-effective point-of-care tests for HIV and hepatitis B viral load testing with CRISPR/Cas techniques to detect nucleic acids will require development of low-cost techniques. Currently, polymerase chain reaction is the preferred method for most nucleic acid-based technologies, but the cost of reagents can be high, particularly when used on a closed analyser or platform, and the technique generally requires sophisticated laboratory equipment that must be maintained and trained personnel. CRISPR-based assays do not require complex, costly laboratory equipment or the reagents used in polymerase chain reaction. Their accessibility will depend on how prices evolve after the development of several tests for viral diseases (7). An example is a project under way in South Africa (8). This innovation would be important for settings where diagnosis is not readily accessible to the population. Cost savings may be achieved; however, diagnostic services often require out-of-pocket expenditure for patients.

Open-source diagnostic toolkits (IG1-11)

A free, open-source toolkit for diagnostics that would allow laboratories in developing countries to produce their own tools (e.g. for research on and diagnosis of coronavirus 19 [COVID-19]) and could reduce dependence on the global supply chain. The open-source approach combines several potential advantages, such as reduced costs and faster innovation, as anyone can improve and contribute to designing devices.

The critical change is the open approach to design, which enables modification for highly specific uses and makes devices easy to repair, at same time reducing the environmental impact. It has been noted that an open-source medical device is safer and more robust, as more people can optimize its design (9). Some cooperative initiatives are being seen. For example, a free, open-source toolkit was developed to allow laboratories in developing countries to work on COVID-19 research and diagnosis (10).

Open-source systems and open platforms may provide advantages such as price reduction; however, their regulation and post-market surveillance may prove complex, such as ensuring accountability in case of adverse events and other incidents (malfunction and deterioration). Functioning quality assurance programmes are necessary to ensure accurate, reproducible results.

Rapid remote diagnostics (IG1-12)

Rapid remote diagnostics connect people through cell phones, watches and other devices (such as smart implants, prostheses and wearable sensors) that can provide information on markers and link health information in real time for clinicians, people and other (public) health entities, supporting individual health promotion, disease prevention and disease (self) management but also providing real-world data (for example for regulatory purposes with post-market surveillance) or informing public health management and health economics. It could be associated with a unique (medical) device identifier and a card containing a chip that stores information that can be used by doctors on any visit.

Rapid remote diagnosis is of particular importance in remote rural locations, far from health-care centres and with difficult access, and can save time and cost (11). Markers such as atrial fibrillation, spikes in blood pressure and falls in blood sugar, heart rate, temperature, blood pressure and oxygen saturation level can be monitored continuously by an individual or by a medical doctor if the data are shared. Devices may start with a few markers and add more over time. Such innovations will require users to be informed on how to read the signs (device result outputs) and act accordingly.

One participant said:

When you get your driver's license, you don't have to have any knowledge whatsoever about how the car works, just needing how to use it. And I think that we pretty much are going to have to go somewhere along those lines with health monitoring. There must be some kind of test that the person who is agreeing to this knows what they are agreeing to.

Lab on a chip (IG1-6)

A “lab on a chip” allows diagnosis of several diseases with a small, easy-to-use device. A laboratory on a chip could be based on CRISPR/cas or a micro-electro-mechanical system with dual-axis confocal micro-endoscopy. These devices automate different laboratory techniques into an integrated system that fits on a chip of up to a maximum of a few square centimetres in size. Manipulation of reagents on a microscale minimizes exposure to dangerous chemicals and waste (12).

One participant reported:

"Lab on a chip is now very close to implementation. For example, laboratory on a chip based on the CRISPR enzyme Cas12."

A key advantage is fast point-of-care testing and initiation of treatment, as no time is required for sending patient specimens to a laboratory and receiving test results.

Home "laboratory" tests and direct-to-consumer genetics tests (IG1-9)

This innovation refers to testing that is usually conducted in a laboratory but that would be accessible at home or in another convenient setting with ability to interpret. Such tests are already available for several diseases; however, the number of diseases for which testing can be done at home could be increased. The COVID-19 pandemic enforced the appeal of self-testing (13). Although home "laboratory" tests hold good promise, their recognition and credibility may still be challenged, and they must undergo proper review and authorization by regulatory authorities. Tests could become available in areas such as genetics, the microbiome, allergies and blood sugar.

One participant said:

At-home laboratory tests are something that became crucial. Because of the pandemic's impact on health care as millions of, I think tens of millions of patients learned how to do at-home laboratory tests, COVID antigen tests. ... And now more and more patients realize that if they can do a laboratory test, even a blood-based laboratory test from home without meeting other sick people and traveling to a point of care, then, of course, they choose the direct-to-consumer solution.

Innovations with high or very high potential impact but less chance of adoption

Molecular multiplex point-of-care testing with new, low-cost, accurate, easy-to-use platforms (IG1-10)

Such tests could be used in primary care facilities to manage illness in a patient-centred rather than a disease-centred way. The illnesses could include respiratory and systemic illnesses or gastrointestinal illnesses.

This innovation was evaluated as having a chance of adoption that was very close to high.

Genomics, including microbial genomics (IG1-5)

Genomics could be used to replace or supplement most current microbiological diagnostic technology. The technology addresses such major issues as pathogen surveillance, global burden of disease and food security. Several other innovations discussed in the exercise are based on genomics.

Investment in genomics and biosensors will be necessary to ensure wide adoption of low-cost point-of-care diagnostics. The WHO Science Council has made recommendations for accelerating access to genomics for global health (14).

Application of genomics for early diagnosis and pre-diagnosis of diseases (IG1-3)

The first such application would be for universal genomic prenatal screening to identify pre-symptomatic metabolic and other congenital disorders to allow precise diagnoses and guide patient management and treatment.

The potential impact and chance of adoption of this specific application of "Genomics including microbial genomics" (IG1-5) were evaluated similarly.

Biosensor-based point-of-care diagnostic platforms (IG1-4)

Diagnostic platforms with chemical, magnetic, optical or nanotechnological modalities would be cheaper, more accessible, more effective alternatives to methods that require polymerase chain reaction. Participants agreed that the chance of adoption would be lower if the point of care was the patient's home. It is, however, expected that the diagnostic could be accessed on a mobile phone.

One participant, referring to the promise of biosensors said:

The field of, of biosensors in general will be growing immensely. Even during this pandemic, simple sensors were widely used. So, with new technology, I think the same thing that you do now, let's say the lateral flow, it will be part of many things that maybe you do automatically, just coughing at your smart watch. So, so I'm pretty sure it's going to go there in 20 years.

Virtual biopsy and in-situ diagnoses (IG1-15)

Use of high-resolution optical imaging would allow analysis of tissues in situ, without having to remove them. This innovation would make biopsy much more efficient, as the process of biopsy currently takes many days. It was considered that, if this innovation became available, it would have a strong impact.

One participant highlighted the possible gains to be expected with this innovation:

The process right now [for biopsy] is going to [magnetic resonance imaging], take the tissue out, look into microscope and reschedule again... But if we can cut all those steps, using high-resolution imaging technology, which is mainly going to be optical, I think that could be the next big thing.

Use of metagenomics in a diagnostics framework (IG1-8)

Use of metagenomics would allow safer, more accurate diagnoses. Metagenomics would allow diagnosis of many diseases at the same time, rather than one by one. One expert considered that this would have a large impact on health, as many diseases are not currently identified.

3.2.2 Innovation group 2: Health products and drug delivery technology

Fig. 8 represents the experts' evaluation of innovations in health products and drug delivery technology in terms of potential impact and chance of adoption.

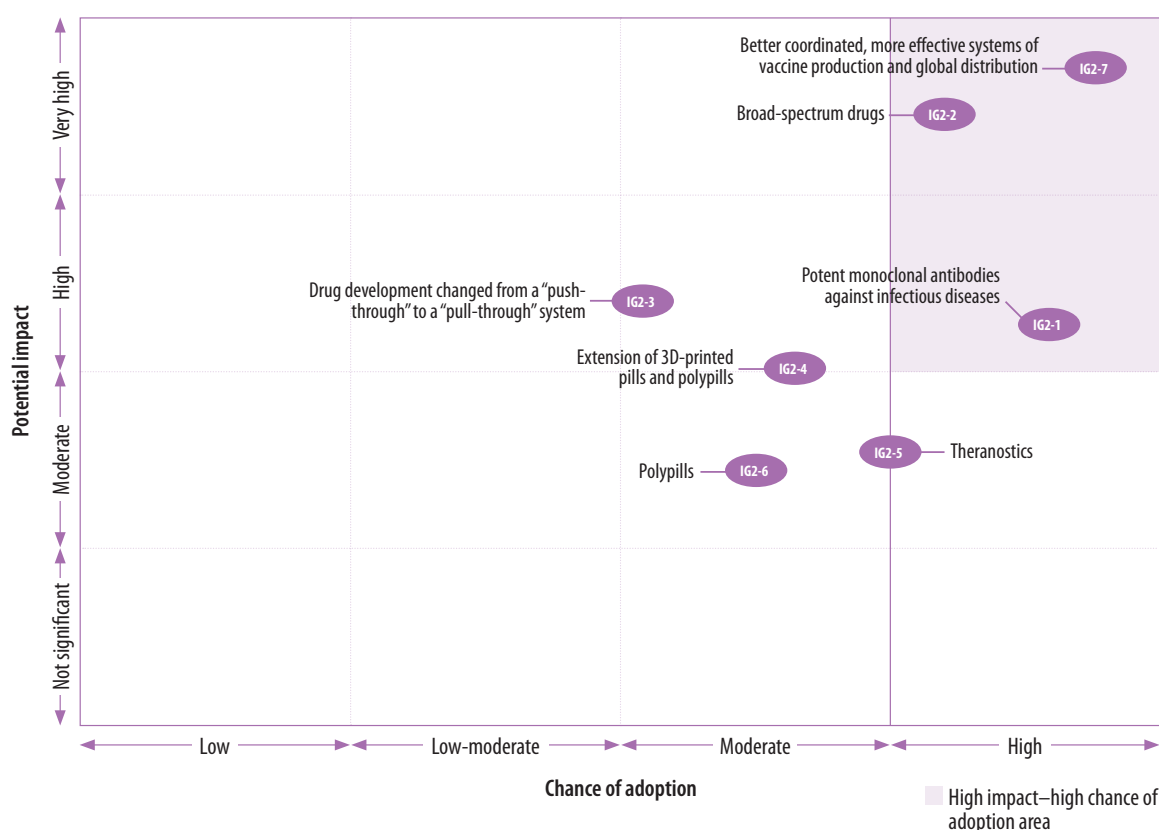


Fig. 8. Innovation group 2: impact vs chance of adoption

Three innovations were considered to have a high or very high potential impact and a high chance of adoption:

- Better coordinated, more effective systems of vaccine production and global distribution
- Broad-spectrum drugs against microbes that do not cause resistance or tolerance, that for example adapt their conformation to target structural changes or mutations
- Potent monoclonal antibodies (mAbs) against infectious diseases

The time horizon for adoption (Fig. 9) is shorter for innovations that were considered to have a high potential impact and a high chance of adoption. Most of the experts considered that all innovations in this group could be adopted within 10 years.

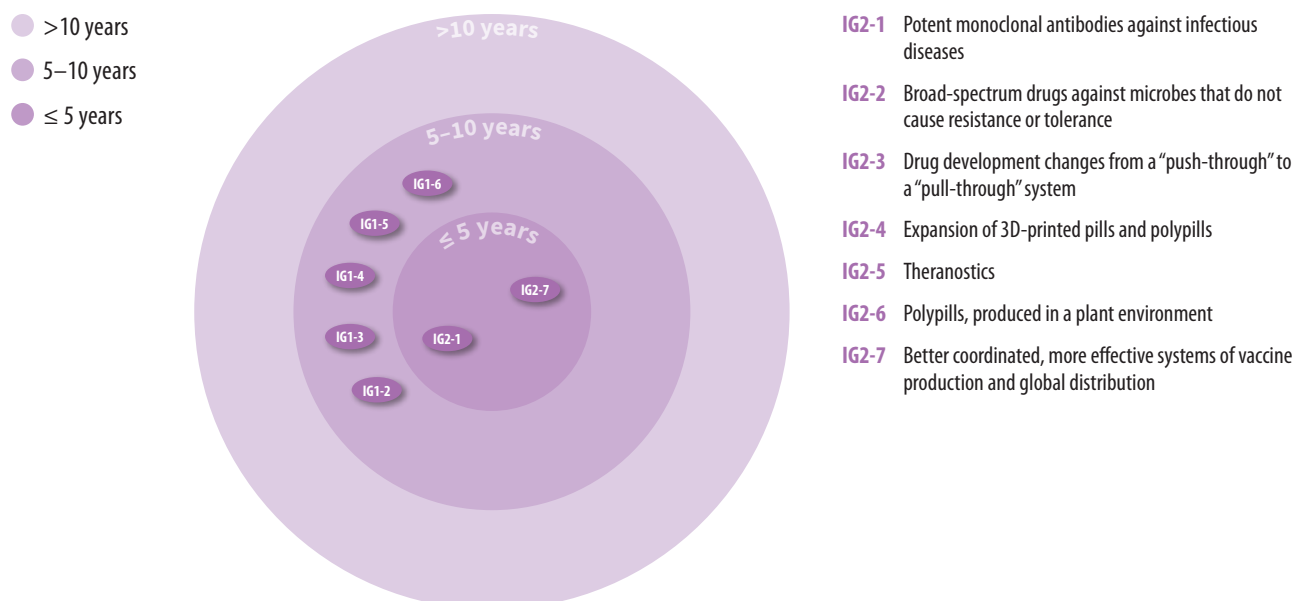


Fig. 9. Innovation group 2: time horizon for adoption

For each innovation considered to have very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

Better coordinated, more effective systems of vaccine production and global distribution (IG2-7)

The COVID-19 pandemic highlighted the importance of more coordinated, effective systems of vaccine production and global distribution. For widespread adoption of this innovation, production centres would be established in several countries, closer to the populations in need. The future would be distributed manufacture. In a recent initiative, the BioNTech company developed containers of a module for mRNA vaccine bulk production to be shipped to Rwanda (15).

One participant noted:

I think we are going to see more and more consciousness and development of sustainable business models to localize production in low middle income countries. Also, for advanced products.

This innovation could result not only in the design of new vaccines but also in faster production and testing. Production systems can be expected to change. Another innovation in this area is re-purposable vaccines using technology platform, such as RNA, DNA and proteins, to optimize production systems for several diseases.

As an imagination of a possible future, one participant said:

We will have old vaccines – rabies, yellow fever – being produced on a platform or a virus-like particle platform or a DNA platform that is rapid, cost-effective, adaptable and easier scaled. So, we will repurpose some of the existing older vaccines.

Application of such innovation could strongly impact the infectious disease landscape.

Broad-spectrum drugs (IG2-2)

This innovation concerns broad-spectrum drugs against microbes, that do not cause or reduce the risk of resistance or tolerance. For instance, drugs could adapt their configuration to match a change in the target microbe or a new structural change caused by mutations. Nanotechnology might be used for developing such drugs in the future.

One participant said:

“Although now the drugs are static, in the future, I can foresee that the nano structures will change as they sense that the target has changed.”

Some concern was expressed about the risk of microbial resistance to broad-spectrum antibiotics associated with non-compliance with long-term use of such drugs. It is, however, foreseen that some innovations will reduce the use of antibiotics, as new technology may be used to increase their functionality and bioavailability. In such an approach, antibiotic use would be restricted to severe infections with non-resistant microbes.

Another topic discussed was the bioavailability of health products to reduce the global burden of microbes in water and soil, in which the ecosystem of antibiotic use would be replaced by vitamins, minerals and natural products.

Traditional funding of innovations for bacterial infections was considered a challenge, as the model is not attractive enough for most private actors. A possible solution could be new pricing models for broad-spectrum drugs and new avenues for funding innovations.

Potent monoclonal antibodies against infectious diseases (IG2-1)

Potent mAbs against infectious diseases were rated as having a high potential impact on global health but were considered to require some improvement before they could be widely adopted. mAbs may be intended for treating or preventing infections. The first and second mAbs for infectious diseases were approved for use in the European Union 18 years apart, suggesting that research may still be necessary (16).

Research is under way on mAbs to treat patients with Middle East respiratory syndrome, and advances were made against Ebola virus disease, which provides some evidence of the promise of this technology (16). mAbs could be also be used against other diseases, including non-communicable diseases.

To be effective, mAbs should be used early in an infectious disease to neutralize the pathogen before it has the chance to establish an infection.

One participant noted:

“It is possible to take B cells from a recovered person and make monoclonal antibodies in a laboratory setting in a week’s time.”

One of the points debated was the high cost of this innovation, which would limit widespread adoption, in particular in low- and middle-income countries (LMIC). Better coordination of research and funding would be required to develop these approaches and find ways to distribute them. Greater potency would require lower doses, which would pave the way for intramuscular administration of these treatments rather than intravenously, so that they might be easier to administer.

One participant commented:

“The potency piece for me, I take as the critical piece of the innovation to reduce cost of goods and increase delivery, to lower middle-income countries”.

Innovations with a high or very high potential impact but less chance of adoption

Change in drug development from “push-through” to “pull-through” systems (IG2-3)

Drug development would change from a “push-through” to a “pull-through” system, and drug developers would act as contractors, instructed to develop drugs with the highest social interest.

Participants commented that, to increase adoption, procurement and funding should be improved.

Further development of 3D-printed pills and polypills (IG2-4)

Further development of 3D-printed pills would make medicines more readily available at points of care. Some of the experts considered that the time horizon for achieving this innovation would be long, especially for polypills.

3.2.3 Innovation group 3: Tissue engineering and regenerative medicine

Fig. 10 represents the experts' evaluation of innovations in tissue engineering and regenerative medicine in terms of potential impact and chance of adoption.



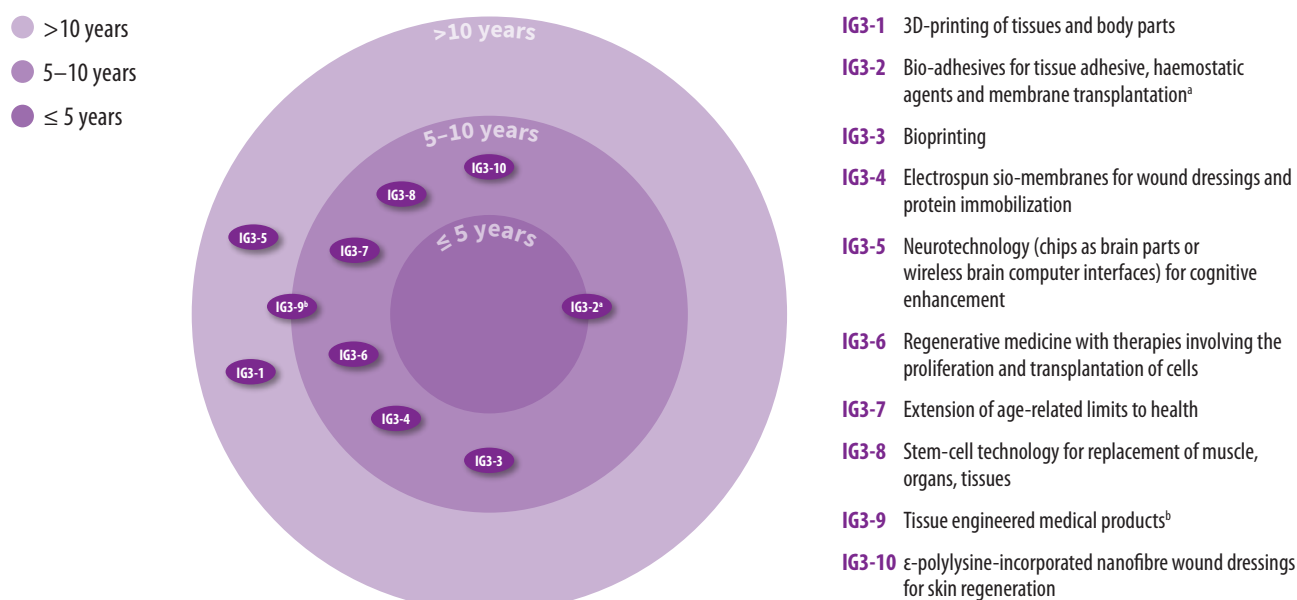
Fig. 10. Innovation group 3: impact vs chance of adoption

Three innovations were considered to have a high or very high potential impact, with a high chance of adoption:

- Stem cell technology for replacement of muscles, organs and tissues
- Regenerative medicine with therapies involving proliferation and transplantation of cells
- Bio-adhesives for tissue adhesion, haemostatic agents and membrane transplantation

Most of the experts considered that all these innovations could be adopted within 10 years (Fig. 11).





^a The numbers of votes for ≤5 years and 5–10 years were very close.

^b The numbers of votes for 5–10 years and >10 years were equal.

Fig. 11. Innovation group 3: time horizon for adoption

For each innovation considered to have very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

Stem-cell technology (IG3-8)

This innovation refers to stem cell technology for replacement or regeneration of muscle, organs (eyes, ears), bone, teeth and, later, heart, brain and neural tissues, such as transplantation of retinal cells to treat blindness. It is part of regenerative medicine.

Stem cells are those from which cells with specialized functions are generated. Stem cells then divide to form daughter cells, which become either new stem cells or are differentiated into cells with more specific functions, such as blood, brain, heart muscle and bone cells (17). Stem-cell technology can be combined with gene editing.

Advances in stem-cell technology could allow testing of new drugs for safety and efficacy. The technology is available, and most of the experts considered that it could be widely adopted in 5–10 years.

Regenerative medicine (IG3-6)

Regenerative medicine, involving the proliferation and transplantation of cells to improve the function of cells, tissues or organs, holds promise for treatment of diseases such as diabetes and nervous system and cardiovascular disorders. For global health, regenerative medicine offers a potentially curative option, which could reduce the burden on health-care systems.

Several barriers remain before regenerative medicine becomes widely adopted. One is incomplete understanding of how to alter cellular systems to enable regeneration, which still contributes to a high failure rate. The second is that regenerative medicine is expensive, as it is in its infancy, limiting its uptake. The third is the manufacture of regenerative medicines, which is complicated by the living nature of the biological products and will limit distribution to some regions.

Bio-adhesives for tissue adhesion, haemostatic agents and membrane transplantation (IG3-2)

The clinical applications of bio-adhesives appear to be multiple, including as tissue adhesives, haemostats and tissue sealants. They have been applied in various fields, such as functional wound dressing, factor delivery vehicles and medical device fixation (18). Bio-adhesives are also promising for amniotic membrane transplantation in ophthalmological surgery (19).

Innovations with a high or very high potential impact but less chance of adoption

Bioprinting (IG3-3)

Bioprinting would enable standardized production, parallelization and tailored design of human tissue, human disease models and patient-specific tissue avatars. Participants noted that bioprinting has already shown wide potential and is already being adopted. The category is broader than 3D-printing of tissues and body parts, which it encompasses.

Tissue-engineered medical products (IG3-9)

Tissue-engineered products require substantial manipulation to regenerate, repair or replace human tissue. A tissue-engineered product may contain cells or tissues of human or animal origin, or both.

Electrospun sio-membranes (IG3-4)

This innovation concerns use of electrospun sio-membranes for wound dressings.

Neurotechnology (chips as brain parts) (IG3-5)

Neurotechnology, including chips as brain parts and wireless brain computer interfaces, could increase cognitive functions such as learning capacity and memory in ageing people who experience changes in memory and brain function.

The experts considered that the existence of external aids and tools to lengthen healthy life would support adoption of this innovation. Consensus was, however, low, mainly because this innovation will become available only in > 10 years.

3D-printing of tissues and body parts (IG3-1)

The experts considered that 3D-printing of tissues or body parts (such as arms and legs) or for organ function would be adopted at the same pace. Printing of tissues and some small parts might become available sooner. The complexity depends on the body part (e.g. leg and liver are of different complexity).

Extension of age-related limits to health (IG3-7)

As people are living longer, innovations that can extend the limits were considered promising, although the chance of adoption was considered low.



3.2.4 Innovation group 4: Molecular biology, cell, immune and gene therapy

Fig. 12 represents the experts' evaluation of innovations in molecular biology and cell, immune and gene therapy in terms of potential impact and chance of adoption.

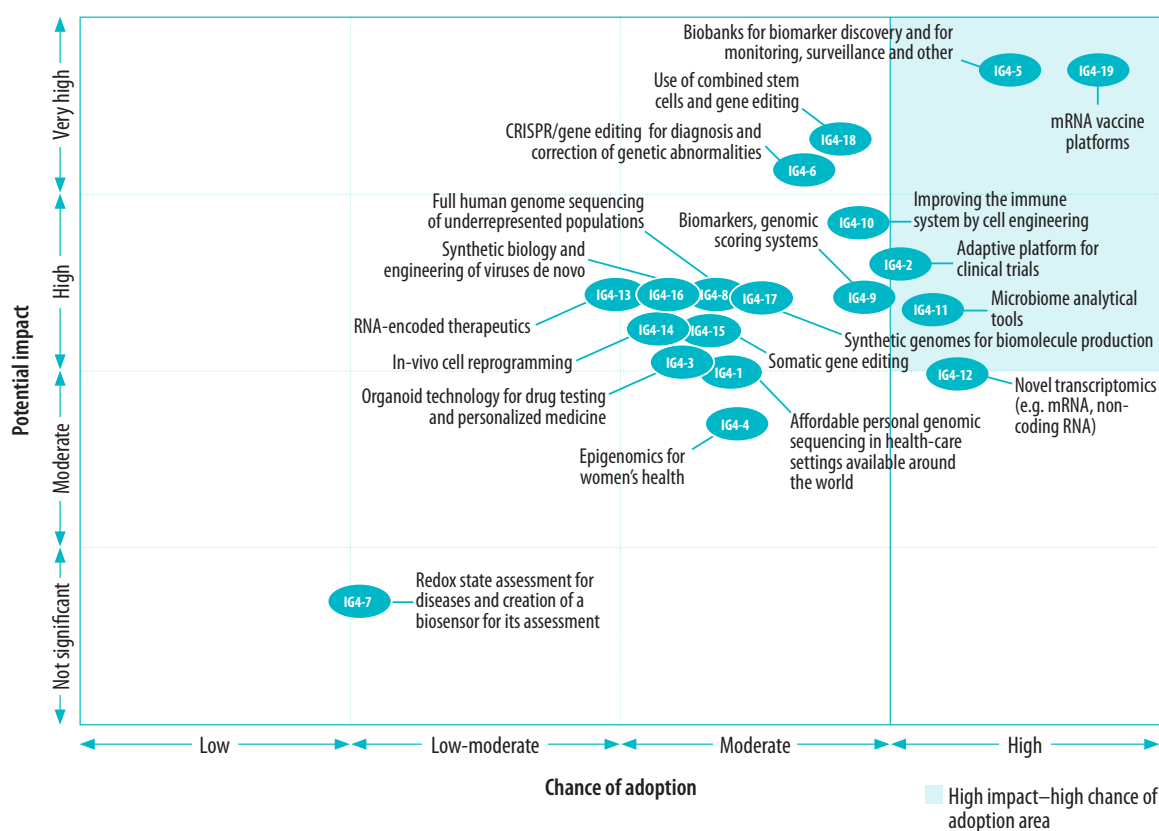


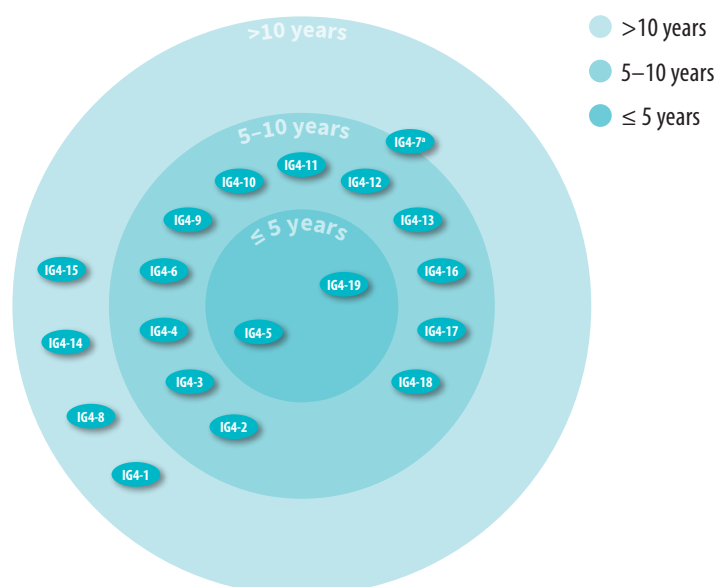
Fig. 12. Innovation group 4: impact vs chance of adoption

Four innovations were considered to have a very high or high potential impact and a high chance of adoption:

- Biobanks for discovery of biomarkers and for monitoring, surveillance, testing, diagnosis and improving the response to pandemics
- mRNA vaccine platforms as a new way of programming for antigenic stimulation, which could result in new vaccines for tuberculosis, HIV, syphilis, hepatitis B, cancer and other diseases with complex immunology
- Adaptive platform trials in which several interventions are studied together
- Microbiome analytical tools for research, clinical prevention and treatment

The time horizon for adoption (Fig. 13) was shorter for the innovations considered to have a high potential impact and a high chance of adoption (IG4-5 and IG4-19). Most of the experts considered that all four innovations could be adopted within 10 years.

- IG4-1** Affordable personal genomic sequencing in health-care settings available around the world
- IG4-2** Adaptive platform trials in which multiple interventions are studied continuously
- IG4-3** Organoid technology for drug testing and personalized medicine
- IG4-4** Epigenomics for women's health
- IG4-5** Biobanks for biomarker discovery and for monitoring, surveillance, testing and diagnosis
- IG4-6** CRISPR/gene editing for diagnosis and correction of genetic abnormalities
- IG4-7** Redox state assessment for diseases and creating a biosensor for its assessment^a
- IG4-8** Full human genome sequencing of underrepresented populations
- IG4-9** Further genomic tools, including biomarkers, genomic scoring systems
- IG4-10** Improving the immune system by cell engineering
- IG4-11** Microbiome analytical tools for research and clinical prevention and treatments
- IG4-12** Novel transcriptomics (mRNA, non-coding RNA) associated with new nano tools
- IG4-13** RNA-encoded therapeutics
- IG4-14** In vivo cell reprogramming



- IG4-15** Somatic gene editing
- IG4-16** Synthetic biology and engineering of viruses de novo
- IG4-17** Synthetic genomes for biomolecule production
- IG4-18** Use of stem cells, cellular senescence and gene editing
- IG4-19** mRNA vaccine platforms

^a The numbers of votes for 5–10 years and > 10 years were equal.

Fig. 13. Innovation group 4: time horizon for adoption

For each innovation considered to have very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

Biobanks for biomarker discovery and for monitoring and surveillance (IG4-5)

Biobanks and associated meta-data are proposed for biomarker discovery and for monitoring, surveillance, testing, diagnosis and improving the response to pandemics. Malsagova et al. (20) noted that collections of biological material are necessary for finding biomarkers of pathological conditions, identifying new therapeutic targets and validating the findings in samples from patients and from healthy people. They noted the growing importance of biobanks during the past few decades, with large national and international biorepositories replacing small collections of biological samples. They commented that the ability to compare data and biological samples from different biobanks is critical to accelerating translational research.

mRNA vaccine platforms (IG4-19)

mRNA vaccination platforms represent a new way of programming for antigenic stimulation, and this innovation could result in new vaccines and therapeutics for tuberculosis, HIV, syphilis, hepatitis B, cancer and other diseases such as malaria, autoimmune diseases.

As expressed by one expert, reflecting on possible future, innovations may be driven from various regions of the world:

We are going to see innovative work around durability of these [mRNA] vaccines, we are going to see innovative work around their stability. Moving away from cold chains that require minus 20 and minus 10 and minus 80, which is fine for the “global north”, but not practical for the “global south” so that innovation is going to be stimulated by the need to reach the last mile.... We are going to see innovations around the cost of goods, we are going to see innovations around the supply of raw materials. We are going to see innovation driven by the need to have health security and by the need to be sustainable, more than ever.

The expectations are high; however further research on and investment in this technology are anticipated. It will be difficult to make mRNA vaccines against some viral, bacterial and protozoal diseases, although the field may progress.

A participant in the horizon scan reflected on how mRNA technology could be extended to other diseases:

We are generating through mRNA technology a whole new way of programming for antigenic stimulation. And I anticipate that we are likely to see in the next five years an explosion of new vaccines based on mRNA technology.... So neglected diseases are going to get a big shot in the arm because of mRNA technology.

mRNA-based therapeutics thus could lead to promising therapeutics for infectious diseases such as malaria and tuberculosis and also for cancer.

Regarding the horizon time, one participant said:

I foresee vaccines against cancers of various types. These have been talked about for many decades. But I think, technology is just now coming to the point where these would be possible.

Microbiome analytical tools (IG4-11)

Microbiology-based research and other applications for wellness, prevention and treatment have a high potential impact for health care and for personalized medicine. The microbiome plays an important role in human health and disease, with possible investigations for the development of innovative treatment strategies, using advances in next-generation sequencing to identify and quantify the microorganisms in human specimens (21).

Adaptive platform trials (IG4-2)

Adaptive platform trials in which several interventions are studied continuously, and for people with multi-morbidity, are required by many stakeholders in clinical trials of innovative molecules and devices in order to compare interventions in subgroups of patients with related conditions or clinical features. In an adaptive platform trial design, several interventions may be investigated continuously, with interventions entering and leaving the platform according to a decision algorithm (22).

For example, the “randomized, embedded, multifactorial adaptive platform trial for community-acquired pneumonia” is an international, phase-IV clinical trial of combinations of conventional care and experimental treatment for adults with severe community-acquired pneumonia (22).

Innovations with a high or very high potential impact but less chance of adoption

Use of stem cells, cellular senescence and gene editing (IG4-18)

Stem cells provide two main benefits for gene and cell therapy. First, they can self-renew and may survive the lifetime of the patient. Secondly, they provide daughter cells that mature into the specialized cells of each tissue.

Reference to stem-cell technology is also made in IG3-8.

CRISPR/cas gene editing for diagnosis and correction of genetic abnormalities (IG4-6)

This innovation refers to use of CRISPR/cas gene editing for diagnosis and correction of genetic abnormalities such as sickle-cell disease. Gene editing might make it possible to eliminate diseases such as HIV infection, by taking out part or all of the CCR-5 gene to cure or prevent disease.

As an imagination of a possible future, one participant commented:

“It’ll be a cure and it’ll be a prevention. So, everybody who’s at risk can just take their CRISPR and avoid getting HIV”.

Improving the immune system by cell engineering (IG4-10)

An example of this innovation is use of chimaeric antigen receptor T cells (CAR-T cells) against blood cancers.

Exploitation of further genomic tools, including biomarkers and genomic scoring systems (IG4-9)

This innovation refers to further genomic tools, including biomarkers, genomic scoring systems for precise prevention and diagnosis and personalized therapies.

Synthetic genome for biomolecule production (IG4-17)

Construction of viruses, bacteria and eukaryotic cells with synthetic genomes would provide new opportunities for medicine, industry and research, such as next-generation vaccines.

Full human genome sequencing of underrepresented populations (IG4-8)

This innovation refers to a human “pangenome” that would represent almost the entirety of human genetic variation (23). The experts considered this an important step, as sequencing of the full human genomes of underrepresented populations would provide much-needed data for research on diseases.

Somatic gene editing (IG4-15)

Somatic gene editing of sperm, eggs and embryos for prevention and treatment would allow, for example, heritable gene editing to prevent genetic diseases such as sickle cell disease and thalassaemia.

Synthetic biology and engineering of viruses de novo (IG4-16)

This innovation in synthetic biology would permit engineering of viruses de novo from publicly available sequence data. The possibility of rapid construction, synthesizing and editing genes and genomes would provide numerous socially useful applications, such as new therapies (24).

RNA-encoded therapeutics (IG4-13)

This innovation refers to RNA-based formulations emerging as potential treatment options for many diseases, including COVID-19 and acute hepatic porphyria.

In-vivo cell reprogramming (IG4-14)

Direct, in-vivo reprogramming for local conversion of cells in situ is emerging as an alternative to regenerative medicine that would not require cell transplantation.

Organoid technology for drug testing and personalized medicine (IG4-3)

Organoids that resemble organs could be grown from adult stem cells or pluripotent stem cells (25), representing promise for use in clinical research and in the development of new treatments for personalized medicine (e.g. inflammatory bowel disease) (25).

This innovation was proposed by experts during a roundtable. Making an organ such as a pancreas to study diseases such as cancer or to develop drugs was cited as an example.

One participant described an example of the use of organoids:

For Zika virus, people have made brain organoids to study what damages the brain. In infectious disease, people are trying to see what is happening in the infected tissue, because you might not get every time the infected tissue from the body.

Affordable personal genomic sequencing for health-care settings globally (IG4-1)

Genomic research is still not translated equitably into patient care, particularly in LMIC. Some recent initiatives to promote capacity-building and infrastructure development include the Human Heredity and Health in Africa (H3Africa), the Qatar Genome Project and the Mexico National Institute of Genomic Medicine (26).

3.2.5 Innovation group 5: Public health: environment, climate change, epidemiology and surveillance, nutrition and health

Fig. 14 represents the experts' evaluation of innovations in public health in terms of potential impact and chance of adoption.

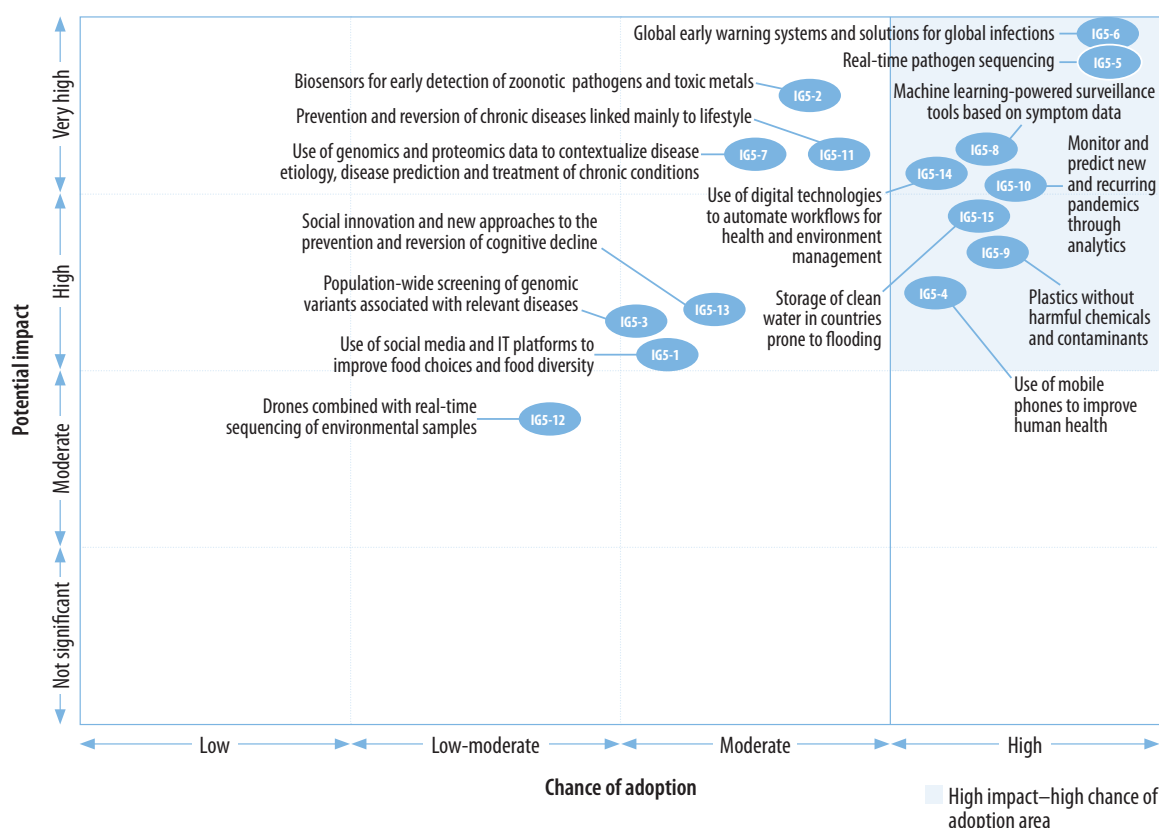


Fig. 14. Innovation group 5: potential impact vs chance of adoption

Eight innovations were considered to have a very high or high potential impact and a high chance of adoption:

- Global early warning systems and solutions for global infections
- Real-time pathogen sequencing
- Machine learning-powered surveillance tools based on symptom data
- Use of digital technology to automate workflows in health and environment management
- Monitoring and predicting new and recurrent pandemics with analytics
- Storage of clean water in countries prone to flooding
- Plastics without harmful chemicals or contaminants
- Use of mobile phones to improve human health

The time horizon for adoption (Fig. 15) is short for five of the eight innovations considered to have a high potential impact and with a high chance of adoption (IG5-6, IG5-5, IG5-10, IG5-15 and IG5-4). Most of the experts considered that all the innovations in this group could be adopted within 10 years.

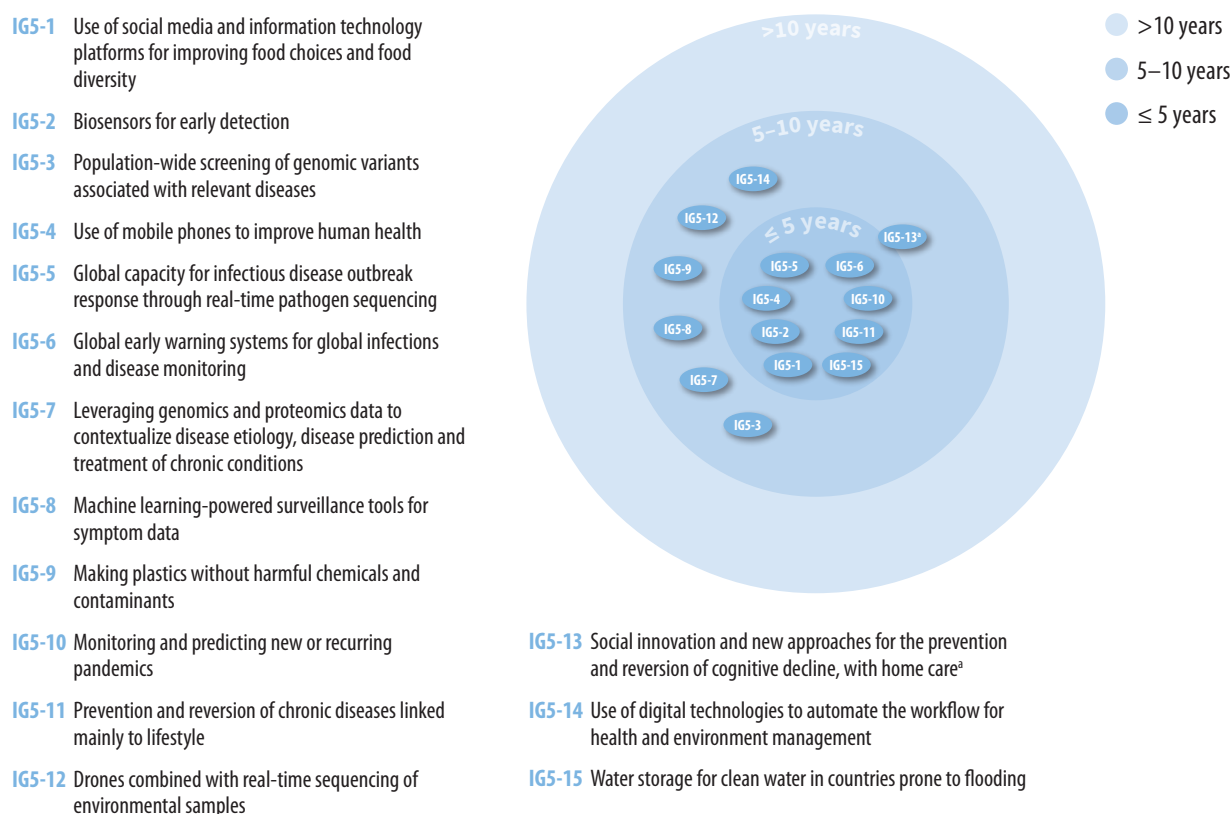


Fig. 15. Innovation group 5: time horizon for adoption

Many of the innovations that were considered to have a high potential impact and a high chance of adoption are for surveillance and real-time monitoring. Full descriptions of each innovation are provided in Annex 1.

One participant commented that several innovations in this group are linked:

I think consistent surveillance systems tailored towards real time is one of the areas that many of these other factors can build on, including monitoring, predicting new pandemics and global early warning system.

For each innovation considered to have a very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan.

Global early warning systems for global infections (IG5-6)

Global early warning systems and solutions for monitoring the conditions related to the emergence of global infections and for disease monitoring include genomic surveillance of pathogens and information technology to identify potential zoonoses.

Consensus on the potential impact of this innovation was strong, and the timeframe for adoption was within 5 years. This innovation could therefore contribute to surveillance and outbreak detection. As information accumulates, its use for prediction will increase.

These warning systems depend on people sharing data, which will be more likely if they know that their data are protected and if they have incentives. During the COVID-19 pandemic, data-sharing increased substantially.

Reflecting on possible future, one participant said:

With climate change going on, the environment will change, and diseases will change, too. So, monitoring of the environment is important. There will be more tropical diseases, even in the cool countries. So, there would be new potential for what we call zoonosis or zoonotic diseases. So, we can predict or monitor the environment using genomics and various [information technology] tools. It is now very easy to have genomics, through the nanopore technology, very quick and very cheap. So, you can really sense the genomes of various microbes and others in the environment.

Real-time pathogen sequencing (IG5-5)

The innovation would increase global capacity for rapid responses to infectious disease outbreaks through real-time pathogen sequencing for surveillance, with equitable sharing and distribution of countermeasures.

There was strong consensus on the potential impact of this innovation for global health. Some experts considered that the chance of adoption was low, mainly because the innovation would be difficult for lower-income countries to adopt. Finding methods for real-time pathogen sequencing in LMIC is a key consideration. Use of portable genomic sequencers might be possible to enable rapid in-situ diagnosis through amplicon-based or metagenomics approaches, creating a stream of genomic data that reveal critical epidemiological aspects of the dynamics of an outbreak or epidemic.

Machine learning-powered surveillance tools with data on symptoms (IG5-8)

Machine learning-powered surveillance tools with data on symptoms, interpretation of in vivo diagnostic tests (e.g. imaging, electrocardiograms) and algorithms for selecting further testing would provide data for improved clinical management and public health surveillance. Early, accurate, reliable signals of disease outbreaks from a heterogeneous collection of data are essential for public health surveillance. Data must be identified to obtain useful signals, with analytical methods to extract and interpret the data.

Machine learning, like AI, requires good data. The experts commented that, in many countries, data are still difficult to obtain, and few countries use electronic health records. Both machine learning and AI require systems for collecting and analysing data.

Use of digital technology to automate the work flow for health and environment management (IG5-14)

Digital technology would be used to automate collection and analysis of data on health and the environment to better predict, prevent and reduce environmental risks to health, combining human and animal health, environment and climate data. Modifiable environmental risks cause about one fourth of global deaths (27).

Understanding the role of the environment in public health often requires collection and analysis of complex data sets (28). Digital technologies that automate the analysis of environmental data to better predict environmental risks to health are valuable, as they can save lives.

Like other innovations, this one depends on collection of data for algorithms to predict environmental risks. The most important technical challenge is a lack of people trained to use such models systematically in public health. Even when data are available, the technical skills to create, analyse and draw conclusions from the data with tools such as AI and machine learning are not currently available in all research hubs and academic institutions. Collaborative data curation and storage, scientific computing and training are essential to empower researchers to realize the full potential of AI approaches (28).

Monitoring and predicting new and recurrent pandemics with analytics (IG5-10)

New and recurrent pandemics could be further monitored and predicted by analysing medical records, mobile phone traffic, social media and other sources. Advanced data analytics can be used in the detection of outbreaks and in predicting future outbreaks from data on risk factors and context. Data on population mobility and data mining in search engines and social media could be used to find timely information on where diseases are occurring and where they might occur next (29).

More and more people use mobile phones, and the technology is also accessible in lower-income countries. Tracking is best conducted by integrating data from diverse data sources, not only from social media but also from public

voluntary and participatory sources, health and environment sources. Such data would facilitate building of models to predict future outbreaks, epidemics or pandemics – preparing the world to act.

A major challenge is the availability of data and the ease of collecting them. Well-organized data ensure progress in these new areas.

One participant commented:

Predicting and dealing with new and recurring diseases, especially pandemics will be important. Ability to monitor or predict new or returning pandemics doesn't involve just medical technologies, also analysis of reports or medical records is critical. You can monitor mobile phone traffic, social media, and you can see some indicators of something that has to be watched for.

Storage of clean water in countries prone to flooding (IG5-15)

Participants considered that innovation in storage of clean water would have a high potential impact, although there was no strong consensus.

Climate change is increasing variations in the patterns and intensity of rainfall, which can have serious consequences, such as floods and drought (30). As contaminated water is a source of several infectious diseases, storage of water in times of heavy rain, to be used when there is no rain, makes countries more resilient to such diseases. Water storage systems could be better managed with use of progress in sensors, satellite technology, machine learning and AI. Innovative materials could also improve infrastructure, such as removable rubber dams, and decrease costs (31,32).

Plastics without harmful chemicals and contaminants (IG5-9)

This innovation calls for a change in the plastics manufacturing process. Plastics account for about 85% of marine pollution (33), and the production of plastics is expected to double in the next 20 years (34). Plastics are broken down into microplastics, which become magnets for contaminants in the oceans, creating concentrations of toxins. Microplastics can also enter the human body by inhalation and absorption (34).

The aim of alternative plastics, such as biodegradable compostable plastics, is a smaller environmental imprint. Their own sustainability should, however, be fully assessed (35).

Use of mobile phones to improve human health (IG5-4)

This innovation concerns the use of mobile phones and other wearable technologies to improve human health with sensors, data linkage and analytics. Penetration of mobile phones in the world is high, and several apps and wearables allow sharing of health information.

One participant reflected on how mobile phones could contribute to improving human health:

70% of people in the world have a mobile phone, therefore 70% of people in the mobile world are our data gatherers. We can reward them for gathering that data also. We are using the potential of having many data points about patients and people and having all their data in one place so that people can use them better. Combine that with the genetic information, genetic makeup, what their likely prospects are, you can in advance manage some of the conditions. That's the capacity of the Web 3, internet of value.

Data provided by mobile phones will be important for public health and surveillance, and experience could be scaled up to make a larger impact on global health at an affordable cost.

Innovations that have a high or very high potential impact but less chance of adoption

Biosensors for early detection of zoonotic pathogens and of toxic metals (IG5-2)

Participants debated the use of biosensors for early detection of zoonotic pathogens and detection of toxic metals in food and water supply systems. They came to a consensus that more biosensors would be used in the future and that the technology will mature.

Use of genomics and proteomics data to contextualize disease etiology, disease prediction and treatment of chronic conditions (IG5-7)

Most of the experts considered that this innovation would be promising for widely different populations around the world. For it to be leveraged, more population-specific data on human genomics and proteomics are necessary.

Prevention and reversion of chronic diseases linked mainly to lifestyle (IG5-11)

Prevention and reversion of chronic diseases linked mainly to lifestyle (such as type 2 diabetes) would require changing health systems and training health workers and patients. Changing the way in which health systems communicate with patients is also important, as the communication channels for young people today are very different from those used previously, and the system should adapt.

One participant said:

"I think that the greatest innovation will be in the change of lifestyle and in the first level of the health system."

Population-wide screening of genomic variants associated with relevant diseases (IG5-3)

There was little consensus on the potential impact of this innovation, even with affordable, population-specific genomic assays. Genomic sequencing has been shown to be useful by providing indicators for diagnosing certain diseases; however, the complete potential of DNA sequencing as a non-diagnostic tool for population screening has not yet been reached. Several challenges would have to be overcome, such as in health equity; ethical, legal and social implications; use in primary care; and lack of evidence on its clinical usefulness and long-term outcomes (36).

Social innovation and new approaches to the prevention and reversion of cognitive decline (IG5-13)

Social innovation and new approaches appear necessary, such as home care and stimulation of brain activity through socialization and well-planned activities, instead of the institutionalized model.

One participant, commenting on social innovation, said:

We need other types of innovations, or different models on how we deal with cognitive decline condition.... There needs to be also a health system as well as a social innovation, which makes it possible to keep old people at home, to keep them not only at home in a wheelchair or looking through a window, but also where there is a social organization that allows these older people to be stimulated intellectually so that they can remain independent, or as much as independent as possible in their own homes.

Use of social media and information technology platforms to improve food choices and food diversity (IG5-1)

This innovation would require consideration of the affordability of foods according to socioeconomic level. Strong consensus was found regarding the potential impact of this innovation on global health. As patients have more and more information and use it to make decisions about their health, good, directed information on food choices can contribute to empowering people to make better choices.

One participant, commenting on the transformative role of patient empowerment, said:

Patient empowerment is, I think, the biggest milestone in the history of medicine.... If anyone asks me what, what the next 5 or 10 years in health care, are going to be, I would say that this idea or concept that patients are becoming the members of their medical team, that they start sitting at the same table where they start becoming, equal partners with their health-care professionals, alone will mark the next decade.



3.2.6 Innovation group 6: Dissemination and implementation

Fig. 16 represents the experts' evaluation of innovations in dissemination and implementation in terms of potential impact and chance of adoption.

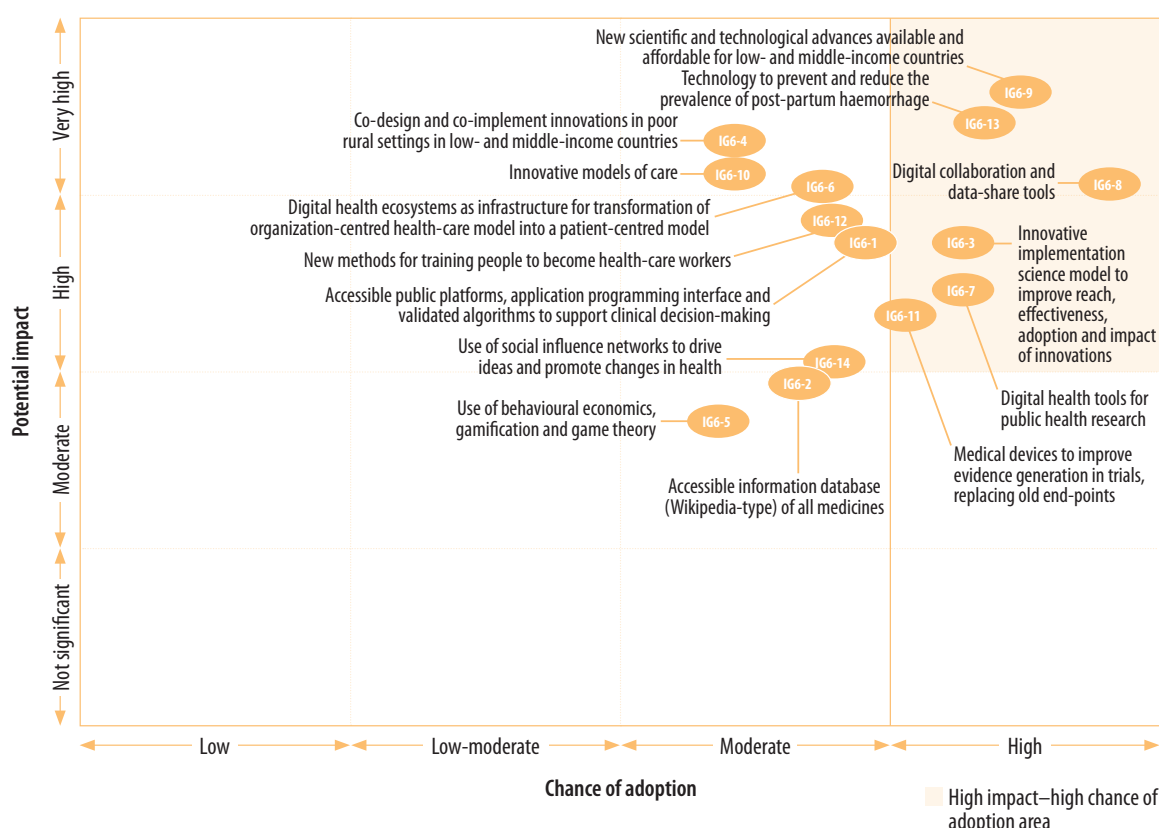


Fig. 16. Innovation group 6: potential impact vs chance of adoption

Six major innovations were considered to have a very high or high potential impact and a high chance of adoption:

- Innovations to make new scientific and technological advances available and affordable in low- and middle-income countries
- Technology to prevent and reduce the prevalence of post-partum haemorrhage that is understood and can be applied by women and adolescent girls in hard-to-reach communities in low- and middle-income countries
- Digital collaboration and data-sharing tools
- An innovative implementation science model for improving the reach, effectiveness, adoption and promise of innovations
- Digital health tools both for public health research and the development of new clinical preventive measures, treatments and vaccines
- Medical devices to improve the generation of evidence in trials, replacing previous end-points

The time horizon for adoption of most of the innovations (Fig. 17) was the next 5–10 years, probably because their adoption depends not only on technology but also on public policy and regulation.

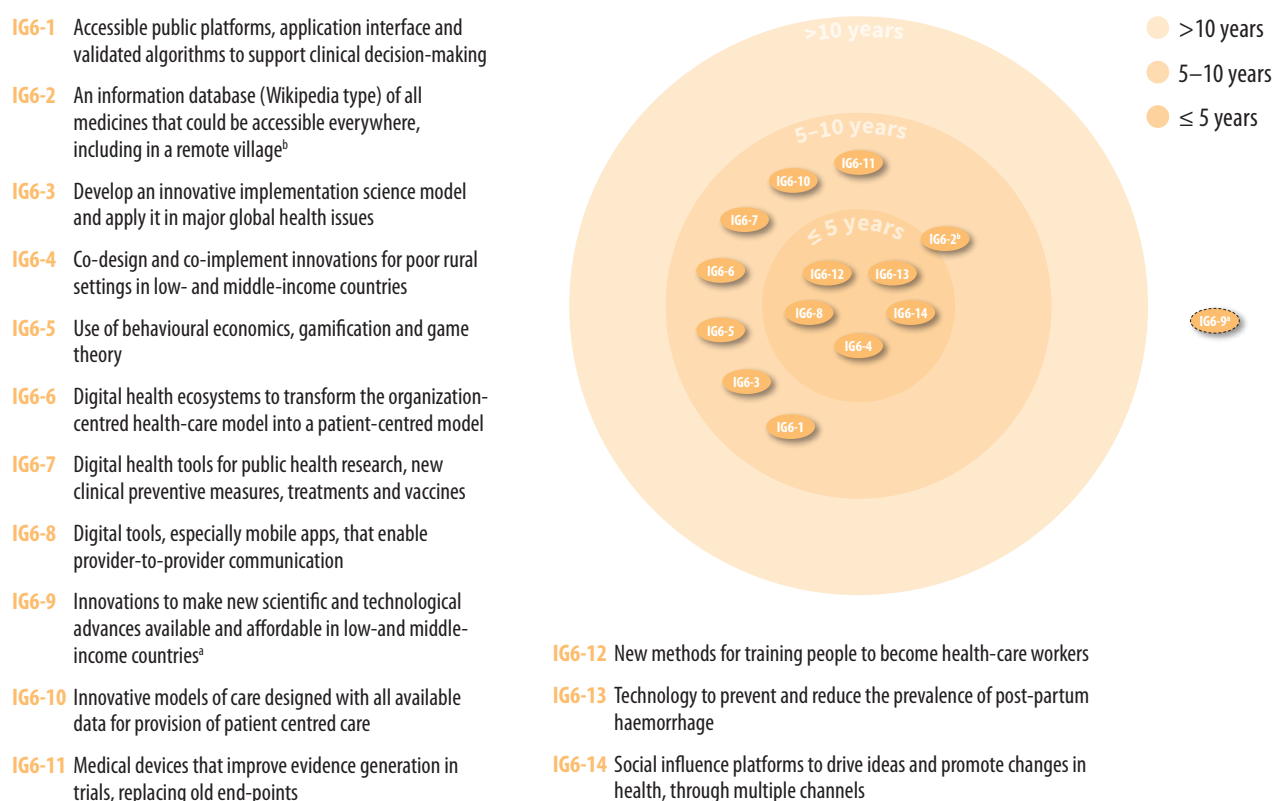


Fig. 17. Innovation group 6: time horizon for adoption

For each innovation considered to have very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

Innovations to make new scientific and technological advances available and affordable in low- and middle-income countries (IG6-9)

Poor health care is a major driver of excess mortality in LMIC (37). Emerging technologies such as the Internet of Things, Big Data and cloud computing are transforming health care, including access and cost. For example, wearable devices allow constant monitoring of a patient's condition. AI and deep learning could also be used in interpreting X-ray images (38).

Technology to prevent and reduce the prevalence of post-partum haemorrhage (IG6-13)

Post-partum haemorrhage is the cause of nearly 25% of maternal deaths (39), particularly in LMIC. Simple technology that is easy to understand and can be applied by women and adolescent girls in hard-to-reach communities in LMIC could prevent and reduce the prevalence of post-partum haemorrhage. Improving health care for women during childbirth is considered an essential step towards achievement of the Millennium Development Goals (40,41).

Digital collaboration and data-sharing tools (IG6-8)

Digital tools for provider–provider communication allow community health workers, clinical officers and other front-line generalists to obtain support from specialists in real time, bringing expertise from medical and surgical specialties to where patients live and seek care. Some companies provide such equipment in various countries.

The future will be “home-spitals” instead of hospitals, with the rise of telemedicine and telemonitoring (42). Pressure on health-care systems, increasing longevity and optimization of some operating costs should lead to making digital collaboration in medicine the norm.

One participant commented on the benefits of telemedicine in remote places:

You should be able to sit in a village in Kashmir and talk to a pathologist at Harvard Medical School and let him see the slides and get informed opinions. I think we can change the practice of medicine very dramatically by making better use of telemedicine and making that cheaper too.

Innovative implementation science model to improve the reach, effectiveness, adoption and impact of innovations (IG6-3)

In this innovation, an implementation science model would be developed and applied to major global health issues, such as the health and mental health consequences of climate change, and to improve the reach, effectiveness, adoption and impact of population interventions and maintain best practices globally.

“We know what we have to do, but we don’t know how to do it” is a common comment by actors in global health. Implementation science is conducted by using theories, concepts and methods to better understand what, why and how interventions contribute in the real world. A meta-analysis showed that the potential effectiveness of an intervention is reduced by 50% by contextual factors that prevent implementation (43).

Digital health tools for public health research (IG6-7)

Digital tools can be used for research into new clinical preventive measures, treatments and vaccines. In public health practice, digital tools such as Internet platforms, social media and machine learning can improve public health surveillance and response. Digital data on population health can be stratified by time, place and personal characteristics, providing a more targeted public health response. Use of digital data might provide more insight into disease occurrence and trends and even be used to monitor the effectiveness of health guidelines and policies.

Digital health tools include geospatial tracking of populations during disease outbreaks to obtain almost real-time information from the field on the emergence of an outbreak and population clustering of behavioural risk factors such as physical inactivity, substance use and a poor diet (44).

Medical devices to improve evidence generation in trials, replacing previous end-points (IG6-11)

Medical devices can improve evidence generation in clinical trials, replacing previous end-points, and contribute to the design of clinical studies that address patient-relevant outcomes and increase compliance with treatment.

It is estimated that there are two million types of medical device on the world market (45). The combination of innovative medical devices and clinical trials appears to be a promising innovation for trial design and conduct.

Innovations with a high or very high potential impact but less chance of adoption

Co-design and co-implementation of innovations for poor rural settings in low- and middle-income countries (IG6-4)

An example of co-design and co-implementation of innovations for LMIC is community-directed interventions for major health problems in Africa organized by the WHO Special Programme for Research and Training in Tropical Diseases (46).

Innovative models of care (IG6-10)

In innovative models of care, all available data on individuals, health systems and communities (such as social media) are used in the provision of patient-centred care.

Patients and communities increasingly demand health-care delivery models that are flexible, person-centred and cost-effective and in which hospital services are linked more closely with primary health care and social services. In such models, patients are encouraged to participate in their design, with integration of services and use of digital technologies such as telehealth (42).

Digital health ecosystems to create the infrastructure for transformation of the organization-centred health-care model into a patient-centred model (IG6-6)

Such ecosystems would also improve the interoperability and sharing of electronic medical records for a comprehensive view of a patient's health. Digital health ecosystems will allow patient-centred care that combines multidisciplinary, collaborative health services with greater efficiency, better access, lower costs, better quality and more personalized medicine for patients (47). Data, information and communication technology will result in a patient-centred model based on prevention rather than treatment.

New methods for training people to become health-care workers (IG6-12)

The methods would include areas such as training more people more rapidly, developing disciplines that combine medicine, AI and robotics, and use of technology such as virtual and augmented reality in training.

One participant reflected on the changes necessary in the training of health-care workers:

One of the things we are aware of is the shortage of health-care personnel. And I don't believe we are operating with modern principles of education. We should bring in people who are experts in developing training programmes, developing new models, teach new people to become teachers. And we can train a lot more people to deliver health care, especially health care that is dependent on more sophisticated technologies.

Virtually every field of medicine has changed substantially, and investment and worldwide commitment to training more people to use modern technology to improve health and prevent disease would be a huge contribution that is based on the kind of technology that most of us don't think about.

Accessible public platforms, application programming interface and validated algorithms to support clinical decision-making (IG6-1)

A growing number of electronic clinical decision-support algorithms are being developed and tested. Such algorithms must be certified before they can be used widely.

Participants discussed the importance of data and its recording, collection from all sources and triangulation of data into a concrete form. Health scientists should therefore work more closely with engineers.

Use of social influence networks to spread ideas and promote changes in health (IG6-14)

Influence networks could be used to drive ideas and promote changes in health in younger generations. Participants considered that the topic is important for scaling up health care and that it has been somewhat neglected.

One participant stressed the importance of using social media and adapting to new means for better communication:

Most health-care organizations are very old-fashioned in the way that they're communicating with people. They're not up to date with the way people are consuming information now. It's about really understanding all the channels, understanding who you can reach with all the channels, but also that the future users of health care are the people who are gen Z and gen alpha (...) and who are used to having immersive experiences. Understanding what these channels are and who are the people who influence the groups that you are trying to influence, then bringing them into your campaigns, and using these different channels as a method of communication will make a difference. Mental health messages, healthy lifestyle tips or other key messages can be disseminated through these channels.

An accessible information database (Wikipedia type) of all medicines (IG6-2)

An accessible Wikipedia-like information database of all medicines could be accessible everywhere, including in remote villages. It would provide an up-to-date database of drug interactions and therapeutic reconciliation for each patient by interoperability with prescribing systems.

One participant said:

One innovation is building an accessible information database, some kind of a Wikipedia of all medicines, so if you get a patient with a rare disease or a patient with a complicated disease you can tap into your phone and get reliable information that can be used in a remote village.

3.2.7 Innovation group 7: Artificial intelligence, the Internet of Things, wearables, telehealth, augmented and virtual reality

Fig. 18 shows the experts' evaluation of innovations in the categories AI, Internet of things, wearables, telehealth and augmented and virtual reality in terms of their potential impact for global health and chance of adoption.

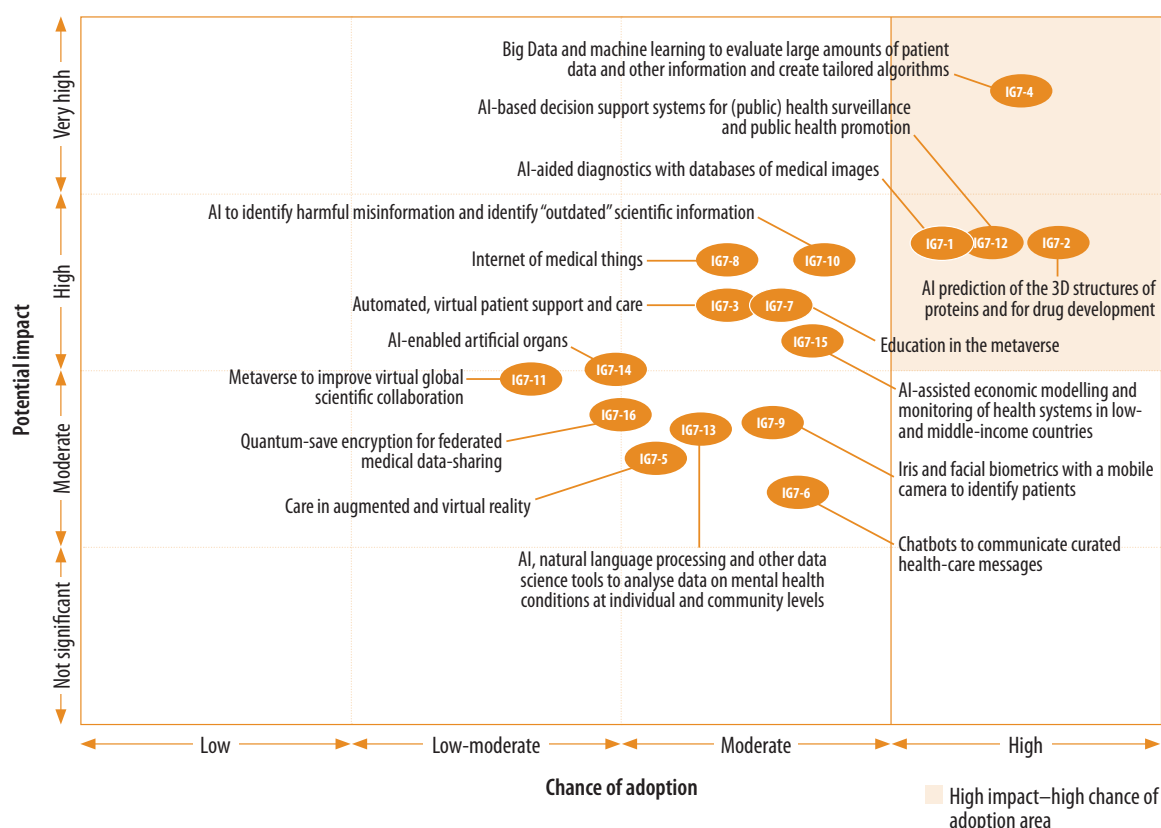


Fig. 18. Innovation group 7: time horizon for adoption

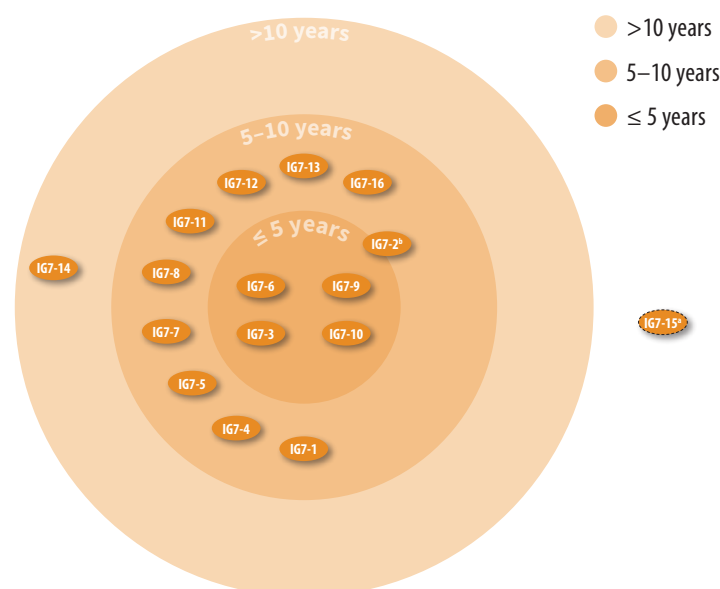
Four innovations were found to have a very high or high potential impact and a high chance of adoption:

- Big Data and machine learning to evaluate large amounts of patient data and other information and create tailored algorithms
- AI prediction of the 3D structures of proteins and for drug development
- AI-based decision-support systems for (public) health surveillance and public health promotion
- AI-aided diagnostics with databases of medical images.

The timeframe for adoption and wide use of most of these innovations was 5–10 years (Fig. 19).



- IG7-1** AI-aided diagnostics using databases of medical images
- IG7-2** AI-prediction of the 3D structures of proteins and for drug development^b
- IG7-3** Automated, virtual patient support and care, e.g. through virtual carers
- IG7-4** Big Data, AI and machine learning to evaluate large amounts of patient data and other information
- IG7-5** Care in augmented and virtual reality, including immersive experiences, to combat anxiety and mental illness
- IG7-6** Chatbots to communicate health care curated messages to the population
- IG7-7** Education in the metaverse
- IG7-8** Internet of medical things
- IG7-9** Iris/facial biometrics
- IG7-10** Use AI to identify harmful misinformation and identify “outdated” scientific information
- IG7-11** Metaverse to improve global virtual scientific collaboration
- IG7-12** AI-based decision support systems for (public) health surveillance and promotion
- IG7-13** AI, natural language processing and other data science tools to analyse data for mental health conditions



- IG7-14** AI-enabled artificial organs to reduce disability to a greater extent
- IG7-15** AI-assisted economic modeling and monitoring of health systems in low- and middle-income countries^a
- IG7-16** Quantum-safe encryption for federated medical data sharing

^a The numbers of votes for ≤ 5 years and 5–10 years were equal, and the number of votes for >10 years was very close to that for 5–10 years.

^b The numbers of votes for ≤ 5 years and 5–10 years were equal.

Fig. 19. Innovation group 7: time horizon for adoption

For each innovation considered to have a very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

Big Data and machine learning to evaluate large amounts of patient data and other information and to create tailored algorithms (IG7-4)

This innovation would support physicians in providing personalized medicine and suggest diagnoses, medications and treatments plans.

Machine learning is a statistical technique for fitting models to data and to “learn” by training the models with data (48). Analysis of Big Data by machine learning allows assimilation and evaluation of large amounts of complex data. Machine learning is more flexible and more readily scaled up than traditional biostatistical methods and can thus be used in many ways, such as in risk stratification, diagnosis and predicting survival. Machine learning algorithms also allow analysis of diverse data (e.g. demographic data, laboratory results, images and health-care professionals’ free-text notes) and their use in predicting disease risk, diagnosis, prognosis and appropriate treatment (49). It nevertheless has many limitations with regard to accessing and linking data.

Technology companies and start-ups are working on the same issues to build prediction models from Big Data to warn clinicians of high-risk health conditions and support them in finding the most accurate diagnosis and the best treatment. AI-based diagnosis and treatment recommendations are, however, sometimes difficult to integrate into clinical workflows and electronic health records, which may be a significant barrier to broad use of AI (48).

One participant reflected on the future of humans and robots:

I imagine that in the future there will be very few tasks for the general practitioners, because we’ll have robots that will do a diagnosis even more accurately than the real doctors. Nurses will be fewer, but they will continue to exist. I think nursing or human care will become more and more important as we get into the future world of robots and artificial intelligence, human touch will be,

become very valuable... In the future, there will be a kind of a blending between real physicians and the technologists, like the AI specialists, robots etc. What I foresee in the future is a mix of humans and robots.

Prediction by artificial intelligence of the 3D structures of proteins and for drug development (IG7-2)

Scientists have been trying to recognize the structure of proteins from their amino acid sequences for decades. Although current genomics technology facilitates identification of amino acid sequences, expensive, time-consuming techniques are required to elucidate its 3D shape, and this is not always possible (50).

Advances have been made in AI prediction of the 3D structures of proteins, including the AlphaFold Protein structure database developed by DeepMind and the European Bioinformatics Institute of the European Molecular Biology Laboratory, which is freely available to the scientific community. The latest database contains over 200 million entries, providing broad coverage of catalogued proteins known to science) (51,52). Researchers and start-ups can build on this library to provide commercial solutions. As more solutions come onto the market, the probability of adoption of these tools will increase. These advances are expected to be valuable for various diseases, such as cancer, because they will contribute to elucidating molecular functioning for use in strategies to stop the cancer.

One participant noted the role of AI in prediction of new drugs, such as an AI-driven antibiotic, which would probably be adopted rapidly.

Decision-support systems based on artificial intelligence for (public) health surveillance and public health promotion (IG7-12)

Such systems could create models of risk to predict both noncommunicable and communicable diseases in an individual within 5 or 10 years. AI can significantly improve data analysis, health surveillance and public health promotion by use of a variety of novel or underexplored data sources, such as those that were not intentionally designed to answer epidemiological questions. For instance, with the rapid development of application of the Internet and the Internet of things, social and device sensing capability is becoming ubiquitous, with significant potential for surveillance. Data external to traditional health surveillance systems can be used to improve them (53).

Analysis and interpretation of large health datasets in AI models lays the foundation for precision public health. Analysis of data from many different people, places and times could provide better insight into disease determinants at both individual and population levels, optimize public health surveillance and guide public health policies and activities (54). During the COVID-19 pandemic, AI has been investigated for example to predict the severity or ensure early diagnosis of disease.

Nevertheless, use of AI in public health is still in its infancy. Improvements should be made in several areas, including data quality and quantity, the transparency of the models, evidence of clinical utility, regulatory challenges, ethical use of data and the effects of equity and bias on the outputs of AI models (55).

One participant commented:

"AI needs more development, as it is not at the level of granularity to provide the outcomes that are promised".

Artificial intelligence-aided diagnostics with databases of medical images (IG7-1)

This innovation refers to diagnoses based on AI searches of databases of medical images in order to improve the quality of care and prevent and differentiate diseases much earlier, which would be particularly useful in cancer diagnosis. AI-driven analysis of medical images could deliver accurate diagnoses rapidly and potentially identify anomalies that humans cannot see (55). The model will nevertheless require training with global data. Over time, it could become more affordable and cost-effective, and, as it becomes more widely used, it could help to resolve the lack of doctors in resource-limited settings.

The area that is advancing quite rapidly. The US Food and Drug Administration has approved about 420 algorithms with imaging for various diseases, although a human being is still the final arbiter of the findings of a machine-learning algorithm. The techniques will be instrumental in ensuring timely results for patients, and, depending on its validated uses, future applications could support people and patients at home, such as via smartphone apps (55).

Innovations with a high or very high potential impact but less chance of adoption

Leverage artificial intelligence to identify harmful misinformation and to identify “outdated” scientific information (IG7-10)

With the proliferation of social media, more misinformation about health matters and even “outdated” scientific studies circulate, uncontrolled. Trials have been conducted of use of AI to detect “fake news” on social media, with promising results. A strong positive correlation was found between the quality of Big Data analytics and detection of “fake news” on digital media (56).

Internet of medical things (IG7-8)

The Internet of medical things allows connection to, location of and monitoring of patients, employees, devices and other critical resources. An example is geographical position locator devices for people with dementia.

The Internet of medical things is already being used in some settings. It would have to be scaled up for global use.

Education in the metaverse (IG7-7)

In this innovation, doctors and students can perform and test various procedures as many times as they wish through use of “digital twins”. One participant defined “the metaverse” as a combination of several technologies, including computer power, visualization and gamification to create an immersive “Web 3”. The metaverse includes blockchain technologies, protocols and non-fungible tokens to provide peer-to-peer interaction, security being provided by blockchains.

In the debate on the metaverse, its development and adoption, experts raised the issue of cost, which limits its accessibility. Some scepticism was expressed concerning use of the metaverse in health care. One expert said:

“One of the issues is the cost of entering the metaverse. The models for the metaverse seem all very advertising driven and not much focused on the health agenda”.

Others provided examples of projects that require light infrastructure, which participants considered would improve adoption of the innovation.

Automated, virtual patient support and care (IG7-3)

Automated, virtual patient support and care was considered by the experts as an innovation that could be adopted within the next 5 years. Avoidance of visits to hospitals during the COVID-19 pandemic accelerated use of virtual patient support and care. Several start-ups have developed solutions for remote monitoring and for physicians to check on their patients online.

Artificial intelligence-assisted economic modelling and monitoring of health systems in low- and middle-income countries (IG7-15)

The aim of this innovation is to use AI to strengthen health systems in LMIC through economic modelling and monitoring. For example, a team of researchers at Harvard University and Salesforce Inc. in the USA developed an AI system for proposing new taxation policies, which they called the “AI economist”. Although it was designed to study tax policies, it can be used in other areas. In the AI economist approach, the actions of participants were learnt from a simplified game economy (57).

Artificial intelligence-enabled artificial organs (IG7-14)

An example of such an innovation is a bionic pancreas, in which next-generation technology automatically delivers insulin. A trial showed that, for people with type 1 diabetes, this innovation was more effective in maintaining blood glucose levels within the normal range than standard management (58).

The participants in the horizon scan achieved some consensus on the potential impact of this innovation but considered that its chance of adoption was currently low–moderate.

Use of the metaverse to improve virtual scientific collaboration globally (IG7-11)

This innovation would set the stage for collaboration with near-human avatars and “digital twins”, a virtual model designed to reflect a physical object accurately, through the metaverse instead of physical meetings.

One participant described the potential benefits of use of the metaverse for scientific collaboration:

The metaverse provides an ongoing immersive environment and opportunity for people to have continuous collaboration with avatars and digital twins, etc. So, I think it's just going to enable a lot better and more frequent scientific collaboration in a way that we haven't had the capacity to do before.

We are talking about metaverse to improve global virtual scientific collaborations, and I think in the next 10 to 15 years, this is going to work. I couldn't imagine that we would be having these online video conferences and workshops before COVID. But now we are here, and we are getting the work done.

3.2.8 Innovation group 8: Materials and biomaterials, prosthetics

Fig. 20 illustrates the experts' evaluation of innovations in the category Materials and biomaterials, prosthetics in terms of potential impact and chance of adoption.

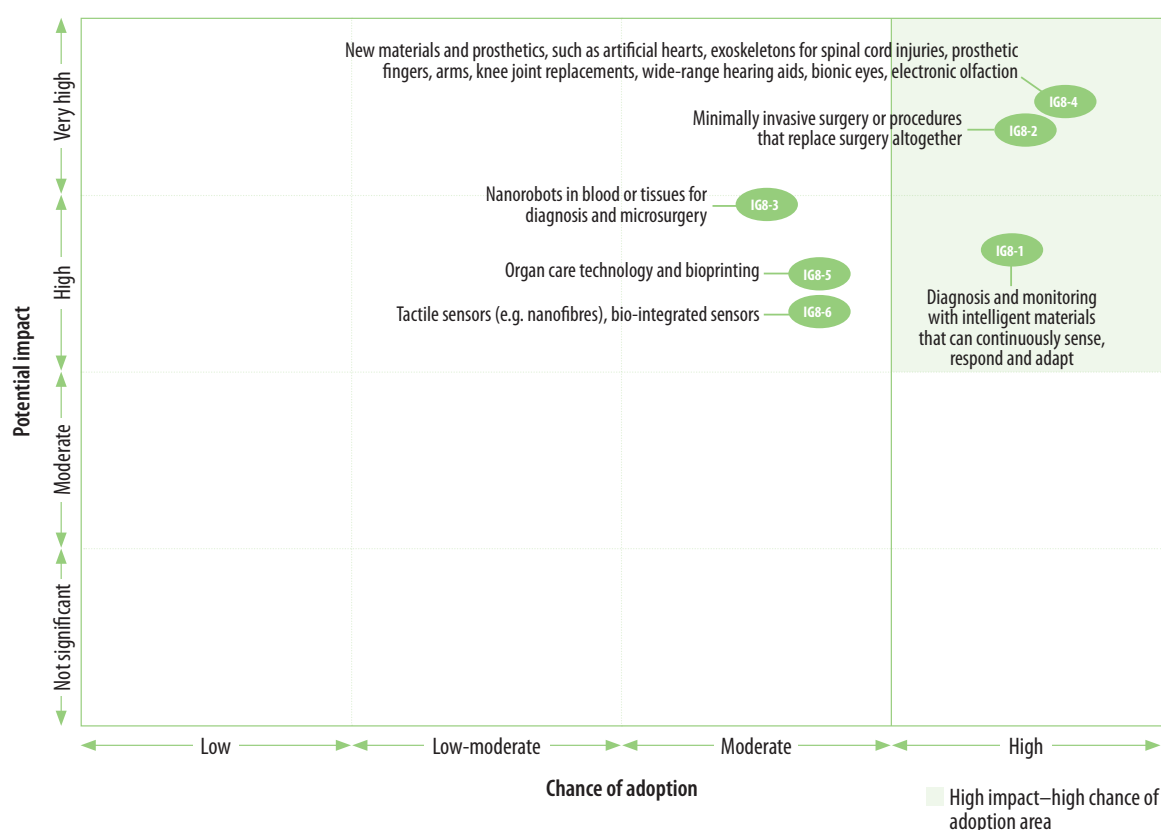


Fig. 20. Innovation group 8: time horizon for adoption

All six innovations in this group were classified as having a high or very high potential impact and a moderate or high chance of adoption. The three considered to be the most promising were:

- Diagnosis and monitoring with intelligent materials that can continuously sense, respond and adapt
- Minimally invasive surgery or minimally invasive procedures that replace surgery altogether
- New materials and prosthetics, such as an artificial heart (heart valves) made of aluminium, exoskeletons for spinal cord injuries, prosthetic fingers, arms, knee joint replacements, wide-range hearing aids, bionic eyes, electronic olfaction).

The time horizon for two of these innovations, minimally invasive surgery and procedures and new materials and prosthetics, was 5–10 years, while that for diagnosis and monitoring through intelligent materials that can continuously sense, respond and adapt was > 10 years (Fig. 21).

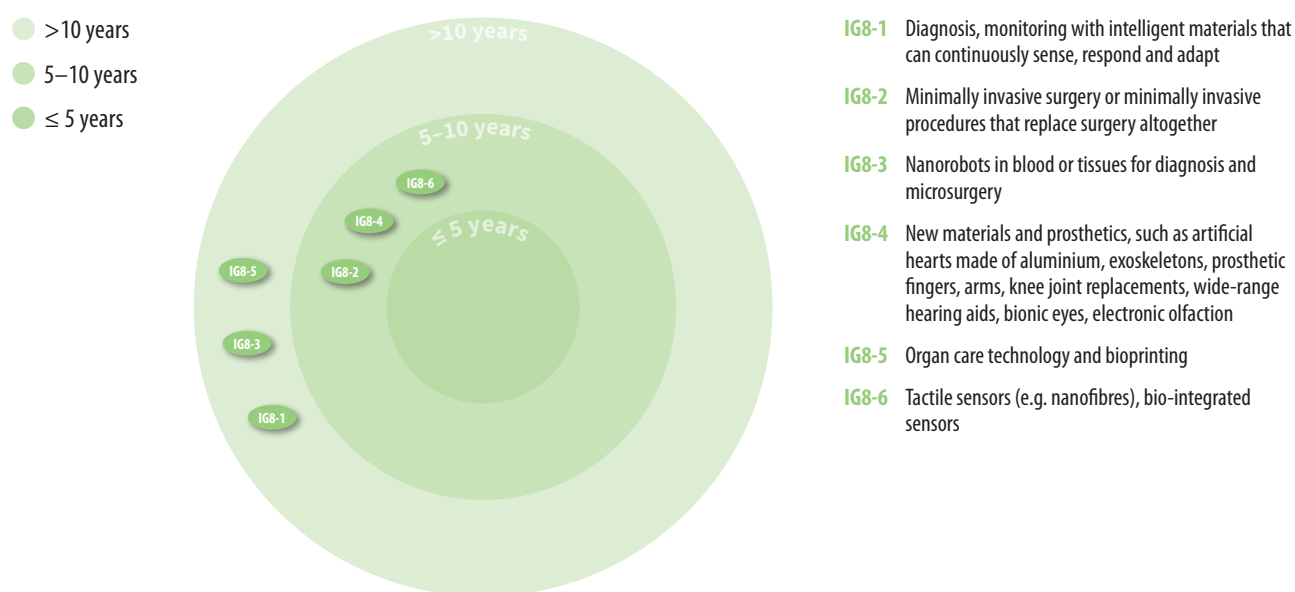


Fig. 21. Innovation group 8: time horizon for adoption

For each innovation considered to have very high or high potential impact and a high chance of adoption, information is provided below from the literature review and the input of participants in the horizon scan. Full descriptions of each innovation are provided in Annex 1.

New materials and prosthetics, such as artificial hearts, exoskeletons for spinal cord injuries, prosthetic fingers and arms, knee joint replacements, wide-range hearing aids, bionic eyes, and electronic olfaction (IG8-4)

Restoration of the functionality of body parts with materials and technology with the proper interface and usability could improve the quality of life, the productivity and the well-being of societies.

Myoelectric prostheses have sensors along the surface that act as sensory interfaces. Electrical signals from the body's neuromuscular system are picked up and translated into movement of an electric-powered prosthetic hand, wrist or elbow, allowing an amputee to perform functions such as tying shoelaces (59).

Minimally invasive surgery and procedures to replace surgery altogether (IG8-2)

In the past two decades, minimally invasive surgery has replaced many conventional procedures, ensuring faster recovery and less time on a hospital ward. The new procedures are also stimulating development and improvement by multidisciplinary teams, which will allow their application worldwide at controlled cost.

Robotic surgery and telesurgery involve new computer-aided approaches to improve the precision of surgical techniques and provide opportunities for remote surgical skill and expertise, abolishing distance factors. Minimally invasive surgical techniques are now used routinely and for more and more indications (60). The Mayo Clinic (USA) noted that surgeons now often perform minimally invasive surgery on specific organs, including removal of one or both adrenal glands, brain surgery, removal of diseased parts of the colon, gallbladder surgery, spine surgery, removal of the spleen and more general surgery (61).

One participant observed that the way in which surgery is performed would change radically in the next 5 years.

Diagnosis and monitoring with intelligent materials that continuously sense, respond and adapt (IG8-1)

“Smart materials” play a significant role, providing sensing and actuation applications in health care by responding to external stimuli such as stress, light, temperature, moisture, pH and electric and magnetic fields (62). Smart materials have a wide range of application, from well-being to disease treatment, combining the disciplines of physics, electronics, chemistry, biology and AI. Various types of smart materials exist, and new ones are appearing continuously with increasing investment in research and development (R&D) (63).

Innovations with a high or very high potential impact but less chance of adoption

Nanorobots in blood and tissues for diagnosis and microsurgery (IG8-3)

Nanorobots could repair and improve damaged muscles, bones and even cells.

One participant said:

Nanorobots in blood and tissues would have safe passage in the body. For example, if it goes through the spleen, it would not be stuck there and not rejected and can be retrieved. This can be used for a diagnosis or for microsurgery.

Organ care technology and bioprinting (IG8-5)

The advent of 3D printing has opened new possibilities in regenerative and personalized medicine. 3D organ bioprinting consists of using 3D-printing technology to assemble several cell types, stem cells or growth factors with other biomaterials, layer by layer, to make bioartificial organs that are closely similar to the natural organ (64).

The complexity of certain organs is a challenge to the general availability of 3D-printing techniques.

Tactile sensors (e.g. nanofibres) and bio-integrated sensors (IG8-6)

Biomaterials with various properties, such as polymer nanomaterials with high flexibility and electrical performance, hold promise for the development of sensors that can be integrated into clothing or mounted on the skin. Such biosensors could be used, for example, to monitor various biological signals, acquire data and anticipate acute clinical episodes.



Enablers of adoption

4

Widespread, timely adoption of innovations depends on factors that include the availability and accessibility of technology, a legal framework, skills, resources and cultural considerations. In this exercise, “enablers” cover initiatives, policies, activities and other factors that would facilitate, accelerate, expand and optimize use of the innovations for the benefit of all. They include responses to potential barriers.

Enablers were grouped into four categories:

- technological enablers for the availability and accessibility of the technology required for the innovation;
- skills- and capacity-building enablers to make the innovations work;
- structural, legal and political enablers to ensure healthy, equitable application of innovations through political sponsorship, governance, standards and regulatory frameworks; and
- cultural enablers, which determine that innovations will be adopted by a population by taking into account factors such as social values, perceptions and behavioural patterns.

Enablers were discussed and rated for their relevance during the horizon scan. Visual depictions of how each enabler was rated in the second round of the Delphi exercise are presented below.

4.1 Technological enablers (Fig. 22)

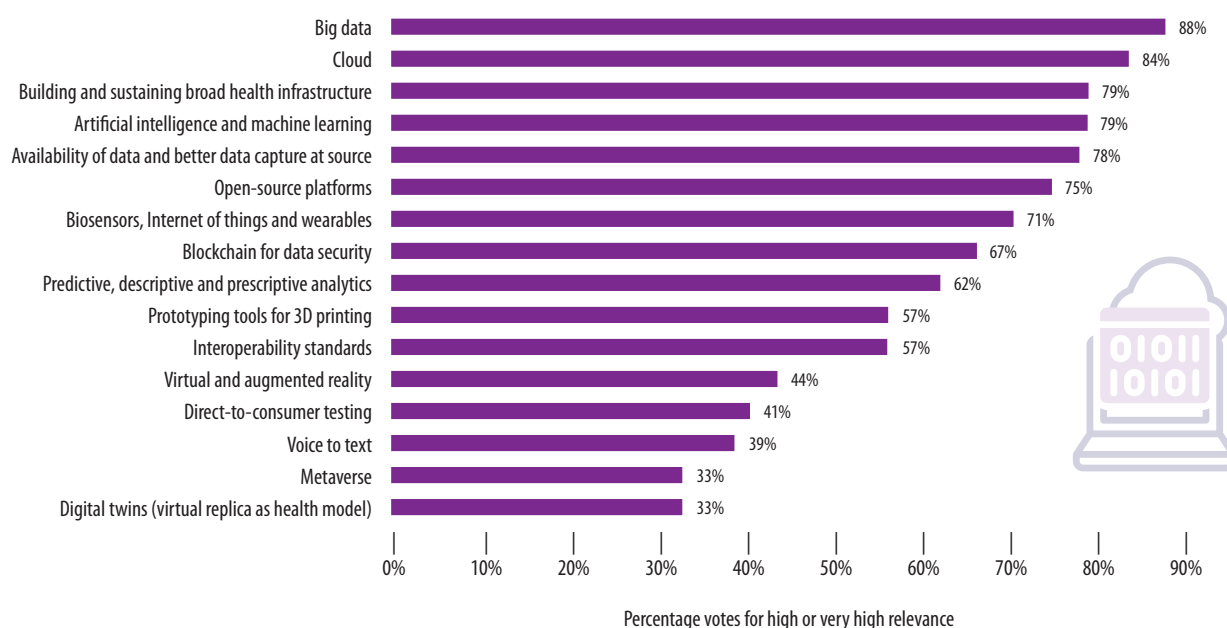


Fig. 22. Percentages of votes for high or very high relevance of technological enablers

The ratings showed good agreement (75% of votes) on the relevance of the enablers Big Data, cloud, AI, machine learning, building and sustaining broad health infrastructure, the availability of data, better data capture at source, and open-source platforms. Enablers that were considered less relevant were digital twins, the metaverse, voice-to-text and virtual and augmented reality.

4.1.1 Big Data

Big Data received 88% of the votes for relevance, the strongest consensus. Big Data can increase the availability of data and of advanced analytics to extract value from the data and can also facilitate management of the challenges in capturing, storing and analysing data; searches; data-sharing, transfer, visualization, querying and updating; information privacy; and data sources.

Use of Big Data in health care is particularly valuable in diagnosis, decision-making and public health management. It is closely linked to other technological enablers, such as analytics, the availability of data, AI and machine learning. Given the unstructured nature of medical data, Big Data are difficult to collect (through, for example, the Internet of medical things, sensors, patient databases) and model.

In some of the discussions, the term “Big Data” was used to refer to unstructured data rather than the size of the database. One participant said:

Medical data most of times, still comes unstructured but that is the beauty of big data that you can use, structured, unstructured, semi-structured data, and the more data, the better. And then so, and even incomplete data sets. So that's even the beauty.

Another participant noted:

There is a difficulty on getting data from the systems or even from electronic medical records. So, it's very important that we have the capacity to transform the voice to text and have this interpretability between the information systems and have this architecture to understand the data, and then we can move forward to big data and AI.

4.1.2 Cloud

From the point of view of innovations, the cloud as an enabler refers to the availability and accessibility of cloud-based solutions that can be accessed by health-care providers, governments, end users or other key stakeholders. Cloud computing received 84% of the votes for its relevance. The strength of cloud is that it allows users to benefit from cutting-edge web applications and infrastructure, without requiring deep knowledge or expertise, while reducing costs. It is seen as a key enabler for low-resource settings, as it obviates the need for expensive infrastructure.

4.1.3 Artificial intelligence and machine learning

The technology and its further development are considered an enabler, with 79% of votes for high or very high relevance. AI and machine learning are the basis of several other innovations, from diagnostics to decision-making and use of digital twins and simulations. Advances in these tools and their hardware have significant relevance for the quality, reliability and accuracy of diagnostics and other outputs.

The general limitations of AI and machine learning include biases in data modelling and the lack of good-quality data to train models.

4.1.4 Building and sustaining broad health infrastructure

This enabler received 79% of votes for high or very high relevance. It refers to sustained availability of the physical and digital infrastructure necessary to manage and operate the health sector, including hospitals, other points of care, research facilities and medical training institutions.

Infrastructure is a key requirement in primary health care and public health and for the medical workforce. Although the ambition to transition from hospital-centred health care is solid, broad infrastructure will still be required.

4.1.5 Availability of data and better data capture at source

A rate of 78% of votes were cast for the high or very high relevance of ensuring the availability of data and better data capture at source. Individual and public health data on patient health are the key input for all health-related decisions. Capturing such data in a timely manner, in relevant formats, and storing, processing and securing them are essential for correct use in health-related decisions.

This innovation was discussed extensively. One participant commented on “datafication” as follows:

People usually say ‘data is the new currency of health care’. What we know is that health data has value, that we have a lot of health data that has not so much value in a monetary sense but high value in a scientific sense. A lot of data is sitting idle all over the place, in health insurance, in hospitals, or in radiologists’ office, in clinics.... People are going to start creating data exchanges where data can be in a secure and de-identified way placed in those exchanges. This has the potential to generate a lot of income for the owners of data and to generate a lot of scientific opportunity for the people who can access those data sets.

4.1.6 Open-source platforms

Open-source, free-of-charge, collaborative platforms were voted as promising by 75% of participants. They are an enabler in the health sector as they provide a wide range of digital assets, including software, applications, databases and libraries for sharing information, experience and expertise between different countries and regions. They provide an essential medium for collaboration in the development of vaccines, treatments, tools and policies and allow transfer of technology to LMIC.

4.1.7 Biosensors, Internet of things and wearables

Enablers with regard to these devices ensure their availability and accessibility for use in, for example, diagnostics, preventive care and management of chronic health conditions. These enablers received 71% of the votes for relevance, as they are a key part of telehealth and enable a transition from a hospital-centred to a patient-centred approach to health care. Biosensors and wearables provide key data.

One participant said:

It's not particularly relating to remote vital signs only. In fact, it could be remote health care monitoring for more than the basic vital signs such as heart rate, temperature, blood pressure, oxygen level. ... There are some other things that if we can actually repackage, patients in developing nations do not need to travel to the hospital, which is sometimes very far away, and they have to wait for a long time. This technology will help rationalize the efforts and spending, helping save time and cost. I work with the hospital a lot, and I have seen so many unnecessary visits which could have been resolved over the phone or even through an app.

4.1.8 Blockchain for data security

Participants considered data security to be essential and also one of the most risk-prone aspects of many innovations. They considered that blockchain could alleviate concerns about data security. Blockchain has many applications in health care, particularly in the management of patient data and in peer-to-peer interactions. Blockchain received 67% of votes for high or very high relevance.

4.1.9 Predictive, descriptive and prescriptive analytics

These analytics can be used for analysing both patient and public health data. Predictive, descriptive and prescriptive analytics ensure the availability of data for models and use of the models in health-related decisions. The vote for a high or very high relevance resulted in 63% votes, which reflects marginal consensus on this enabler, as it requires good-quality data, a skilled workforce and packages of programmes.

Predictive analytics are used to predict the prognosis of patients with certain conditions, while descriptive analytics are used to better understand the data, make a diagnosis and for public health. Prescriptive analytics are used in selecting the treatment that is best adapted to each case and in developing policy options in public health.

The reliability and accuracy of analytics depend on the availability of good-quality data, good modelling and a skilled workforce. Use of these analytics would allow physicians to use “plug-and-play” package software, while novel models would be necessary for use in public health by experts in data modelling and visualization.

4.1.10 Prototyping tools for 3D printing

The relevance of this enabler was considered high or very high by 57% of participants. Prototyping of various sensitive products would ensure their greater use in the health sector. 3D-printing potentially has a wide range of use in medicine, including printing of artificial joints, implants and pills. Prototyping of both the hardware configuration and the software for designing, modelling and choosing materials are therefore important.

4.1.11 Interoperability standards

Interoperability standards received 57% of votes for its relevance as an enabler of interoperability, which permits sharing for collaboration among organizations for work and exchange of information. Interoperability is especially important for decisions in public health, in which data from several sources are consolidated and processed.

One expert participant commented

If you don't have interoperability, it's going to be difficult to get the data, because data or big data needs to come from several systems. And if these systems don't talk to each other, you still have big data in AI, but maybe not working as you needed.

4.1.12 Virtual and augmented reality

This enabler received 44% of the votes for high or very high relevance. Augmented, virtual and extended reality allow visual combination of information. They have many applications in education, entertainment and, to some extent, therapy, with potential application in psychiatry but currently have relatively few applications in health care. Augmented and virtual reality have been used in medical training and are considered to be complementary to virtual twins in education.

One expert said:

A lot of medical education universities have been experimenting with [augmented and virtual reality], extended reality, etc. for some time. But I think we're just going to see an increase in that. A surgeon practising an operation many, many, many times on a digital twin of the patient's heart that they were going to operate on is a very helpful approach. It is the same for the medical students: they can practise on digital twins, they can go inside the body, they can see how all the different organs interact with each other, where the blood flows.

The experts discussed the possibility of improved global access to complete medical education through the metaverse.

4.1.13 Direct-to-consumer testing

The role of direct-to-consumer testing as an enabler would be to increase the availability and accessibility of tests for consumers. Only 41% of the votes were cast for its relevance, indicating little consensus among the participants. Self-testing for COVID-19 revealed the importance of commercially available tests for use at home or other convenient setting. Self tests are considered a key first step in changing from hospital-centred health care to a “patient as the point of care” approach.

Although the technology for this innovation is being developed rapidly, so that the tests could be made available commercially soon, the participants debated the cultural and social factors that would limit their uptake. They further discussed cases of misuse, in which the reliability of such tests is questionable and when people self-diagnose and treat themselves inaccurately.

4.1.14 Voice to text

The relevance of this enabler was considered to be high or very high by only 39% of participants, mainly because of its narrow or limited use. In the health sector, voice to text is potentially applicable in medical documentation and in research. The experts considered voice to text to be practical for physicians in managing their time and allowing them to maintain eye contact with patients while the AI-based solution wrote everything down, thus improving the patient–doctor relationship.

4.1.15 Digital twins

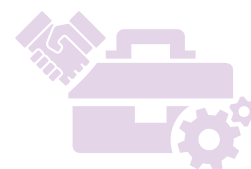
The concept of digital twins refers to virtual replicas of, for example, an organ, a system or the whole human body. It is now possible to build personalized models for patients, which can be continuously adjusted by tracking health and lifestyle parameters, ultimately resulting in a virtual patient and a detailed description of the healthy state of the human patient. Digital twins are also valuable for practice and training.

Because of the narrow use of digital twins as an enabler, however, it was considered to be potentially relevant by only 33% of participants.

4.1.16 Metaverse

The relevance of the metaverse as an enabler was considered high or very high by 33% of participants. Its benefits were considered to be in training and collaboration.





4.2 Skill- and capacity-building enablers (Fig. 23)

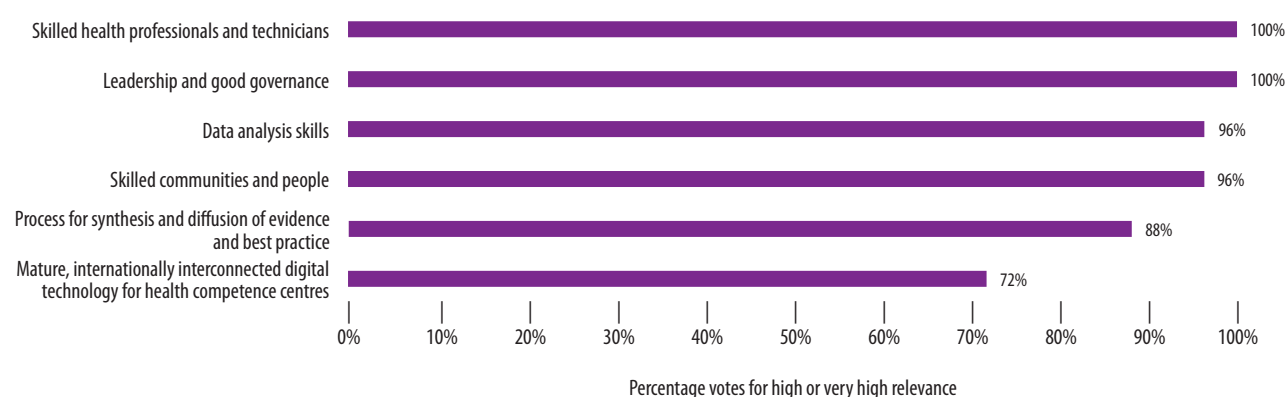


Fig. 23. Percentages of votes for high or very high relevance of technological enablers

There was good agreement among the participants on the high or very high relevance of these enablers, most gaining more than 75% of the vote.

4.2.1 Skilled health professionals and technicians

Application of all the innovations requires skill, from use of certain equipment to making health-related decisions. The relevance of this enabler was unanimously considered high or very high, with 100% of votes. Its importance was highlighted in the discussions:

Technology is there, but you need skilled people to use it.

Virtually every field of medicine has changed substantially, and investment and worldwide commitment to training more people to use modern technology to improve health and prevent disease would be a huge contribution.

For example, metagenomics has the power to change the diagnostics framework entirely. It allows for diagnosing in a much more accurate and safe way. Metagenomics is essentially “sequencing” the material to understand what is in it. The technology (machinery) is advanced and expensive, however experts to operate the machine and run the process are even rarer. Training experts for operation of the technology is key.

Reference was also made to networking and cooperation:

“Networking skill, which is the capacity of professionals and researchers and innovators to network with each other, is very important”.

4.2.2 Leadership and good governance

Given the complexity of the health sector and its institutions, from research to delivery and to overall management, the experts considered that good governance of complex systems and their interactions in a fair, transparent framework, by skilled leaders at institutional, regional or national level, is crucial, with 100% of votes for high or very high relevance. One expert commented:

“Just focusing on clinical skills is not enough. We need leadership skills and diplomacy skills of how to get cooperation to happen.”

4.2.3 Data analysis skills

Skilled human resources comprise data scientists, technicians and researchers working in collaboration with practitioners. Skill in data analysis was considered to have high or very high relevance by 96% of the participants. The enabler includes skilled human resources to apply descriptive, predictive and prescriptive analytics to analyse

data or Big Data. The participants noted that the availability of the technology and tools is not enough: the key ingredient is the availability of people to establish hypotheses, make inferences from the findings and use tools in making decisions by combining results on the basis of their professional judgement.

4.2.4 Skilled communities and people

In view of the recognition of an empowered patient as “an equal partner at the table with the doctor”, this enabler refers to understanding by patients and the general population of key concepts related to their health. The relevance of this enabler was considered to be high or very high by 96% of the participants.

There was some debate about application of the same enabler to both empowered patients and skilled communities and people. It was considered that referring only to patient empowerment was limited, as many people can access their health information on their mobile phones and must therefore have the skill to understand it. Skilled communities and people have important roles in prevention and taking up healthy habits, thus bringing about change.

One participant referred to the democratization of health:

In many papers, you see the terms ‘democratization of health’. What does it mean? It means that the government trusts the citizen to make decisions about how their money is used for health.

The participants also discussed rational use of health data by patients. One participant noted that, in some countries, most patients search their health symptoms online. As people use computers more and more, they will naturally look online for information on their health and disease management. Closing the communication gap between the patient and the doctor was seen as indispensable to empowerment.

4.2.5 Process for synthesis and diffusion of evidence and best practice

This enabler received 88% of votes for high or very high relevance. It was considered critical to build trust in science and bring people closer to research, allowing all evidence to be discussed and encouraging outreach to scientific and non-scientific audiences.

4.2.6 Mature, internationally interconnected digital technology for health competence centres

This enabler received 72% of votes for high or very high relevance. The enabler increases collaboration in health research to improve outcomes and wider sharing of benefits between countries.

4.3 Structural, legal and political enablers (Fig. 24)

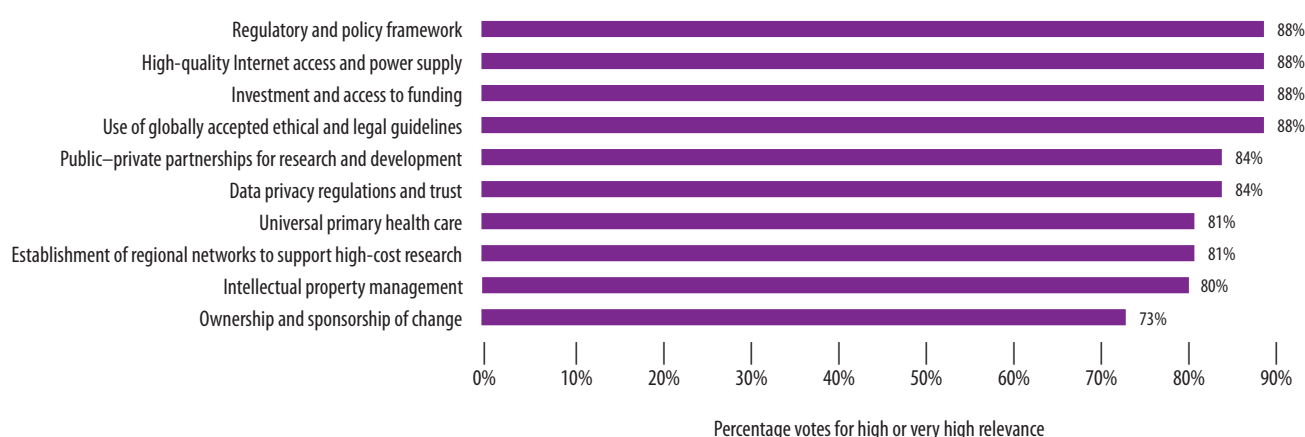


Fig. 24. Percentages of votes for high or a very high relevance of structural, legal and political enablers

The ratings show significant agreement on the strong relevance of all these enablers, most being > 75%.

4.3.1 Regulatory and policy framework

As much as 88% of the participants draw attention to the relevance of the regulatory and policy framework. All innovations, to a varying degree, are accompanied by legal and ethical issues, compliance requirements, issues of competition and consumer protection, safety and quality requirements. A proper regulatory and policy framework is crucial for safe, equitable, compliant implementation of innovations.

4.3.2 High-quality Internet access and power supply

This was considered a key enabler, 88% of participants considering that it was of high or a very high relevance. Access to a high-quality Internet connection and a reliable power supply are essential for using innovations that require real-time collaboration, use of the Internet of things, use of biosensors and other innovations in which instant data transfer is necessary. Especially in LMIC, a high-quality Internet connection and a reliable power supply are not always available, which is an obstacle to wide adoption of some of the innovations.

4.3.3 Investment and access to funding

The relevance of this enabler was considered to be high or very high by 88% of the participants, as access to funding is essential for both R&D of innovations and for their dissemination to ensure general access.

4.3.4 Use of globally accepted ethical and legal guidelines

As many as 88% of participants voted for the high or very high relevance of use of globally accepted ethical and legal guidelines. Adherence to globally accepted ethical and legal guidelines in research and innovation is critical for adoption of innovations. Such guidelines address many concerns, from international data-sharing to dissemination of the results of research and respect for rights and welfare.

4.3.5 Public-private partnerships for research and development

This enabler was considered to be of high or very high relevance by 84% of the participants. Such partnerships provide governments with alternative methods of financing, infrastructure development and service delivery. By making capital investment more attractive to the private sector, these partnerships can reduce the risk of private investment in new markets and ease barriers to entry. Medical research is an expensive, long-term activity, which must therefore be funded in a sustainable way. Public-private partnerships can provide long-term financing for R&D.

4.3.6 Data privacy regulations and trust

The relevance of this enabler was considered to be high or very high by 84% of the participants. Many innovations depend on the availability of data and therefore on their privacy and the trust of the users and holders of data. Regulation of data privacy builds the trust of communities, which are assured that they can share their data, knowing that it will be treated with respect and in compliance with the regulations.

One expert participant said:

"We need data privacy regulations and the data protection, but also we need to have data fiduciary, making sure that data is protected while we can make a wide use of data".

Trust is the keystone, as noted by one participant:

Each country must decide by themselves the regulations that they have to put in place. But the common element and the most important thing is building trust: Because if you don't have trust towards the collectors and managers of your data, you will not want to share your data.

4.3.7 Universal primary health care

The relevance of universal primary health care as an enabler was considered to be high or very high by 81% of participants, as it is a prerequisite for the use of any innovation.

One expert said:

For securing a healthy world, we should take primary health care as priority. Primary health care is health care devoted to everyone, regardless of them being poor or rich.... A good innovation is one that leaves no one behind.

Another participant noted that:

"Strengthened primary health care will ensure that the innovations are within reach of the majority".

4.3.8 Establishment of regional networks to support high-cost research

Medical research often incurs high costs and requires collaboration and long-term investment. Accelerating the development and wide adoption of innovations requires collaboration, which is facilitated by regional networks. Thus, establishment of regional networks was considered to be of high or very high relevance by 81% of the experts. The importance of establishing regional networks for high-cost research, especially in LMIC, was discussed extensively during the roundtables and in the interviews. One participant commented:

Networks are extremely important in research. Internet, technology and apps allow for more networking and collaboration. It is not easy to handle complicated research on one's own and not easy to have an impactful one-author research: When we look at the most impactful research and big innovations, we see that it's produced by a set of scientists from different backgrounds and institutions.

The experts regarded collaboration within and across different world regions as crucial. One said:

I think the one thing that COVID-19 has done for the "global south" is a shot in the arm that woke us all up again. We had it with HIV, we had it with the flu vaccine, we had it with Ebola. But with COVID it was just too profound, too visible and too painful.

In 10 years in the vaccine space, we are going to see a redistribution of manufacturing capacity globally. We are going to see a shift in the power base of vaccine manufacturing. And we're going to see innovation from the "global south" going to the "global north". I think we're going to see a different traffic direction in innovation in product development.

4.3.9 Intellectual property management

Intellectual property management was considered highly or very highly relevant by 80% of the participants. One expert commented:

"Intellectual property rights are a key enabler to help spread new innovations and should be seen as a part of the regulatory and policy framework".

4.3.10 Ownership and sponsorship of change

The relevance of this enabler was considered high or very high by 73% of participants. Most innovations disrupt the operating model of health care provision, and their adoption requires changes. Sometimes, a full change is required, including organizational changes, changes in governance requirements, new work processes, new regulations and new partners. Securing the necessary funding can be difficult, and management of such change requires a strong owner or sponsor to ensure that the change is made.

4.4 Cultural enablers (Fig. 25)

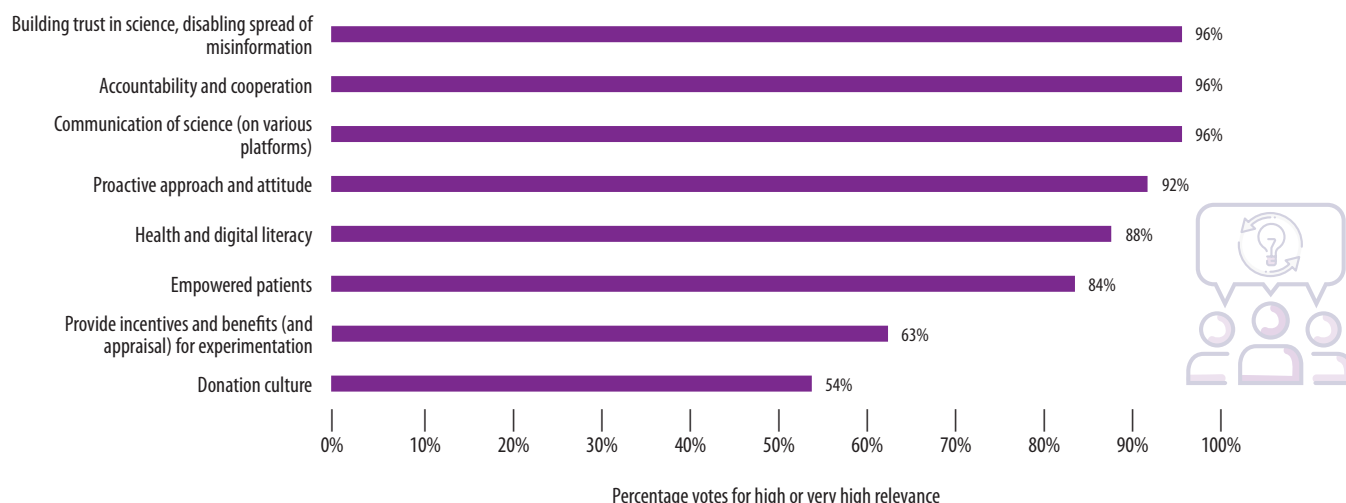


Fig. 25. Percentages of votes for high or very high relevance of cultural enablers

The experts agreed on the relevance of most of these enablers: building trust in science, disabling the spread of misinformation, accountability and cooperation, communication of science (on various platforms), a proactive approach and attitude, health and digital literacy, and empowered patients, for which all the votes were $\geq 75\%$. There was less agreement on the relevance of the provision of incentives or benefits for experimentation and on a culture of donation.

4.4.1 Accountability and cooperation

As much as 96% of votes were cast for the high or very high relevance of accountability and cooperation as an enabler. In the context of health innovation, accountability refers to transparency and the responsibility of research institutions, government bodies, politicians, regulators and nongovernmental organizations active in the area. Accountability was considered a cultural trait rather than a regulatory aspect, as it is not imposed. A culture of cooperation is one in which stakeholders work together, which also cannot be regulated or imposed. Cooperation is critical for both R&D and for scaling up innovations.

4.4.2 Building trust in science and disabling the spread of misinformation

For 96% of the participants, this enabler was of high or very high relevance. Distrust in science has spread in some communities, and a number of non-scientific messages have become popular, especially through social media. Disinformation and lack of trust in science are potentially damaging to both individuals and communities and are a barrier to scaling up some innovations.

One expert said:

Anti-science (e.g. anti-vaccine) type of misinformative conspiracy theories, fake news that emits distrust to science damages the health-care sector vastly, as seen in the COVID-19 pandemic.

4.4.3 Communication of science (on various platforms)

This enabler was considered by 96% of the participants to be of high or very high relevance. The various platforms include social media. The experts emphasized that the right message must be conveyed through the right channel. Understanding non-traditional communication channels and who can be reached through each channel and sending key health messages to communities in the right way will make a difference.

4.4.4 A proactive approach and attitude

A proactive approach was regarded as a cultural trait essential for both the R&D of innovations and scaling them up. It was considered to be closely linked to patient empowerment. Its relevance was voted as high or very high by 92% of the participants.

4.4.5 Health and digital literacy

Health and digital literacy are important for the adoption of several innovations that require people and patients to use an application. Patient empowerment is directly associated with their health and digital literacy. This enabler is also linked to trust in science and eliminating misinformation. Its relevance as an enabler was considered to be high or very high by 88% of participants.

4.4.6 Empowered patients

Patients are increasingly more empowered, which will change the character of health care. With 84% of participants voting for the high or very high relevance of this enabler, empowered patients were viewed as a “game change”.

One expert participant said:

Based on every research I've done during the last one and a half decades regarding the biggest innovation, I should say it is not a technology, but it is the concept of patient empowerment. The fact that the paradigm shift that we call 'digital health' has been taking place for the last 10 years or so, and that patients can now sit at the same table where only physicians have been sitting for 2000 years, since Hippocrates. Patient empowerment is not innovation, based on the definition of innovation, but that's far the biggest thing that will impact the next 5 to 10 years in health care, even globally in general. Global impact of concepts like patient empowerment, the cultural transformation of digital health, and the changing roles of physicians and patients in all this will be much higher than the impact of technology-based innovations.

In another discussion, empowered patients were referred to by a participant as part of the cultural transformation:

We are having a cultural transformation: Roles of the physicians and patients are shifting due to the flux of technology. Social media, online communities, digital communications, etc. role of patients is evolving from a passive stakeholder to an active one, that manages the diseases and their overall health. Patients sit in the advisory boards of major medical companies, nongovernmental organizations and publish papers with the physicians.

4.4.7 Provide incentives or benefits (and appraisal) for experimentation

Although medical research and development may be costly, time-consuming and risky, encouraging experimentation without expecting immediate results is the first step in R&D. Less agreement (63%) was seen for the relevance of providing incentives or benefits for experimentation as an enabler.

4.4.8 Culture of donation

Donation of organs or tissues varies culturally. Some countries have policies in which people are, by default, organ or tissue donors, unless they officially opt out. Opt-in systems also exist. Although donation could be made mandatory, it is best that it be purely voluntary and part of the culture.

The relevance of this enabler was considered high or very high by 54% of participants.

Risks and other considerations

5

Emerging technologies and scientific innovations provide many opportunities but are also associated with risks. This section describes some risks and other considerations that were discussed, in particular those with important implications for global health. A more detailed discussion of risks, including different associated ethical questions would require more reflection.

The risks that are common to all the categories of innovations that were identified from the reflections shared by the experts during the exercise included:

- potential accentuation of health inequity individually (favouring high-income individuals), nationally and institutionally (favouring well-resourced institutions and high-income countries);
- unreliability and inaccuracy due to poor-quality inputs (such as data), processes (such as models, algorithms and physical or chemical aspects of certain innovations) and use of the results (such as lack of skill in interpretation);
- lack of wide access to high-cost innovations, which would accentuate gaps in health equity, due to the cost of development to ensure the desired quality, accuracy and reliability and also the costs of commercialization and scaling-up; and
- inadequate data privacy with application of all the innovations in which data are collected and processed, including cyber security and misuse of data for purposes other than those intended, such as marketing and discrimination, leading to serious ethical concern.

Further potential risks frequently associated with innovations included:

- difficulty in understanding and interpreting results, misinterpretation, overinterpretation and/or overdiagnosis, leading to unnecessary treatment;
- difficulty in achieving consistent manufacturing standards;
- potential risks of toxicity and safety concerns;
- possible misuse of a technology or innovation, resulting in harm to patients;
- potential risk to the efficacy of operations; and
- the availability, quality and reliability of data, modelling and testing.



Discussion

6

In this horizon scan, over 100 innovations in science and technology that could help solve global health challenges were analysed for their potential impact and their adoption within 5, 5–10 or over 10 years. The experts also evaluated 40 enablers for their relevance in facilitating and optimizing development or adoption of the innovations and discussed potential risks associated with each innovation.

The five most promising innovations that could be available within 10 years were considered by the experts to be:

- application of genomics for early diagnosis and pre-diagnosis of diseases;
- better coordinated, more effective systems of vaccine production and global distribution;
- low-cost point-of-care diagnostics for viruses such as HIV and hepatitis B virus with CRISPR/Cas techniques;
- broad-spectrum antimicrobial drugs that do not cause resistance or tolerance; and
- rapid remote diagnostics, connected through cell phones, watches and other wearable devices, linking health information to health providers in real time.

Genomics applications for early diagnosis were considered highly promising, from universal genomic prenatal screening to identify metabolic and other congenital disorders before the appearance of symptoms and to ensure a precise diagnosis and to guide patient management and treatment. More broadly, genomics could be used to replace or supplement most current microbiological diagnostic technology. Of the top five most promising innovations,

this is the only one that was considered to have only a moderate chance of adoption and wide use. There was some debate about investment in genomics and biosensors for point-of-care diagnostics to ensure their wide adoption.

The COVID-19 pandemic highlighted the importance of better coordinated, more effective systems of vaccine production and global distribution. For widespread adoption, production centres would be established in several countries, closer to the populations in need, resulting in distributed manufacture. This innovation could result not only in the design of new vaccines but also in faster production and testing of existing vaccines and would also contribute to a shift in the power base of vaccine manufacture and innovation in product development.

Cost-effective point-of-care diagnostics for HIV and hepatitis B with techniques to identify nucleic acids will require development of low-cost CRISPR/Cas techniques. Unlike polymerase chain reaction, CRISPR assays do not involve complex, costly laboratory equipment. This innovation would be important in settings where diagnosis is not readily accessible to the population and could result in cost savings.

Broad-spectrum antimicrobial drugs that do not cause resistance or tolerance in microbes could, for example, adapt their configuration to a change in the target microbe or to a new structural change caused by mutations. Nanotechnology could be used for developing such drugs. They might also contribute to reducing use of antibiotics, as some of the drugs will be more functional and bioavailable.

Rapid remote diagnostics connect people through cell phones, watches and other devices, such as smart implants, prostheses and wearable sensors, that can provide information on markers and link health information in real-time to clinicians and other health workers. These innovations will also support individual health promotion, disease prevention and disease self-management. Rapid remote diagnosis is of particular importance in remote rural locations and can save time and cost.

Innovations in other categories – tissue engineering and regenerative medicine, molecular biology, public health (including the environment, climate change, epidemiology, surveillance, nutrition and health), dissemination and implementation, AI and related tools and materials and biomaterials – were also discussed during the exercise. This report highlights the innovations in each category that combined a high or very high potential impact for improving global health with a high chance of adoption. Other innovations discussed were ranked highly with regard to their potential impact for improving global health but with a lower chance of adoption. Many of the innovations in these areas are nevertheless highly promising and may only require certain enabling factors to optimize their chance of wide, rapid adoption to reach their full potential for global health.

Widespread, timely broad adoption of innovations depends on numerous factors, identified in this horizon scan as “enablers”, covering initiatives, policies, activities and other factors that would facilitate, accelerate, expand and optimize use of the innovations. Technological factors; building of skills and capacity; structural, legal and political factors; and cultural enablers were rated for their relevance. The highest ratings for technological enablers were based on 75–88% agreement on the high and very high relevance of Big Data, cloud, AI and machine learning, broad health infrastructure, the availability of data, better data capture at source, and open-source platforms.

Big Data can increase the availability of data, even if they are unstructured or incomplete, and of advanced analytics. They can facilitate the capture, storage and analysis of data and information privacy, while the cloud allows health-care providers, governments, users and others to access a wide variety of information at low cost. AI and machine learning provide the technology to develop innovations further and are the basis of several innovations, from diagnostics to decision-making. They are highly relevant for ensuring the quality, reliability and accuracy of diagnostics.

There was extensive discussion and strong consensus among participants on the relevance of ensuring the availability of data and better data capture at source, including methods, protocols and techniques for better collection and management of data for use in health decisions.

Open-source, free-of-charge, collaborative platforms provide software, applications, databases and libraries for sharing information, experience and expertise and are an essential medium for collaboration between countries in the development of vaccines, treatments, tools and policies and for transfer of technology.

Although most of the innovations require data, in many countries, data are not collected or recorded, and data systems are not interoperable, whereas interoperability is essential for aggregating data for use in clinical and surveillance tools and technology development. It was suggested that interoperability be built into new systems when possible.

The relevance of a skilled workforce of health professionals and technicians as an enabler was considered high or very high by 100% of votes, as was the relevance of strong leadership and good governance for managing complex systems and their interactions transparently and democratically. High scores for relevance were also given for skill in data analysis and for skilled communities and people, so that they become “equal partners at the table with the doctor”, resulting in “democratization of health”. Other innovations that received high scores for relevance were the synthesis and diffusion of evidence and best practices and increasing collaboration in health research to improve outcomes and wider sharing of the benefits between countries.

Structural, legal and political enablers were considered highly relevant by most experts, including regulatory and policy framework (such as for data privacy), high-quality Internet access and a reliable power supply, investment and access to funding, use of globally accepted ethical and legal guidelines, public–private partnerships for research and development and universal primary health care. They also agreed on the importance of establishing regional networks to support high-cost research. Collaboration among countries and regions was considered crucial.

Another enabler for which there was strong consensus was intellectual property management. There was significant agreement on the relevance of most of the cultural enablers: building trust in science, disabling the spread of misinformation, accountability and cooperation, modern means of communicating science, a proactive approach and attitude, health and digital literacy, and empowering patients. Digital health, online communities and social media have empowered patients and have changed their relationships with physicians, so that they have become more active in managing their health.

Some potential risks associated with emerging technologies and scientific innovations were identified that are common to all the innovations, such as potential accentuation of health inequity; unreliability and inaccuracy due to poor-quality aspects of certain innovations; reduced accessibility of high-cost innovations; and inadequate data privacy.

Reflections on the exercise and limitations

The experts noted some imbalance in the areas of innovation. While many innovations in stem-cell and regenerative medicine tend to converge, more innovations should be found in some areas, such as mental health and women's health. Both are key areas of research. Participants also discussed promotion of equitable access to emerging technologies in general. Although there are global trends in promising innovations, needs and challenges depend on the context: perspectives on which innovations are promising may vary. In some settings, the most promising innovations appear to be precision medicine, digital and machine learning and mining biological and chemical information for the development of innovative health products. In other contexts, the most promising innovations are considered to be cost-effective vaccine platforms and new vaccines on existing platforms for unmet needs, such as HIV. AI can also play a role in clinical development programmes and in changing business models. The aim of monitoring emerging technologies and scientific innovations for global health for different needs, contexts and perspectives is to limit gaps and promote equity in accessing innovations for healthier lives.

Participants considered cost a remaining barrier to adoption, especially in LMIC, and many considered removal of this barrier to be a priority. Some participants concluded that it is more important to find ways to lower the costs of certain technologies already in use to ensure that they are widely used than to find the most promising innovations. Although cost is a focus in a few innovations, such as low-cost diagnostics and improvements in certain treatments, research could be conducted specifically on making innovations more accessible and available.

Some limitations to the exercise are acknowledged. As in all structured expert consultations, the results of this exercise reflect the combined judgement of experts. As there were only two Delphi rounds and limited virtual discussion between the two rounds, the degree of consensus on individual innovations varied. In the group that discussed innovations in diagnostic technology in particular, several innovations were seen as promising but with varying rates of consensus, and some difficulty was expressed in comparing the innovations overall. The broad scope of the exercise, with over 100 innovations, added to the complexity of the exercise. Furthermore, the experts had no face-to-face interaction, limiting conversation and the depth of the discussions on each topic.

Conclusions

7

This exercise should be viewed as a snapshot. It presents the aggregated views of an expert group for forward-looking prioritization, with a global public health approach. While it is not a definitive list, it calls for further reflection on the most promising innovations for global public health, their enablers and their potential risks. The aim is not to predict the future but to identify trends and emerging technologies and to use the opportunities as early as possible.

This horizon scan is a first step in a foresight approach. It invites readers to consider the innovations from a public health perspective: What innovations are being made? How can they be made available rapidly for the benefit of all? Further, what risks are associated with the innovations, and how could they be mitigated? The next steps may include planning plausible future scenarios, deep dives into the most promising innovations, and defining means to enable their adoption. Information updates, monitoring of signals of change and plausible scenarios are necessary to understand how the global health landscape would change if some of the identified technologies and scientific innovations were widely used. A horizon scan must, however, be repeated as new innovations appear and others fade because they did not fulfil their promise: the horizon must be scanned continuously to identify actions that will improve global health and result in a better future for all populations.

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Annex 1. List of innovations considered

The following innovations were considered by the experts in the second Delphi round.

Note: The innovations listed to vote for global ranking do not include three (IG7-5, care in augmented and virtual reality; IG7-7, education in the metaverse; and IG7-11, metaverse to improve global virtual scientific collaboration. The effect of their omission is, however, considered to be minimal, as none of the three was in the top three in their innovation group (Internet of things, wearables, telehealth, augmented and virtual reality).

Innovation group (IG), number and description	
IG1 Diagnostic technologies	
IG1-1	Vocal biomarkers
IG1-2	Body on a chip for diagnosis, prognosis, drug development
IG1-3	Application of genomics for early diagnosis and pre-diagnosis of diseases, starting from universal genomic prenatal screening to identify metabolic and other congenital disorders pre-symptomatically to enable precise diagnosis and to guide management and treatment
IG1-4	Biosensor-based point-of-care diagnostic platforms with chemical, magnetic, optical or nanotechnological modalities that would be cheaper, more accessible, more effective than polymerase chain reaction methods
IG1-5	Genomics, including microbial genomics to replace or supplement most current microbiological diagnostic technologies
IG1-6	Lab on a chip to diagnose several diseases with small devices easy to use. For example, "lab on a chip" based on the CRISPR enzyme Cas12 or micro-electro-mechanical system-based dual axes confocal microendoscopy
IG1-7	Low-cost viral diagnostics. Rapidly design and construct cost-effective point-of-care diagnostics for HIV and hepatitis B virus load testing with CRISPR/Cas techniques to identify nucleic acids
IG1-8	Use of metagenomics in the diagnostics framework, for safer, more accurate diagnoses
IG1-9	Home "laboratory" tests and direct-to-consumer genetic tests
IG1-10	Molecular multiplex point-of-care testing with new, low-cost, accurate, easy-to-use platforms for use in primary health care for patient-centred management (not disease-centred) of respiratory illness, systemic illnesses, meningitis, typhoidal or gastrointestinal illnesses
IG1-11	Open-source diagnostic toolkits (free, open-source toolkits that would allow laboratories in developing countries to produce their own tools (e.g. for COVID-19 research and diagnosis), reducing dependence on the global supply chain)
IG1-12	Rapid remote diagnostics. Connect people through cell phones, watches and other devices (such as smart implants, prostheses and wearable sensors) that can provide information on markers and link health information in real time for clinicians and other (public) health entities, supporting individual health promotion, disease prevention and disease (self) management and also real-world data for public health management and health economics. Could be associated with a small card with a chip that stores information and may be used by doctors on any visit.
IG1-13	Single-cell omics technologies to better understand and intercept diseases, intervene earlier and more effectively in prevention, diagnosis and treatment
IG1-14	Nutrigenomics
IG1-15	Virtual biopsy and in situ diagnostic technology based on high-resolution optical imaging to analyse tissues in situ, without having to remove them
IG2 Health products and drug delivery technology	
IG2-1	Advances supporting potent monoclonal antibodies against infectious diseases
IG2-2	Broad-spectrum drugs against microbes that do not cause resistance or tolerance, e.g. adapt their conformation to structural changes or mutations in the target
IG2-3	Drug development changes from a "push-through" to a "pull-through" system with drug developers acting as contractors who are instructed to develop drugs with the greatest societal interest
IG2-4	Expansion of 3D-printed pills and polypills
IG2-5	Theranostics
IG2-6	Polypills, produced in a plant environment (e.g. a single pill containing aspirin, statin and anti-hypertensive therapy)
IG2-7	Better coordinated, more effective systems of vaccine production and global distribution

Innovation group (IG), number and description

IG3 Tissue engineering and regenerative medicine

IG3-1	3D-printing of tissues or body parts (such as arms and legs) or for the function of organs
IG3-2	Bio-adhesives for tissue adhesive, haemostatic agents and membrane transplantation
IG3-3	Bioprinting to enable standardized production, parallelization and application-tailored design of human tissue, human disease models and patient-specific tissue avatars
IG3-4	Electrospun sio-membranes for wound dressings and protein immobilization
IG3-5	Neurotechnology (chips as brain parts or wireless brain computer interfaces) for cognitive enhancement, e.g. increasing capacity and memory
IG3-6	Regenerative medicine with therapies involving proliferation and transplantation of cells to improve the functioning of tissues or organs, potentially to treat diseases such as diabetes, nervous system disorders and cardiovascular disorders
IG3-7	Extension of age-related limits to health
IG3-8	Stem-cell technology for replacement of muscles, organs (eyes, ears) and bone or teeth, and later, heart, brain and neural tissue; e.g. transplants of retinal cells to treat blindness
IG3-9	Tissue-engineered medical products
IG3-10	ε-Polylysine-incorporated nanofibre wound dressings for skin regeneration

IG4 Molecular biology, cell, immune and gene therapy

IG4-1	Affordable personal genomic sequencing in health-care settings around the world
IG4-2	Adaptive platform trials in which several interventions are studied continuously
IG4-3	Organoid technology for drug testing and personalized medicine
IG4-4	Epigenomics for women's health
IG4-5	Biobanks for discovery of biomarkers and for monitoring, surveillance, testing and diagnostics, improving response to pandemics
IG4-6	CRISPR/gene editing for diagnosis and correction of genetic abnormalities, such as sickle cell disease. Might eliminate diseases such as HIV, by taking out part or all the CCR-5 gene to cure or prevent the disease
IG4-7	Redox state assessment for diseases and creating a biosensor for its assessment
IG4-8	Full human genome sequencing of underrepresented populations
IG4-9	Further genomic exploitation, including biomarkers, genomic scoring systems for precise prevention, diagnosis and personalized therapies
IG4-10	Improving the immune system by cell engineering, e.g. CAR-T cells against blood tumours
IG4-11	Microbiome analytical tools for research and clinical prevention and treatment
IG4-12	Novel transcriptomics (e.g. mRNA, non-coding RNA) with new nano tools for development and clinical use
IG4-13	RNA-encoded therapeutics
IG4-14	In-vivo cell reprogramming
IG4-15	Somatic gene editing of sperm, eggs and embryos for therapy and prevention, e.g. germline gene editing to prevent genetic diseases (for example, sickle cell disease or thalassaemia)
IG4-16	Synthetic biology and engineering of viruses de novo, based on publicly available sequence data
IG4-17	Synthetic genomes for biomolecule production
IG4-18	Combination of stem cells, cellular senescence and gene editing for therapy or prevention
IG4-19	mRNA vaccination platforms as a new way of programming for antigenic stimulation, which could result in new vaccines for tuberculosis, HIV, syphilis, hepatitis B, cancer and other diseases with complex immunology

IG5 Public health

IG5-1	Use of social media and information technology platforms to improve food choices and food diversity according to affordability and socioeconomic stratification
IG5-2	Biosensors for early detection of zoonotic pathogens and detection of toxic metals in food and water supplies
IG5-3	Population-wide screening of genomic variants associated with relevant diseases through affordable, population-specific genomic assays
IG5-4	Use of mobile phones (and other wearable technology) to improve human health, specifically with sensors, data and analytics
IG5-5	Global capacity for rapid response to infectious disease outbreak through real-time pathogen sequencing for surveillance, with equitable sharing and distribution of countermeasures
IG5-6	Global early warning systems and solutions to monitor conditions related to development of global infections and for disease monitoring, worldwide genomic surveillance of pathogens to identify potential zoonoses with information technology
IG5-7	Use of genomics and proteomics data to contextualize disease etiology, disease prediction and treatment of chronic conditions for widely different global populations

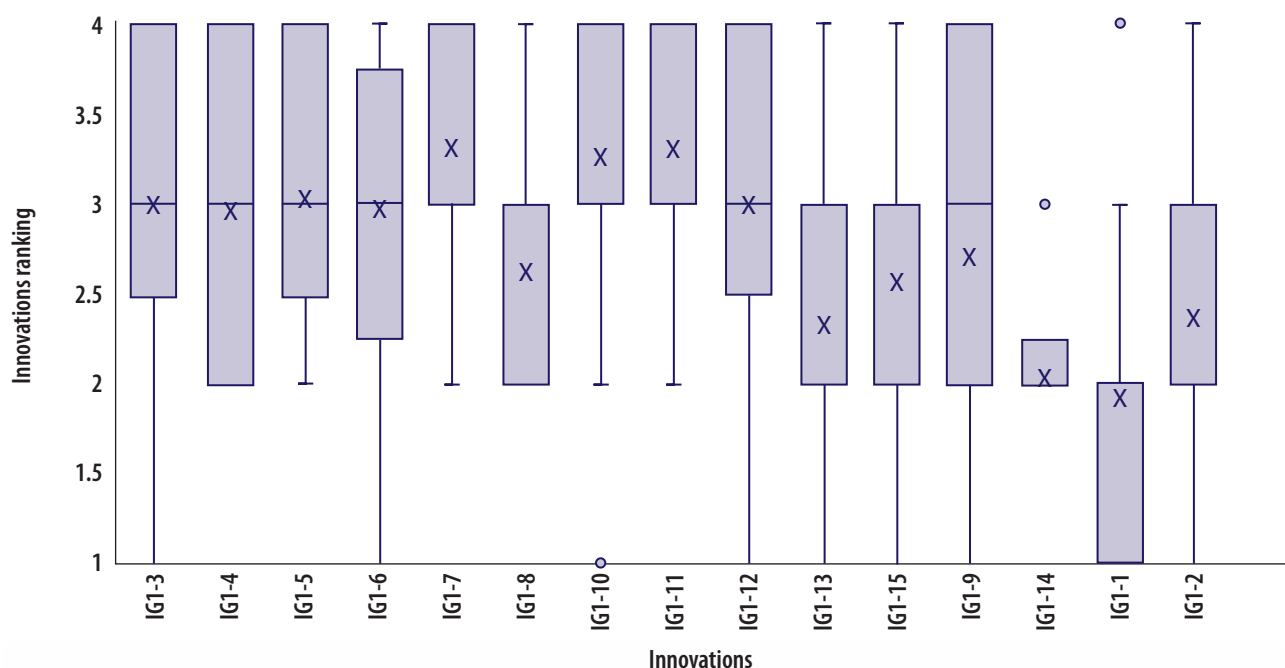
Innovation group (IG), number and description	
IG5-8	Machine learning-powered surveillance tools with symptomatic data, interpretation of basic tests (e.g. imaging, electrocardiograms), with algorithms for selecting further laboratory testing
IG5-9	Making plastics without harmful chemicals and contaminants
IG5-10	Monitoring and predicting new or recurrent pandemics from analysis of e.g. reports, medical records, mobile phone traffic, social media
IG5-11	Prevention and reversion of chronic diseases linked to lifestyle (such as type 2 diabetes) through training and changes in behaviour and lifestyle
IG5-12	Drones combined with real-time sequencing of environmental samples
IG5-13	Social innovation and new approaches to prevention and reversion of cognitive decline, with home care to stimulate brain activity through socialization and well-planned activities (instead of the institutionalized model)
IG5-14	Use of digital technologies to automate the collection and analysis of data at the intersection of health and environment to better predict, prevent and reduce environmental risks to health, such as enhanced, widely deployed aerosol and wastewater surveillance technologies
IG5-15	Water storage for clean water in countries prone to flooding (heavy rain catchment areas)
IG6 Dissemination and Implementation	
IG6-1	Accessible public platforms, application programming Interface and validated algorithms to support clinical decisions
IG6-2	An accessible information database (Wikipedia type) of all medicines that could be accessible everywhere, including in villages
IG6-3	An innovative implementation science model for use in major global health issues, such as the health consequences of climate change and mental health to improve reach, effectiveness, adoption and impact of innovations at population level and to implement (and sustain) best practices
IG6-4	Co-design and co-implement innovations in poor rural settings in low- to middle-income countries, such as the community-directed Interventions in the WHO Special Programme for Research and Training in Tropical Diseases, which were designed and used by rural communities in more than 30 countries in sub-Saharan Africa
IG6-5	Use of behaviour economics, gamification and game theory
IG6-6	Digital health ecosystems, creating infrastructure for transforming organization-centred health systems into a patient-centred model, improving interoperability and enabling sharing of virtual health records for a 360-degree view of patient health
IG6-7	Digital health tools for public health research and for development of new clinical preventive measures, treatments and vaccines
IG6-8	Digital tools, especially mobile apps, that enable provider-to-provider communication and to provide community health workers, clinical officers and other front-line generalist health workers with support from specialists in real time, bringing expertise from medical and surgical specialties to where patients live and seek care
IG6-9	Innovations to make new scientific and technological advances available and affordable for low- and middle-income countries
IG6-10	Innovative models of care based on data for individuals, the health system and the community (such as social media) for provision of patient-centred care.
IG6-11	Medical devices to improve evidence generation in trials, replacing old end-points, to design clinical studies that address patient-relevant outcomes and, when used while on treatment, increase compliance with treatment
IG6-12	New methods to train people to become health-care workers (new areas, train more people faster), develop disciplines that combine medicine, artificial intelligence and robotics, and use of technology (virtual and augmented reality) in training
IG6-13	Simple technology to prevent and reduce the prevalence of post-partum haemorrhage that is understood and can be applied by women and adolescent girls in hard-to-reach communities in low- and middle-income countries
IG6-14	Use of social influencer networks to drive ideas and promote changes in health through multiple channels for new generations
IG7 Artificial intelligence, Internet of things, wearables, telehealth, augmented and virtual reality	
IG7-1	Artificial intelligence-aided diagnostics from databases of medical images to ensure earlier, more accurate detection of various pathologies
IG7-2	Artificial intelligence prediction of the 3D structures of proteins and for drug development
IG7-3	Automated, virtual patient support and care, e.g. virtual carers
IG7-4	Big Data, artificial intelligence and machine learning to evaluate large amounts of patient data and other information and create tailored algorithms to support physicians in personalized medicine, possible diagnoses, medications and treatments plans
IG7-5	Care in augmented and virtual reality, including immersive experiences to combat anxiety and fight mental illness
IG7-6	Chatbots to communicate health-care messages to the population
IG7-7	Education in the metaverse: doctors, students can perform and test different types of procedures as many times as they wish, using digital twins
IG7-8	Internet of medical things allows connection with and location and monitoring of employees, patients, devices and other critical resources, e.g. a GPS locator device for people with dementia
IG7-9	Iris and facial biometrics with a mobile camera to identify patients presenting in health facilities or authorized health personnel
IG7-10	Use of artificial intelligence to identify harmful misinformation and identify “outdated” scientific information

Innovation group (IG), number and description	
IG7-11	Metaverse to improve global virtual scientific collaboration: setting the stage for ongoing collaboration, near-human type, avatars and digital twins (virtual model designed to accurately reflect a physical object), through the metaverse instead of physical conferences
IG7-12	Artificial intelligence-based decision support systems for public health surveillance and public health promotion, creating risk models for noncommunicable and communicable diseases in order to predict the risk of an individual in 5 or 10 years
IG7-13	Use of artificial intelligence, natural language processing and other data science tools to analyse data from social media, language patterns and images in posts to alert about mental health
IG7-14	Artificial intelligence-enabled artificial organs to reduce disability
IG7-15	Artificial intelligence-assisted economic modelling and monitoring of health systems in low- and middle-income countries
IG7-16	Quantum-safe encryption for federated medical data sharing
IG8 Materials and biomaterials, prosthetics	
IG8-1	Diagnosis and monitoring with intelligent materials that can continuously sense, respond and adapt
IG8-2	Minimally invasive surgery or minimally invasive procedures that replace surgery altogether
IG8-3	Nanorobots in blood or tissues (safe passage in body, not rejected and can be retrieved) for diagnosis and microsurgery
IG8-4	New materials and prosthetics, such as an artificial heart (heart valves) made of aluminium, exoskeletons for spinal cord injuries, prosthetic fingers, arms, knee joint replacements, wide-range hearing aids, bionic eyes, electronic olfaction
IG8-5	Organ care technology and bioprinting
IG8-6	Tactile sensors (e.g. nanofibres), bio-integrated sensors

Annex 2. Consensus among experts in scoring the potential impact of innovations

The “box” represents the interquartile range, and the lines show the minimum and maximum scores. Dots show outliers. Thus, the innovations with the smallest boxes and shortest lines were associated with the greatest convergence of opinion and vice versa.

Innovation group 1. Diagnostic technology



IG1-1 Vocal biomarkers

IG1-2 Body on a chip

IG1-3 Application of genomics for early diagnosis and pre-diagnosis of diseases

IG1-4 Biosensor-based point-of-care diagnostic platforms

IG1-5 Genomics, including microbial genomics

IG1-6 Lab on a chip

IG1-7 Low-cost viral diagnostics

IG1-8 Metagenomics use in the diagnostics framework

IG1-9 Home “laboratory” tests

IG1-10 Molecular multiplex point-of-care testing with new low-cost, accurate, easy-to-use platforms

IG1-11 Open-source diagnostic toolkits

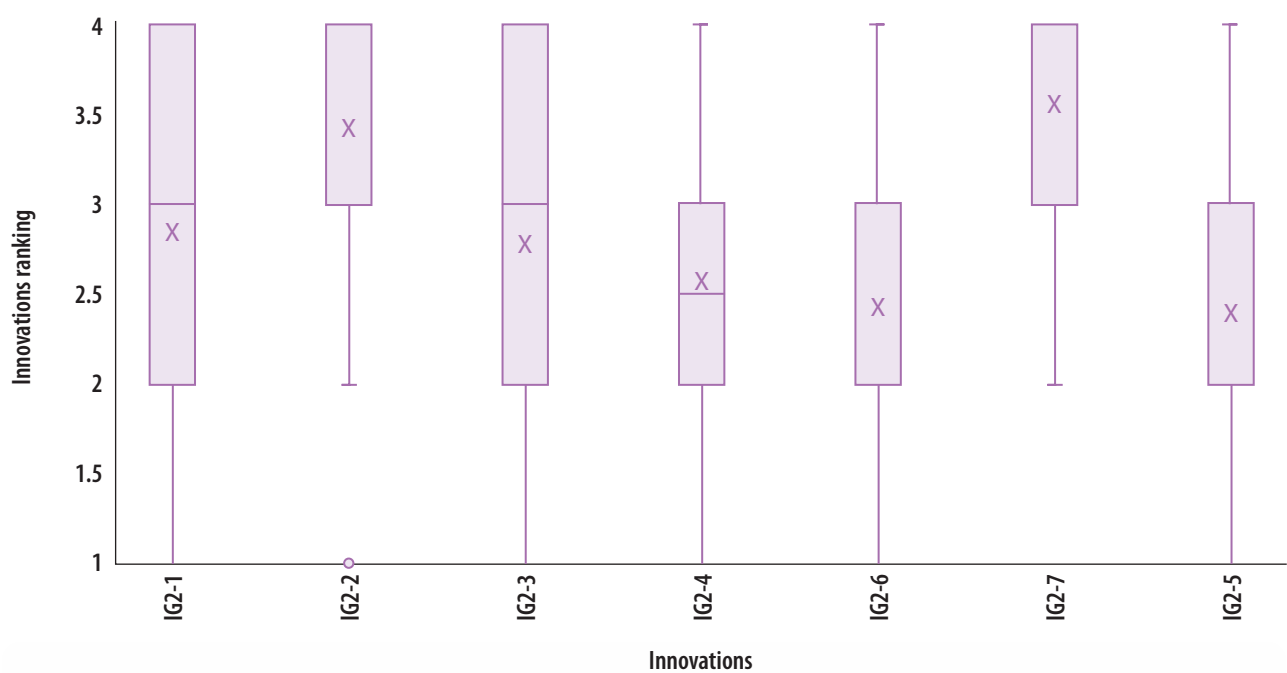
IG1-12 Rapid remote diagnostics

IG1-13 Single-cell omics technologies

IG1-14 Nutrigenomics

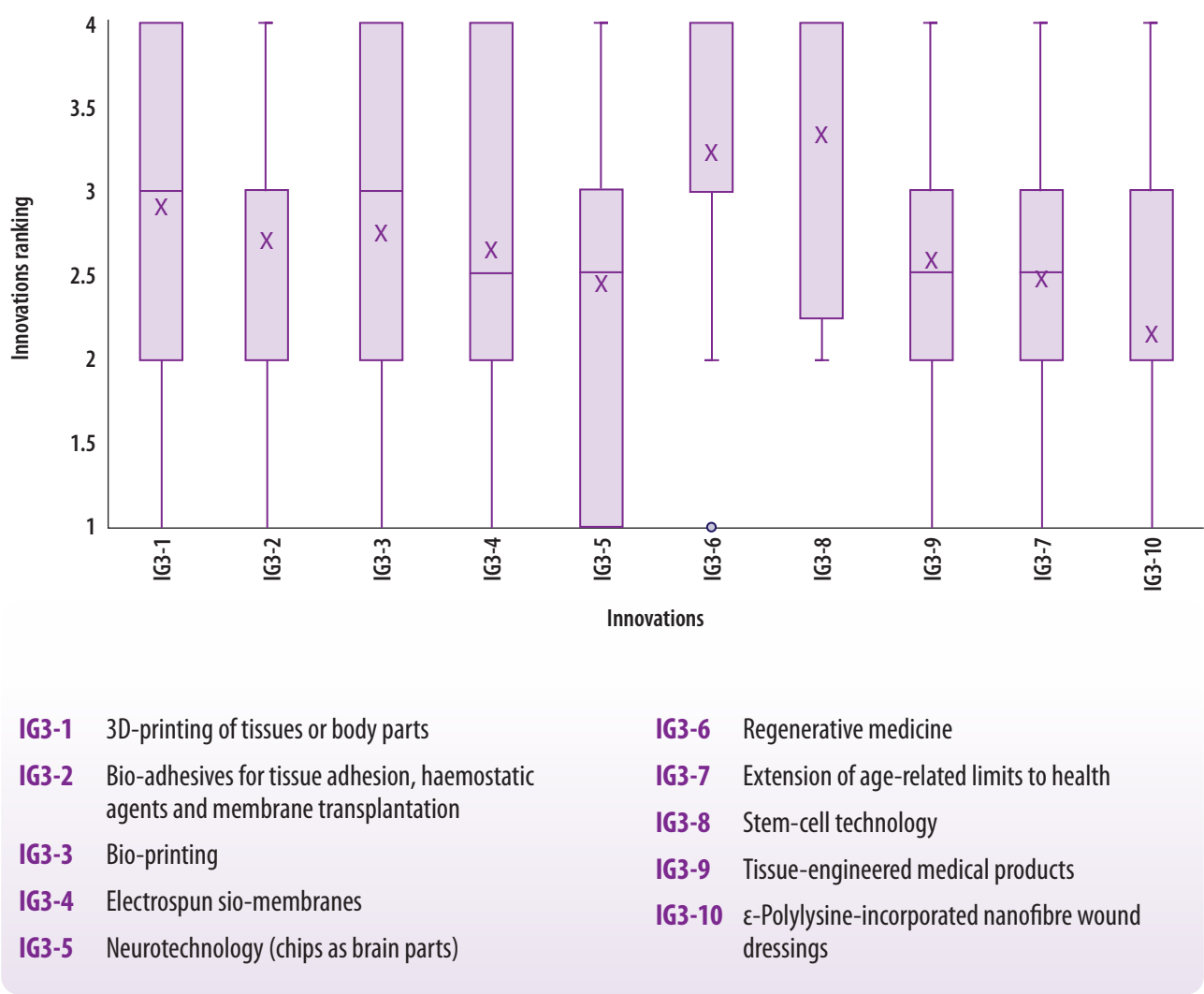
IG1-15 Virtual biopsy and in situ diagnoses

Innovation group 2. Health products and drug delivery technology

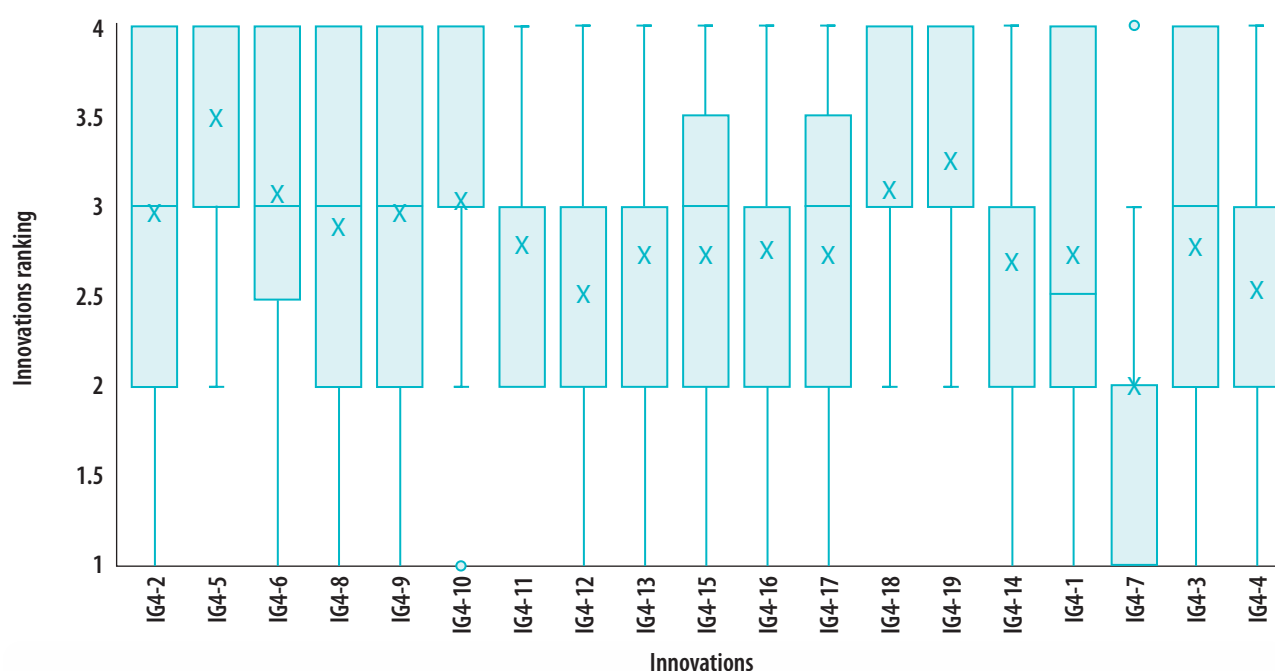


- | | | | |
|--------------|--|--------------|--|
| IG2-1 | Potent monoclonal antibodies against infectious diseases | IG2-5 | Theranostics |
| IG2-2 | Broad-spectrum drugs | IG2-6 | Polypills |
| IG2-3 | Drug development change from a “push-through” to a “pull-through” system | IG2-7 | Better coordinated, more effective systems of vaccine production and global distribution |
| IG2-4 | Expansion of 3D printed pills and polypills | | |

Innovation group 3. Tissue engineering and regenerative medicine



Innovation group 4. Molecular biology and cell, immune and gene therapy



IG4-1 Affordable personal genomic sequencing in health-care settings available around the world

IG4-2 Adaptive platform trials in which multiple interventions are studied continuously

IG4-3 Organoid technology for drug testing and personalized medicine

IG4-4 Epigenomics for women's health

IG4-5 Biobanks for biomarker discovery and for monitoring, surveillance, testing and diagnostics

IG4-6 CRISPR/gene editing for diagnosis and correction of genetic abnormalities

IG4-7 Redox state assessment for diseases and creating biosensors

IG4-8 Full human genome sequencing of underrepresented populations

IG4-9 Further genomic tools, including biomarkers, genomic scoring systems

IG4-10 Improving the immune system by cell engineering

IG4-11 Microbiome analytical tools for research and clinical prevention and treatment

IG4-12 Novel transcriptomics (e.g. mRNA, non-coding RNA) associated with new nano tools

IG4-13 RNA-encoded therapeutics

IG4-14 In vivo cell reprogramming

IG4-15 Somatic gene editing

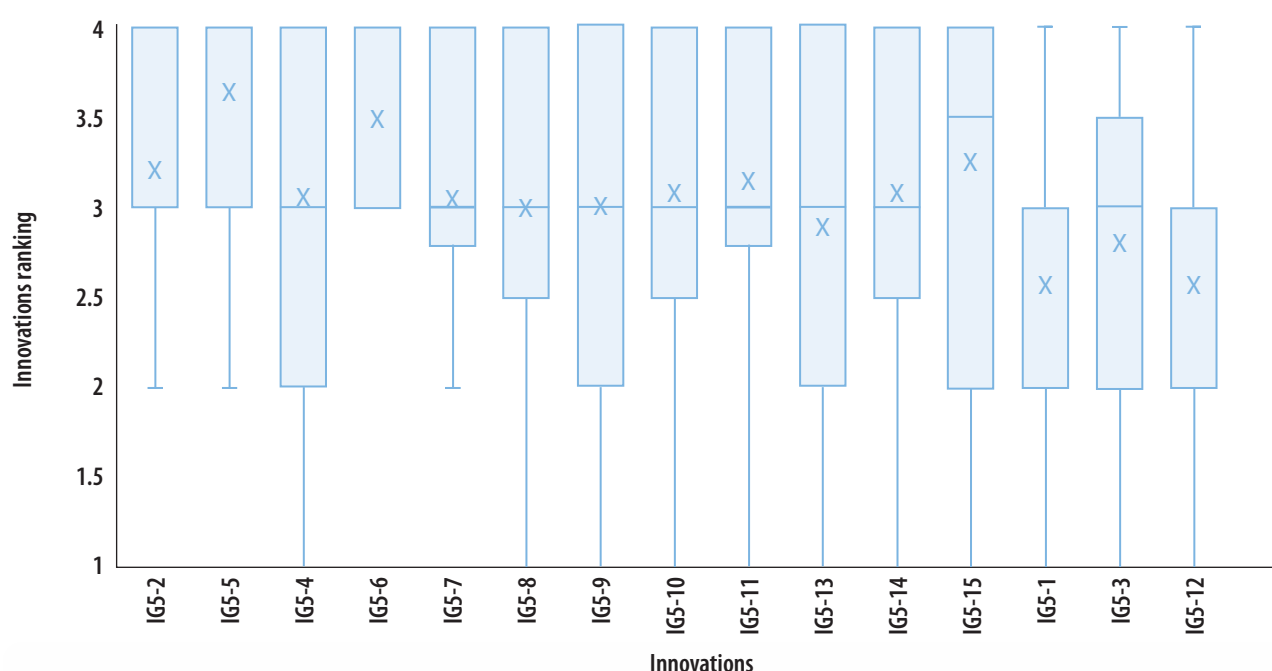
IG4-16 Synthetic biology and engineering of viruses de novo

IG4-17 Synthetic genomes for biomolecule production

IG4-18 Use of stem cells, cellular senescence and gene editing

IG4-19 mRNA vaccine platforms

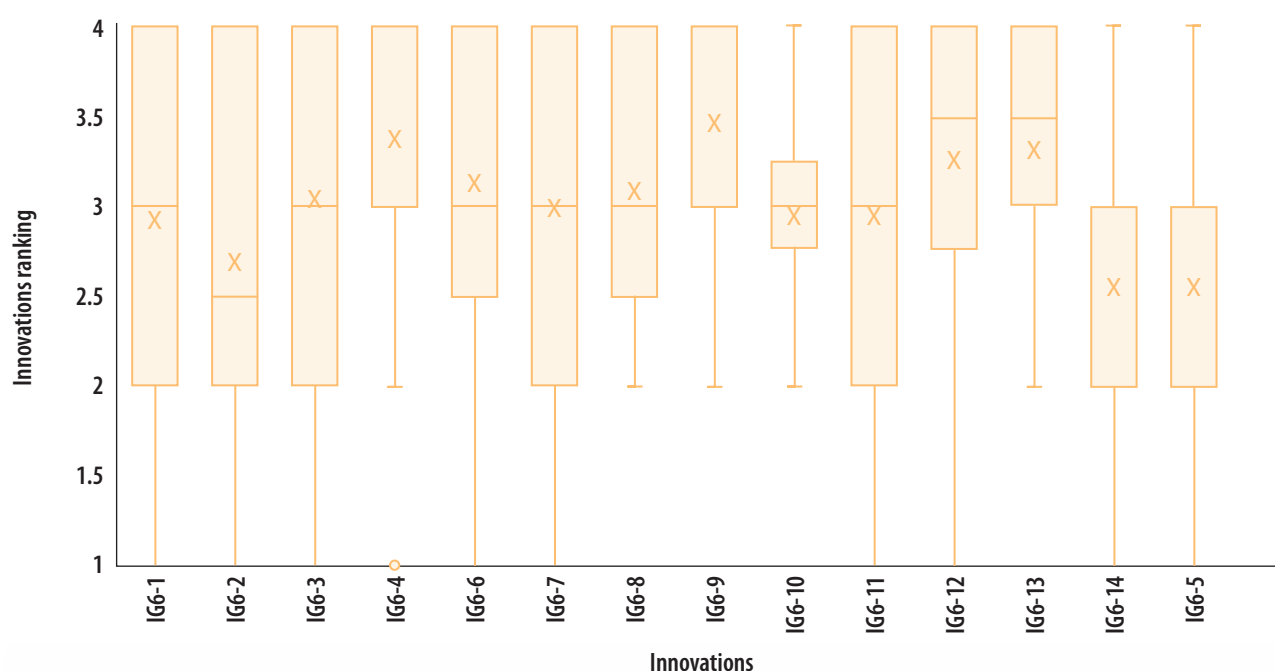
Innovation group 5. Public health: environment, climate change, epidemiology and surveillance, nutrition and health



- IG5-1** Use of social media and information technology platforms for improving food choices and food diversity
- IG5-2** Biosensors for early detection
- IG5-3** Population-wide screening of genomic variants associated with relevant diseases
- IG5-4** Use of mobile phones to improve human health
- IG5-5** Global capacity for infectious disease outbreak response through real-time pathogen sequencing
- IG5-6** Global early warning systems for monitoring global infections and diseases
- IG5-7** Use of genomics and proteomics data to contextualize disease etiology, disease prediction and treatment of chronic conditions
- IG5-8** Machine learning-powered surveillance tools for symptom data

- IG5-9** Making plastics without harmful chemicals and contaminants
- IG5-10** Monitoring and predicting new and recurrent pandemics
- IG5-11** Prevention and reversion of chronic diseases linked mainly to lifestyle
- IG5-12** Drones combined with real-time sequencing of environmental samples
- IG5-13** Social innovation and new approaches to the prevention and reversion of cognitive decline, with home care
- IG5-14** Use of digital technologies to automate the workflows for health and environment management
- IG5-15** Water storage for clean water in countries prone to flooding

Innovation group 6. Dissemination and implementation



IG6-1 Accessible public platforms, application programming interface and validated algorithms to support clinical decision-making

IG6-2 An accessible information database (Wikipedia type) of all medicines

IG6-3 Innovative implementation science model for improving reach, effectiveness, adoption and impact of innovations

IG6-4 Co-design and co-implementation of innovations in poor rural settings in low- and middle-income countries

IG6-5 Use of behavioural economics, gamification and game theory

IG6-6 Digital health ecosystems, creating infrastructure to support transformation of the organization-centred health-care model into a patient-centred model

IG6-7 Digital health tools for public health research

IG6-8 Machine learning-powered surveillance tools for symptom data

IG6-8 Digital collaboration and data-sharing tools

IG6-9 Innovations to make new scientific and technological advances available and affordable for low- and middle-income countries

IG6-10 Innovative models of care

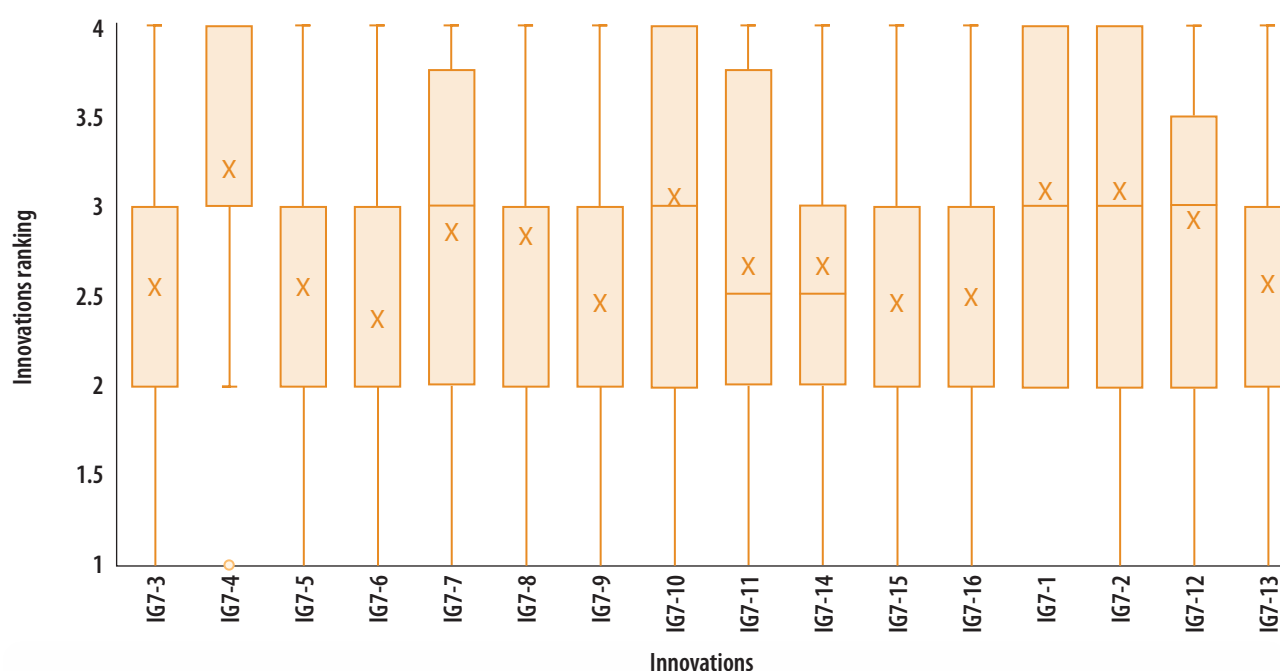
IG6-11 Medical devices that improve evidence generation in trials, replacing old end-points

IG6-12 New methods to train people to become health-care workers

IG6-13 Technology to prevent and reduce the prevalence of post-partum haemorrhage

IG6-14 Use of social influence networks to drive ideas and promote changes in health

Innovation group 7. Artificial intelligence, Internet of things, wearables, telehealth, augmented and virtual reality



IG7-1 AI-aided diagnostics from databases of medical images

IG7-2 AI-prediction of the 3D structures of proteins and for drug development

IG7-3 Automated, virtual patient support and care

IG7-4 Big Data and machine learning to evaluate large amounts of patient data and other information and create tailored algorithms

IG7-5 Care in augmented and virtual reality

IG7-6 Chatbots to communicate curated health care messages

IG7-7 Education in the metaverse

IG7-8 Internet of medical things

IG7-9 Iris and facial biometrics with a mobile camera to identify patients

IG7-10 Use of AI to identify harmful misinformation and identify “outdated” scientific information

IG7-11 Metaverse to improve global virtual scientific collaboration

IG7-12 AI-based decision support systems for (public) health surveillance and public health promotion

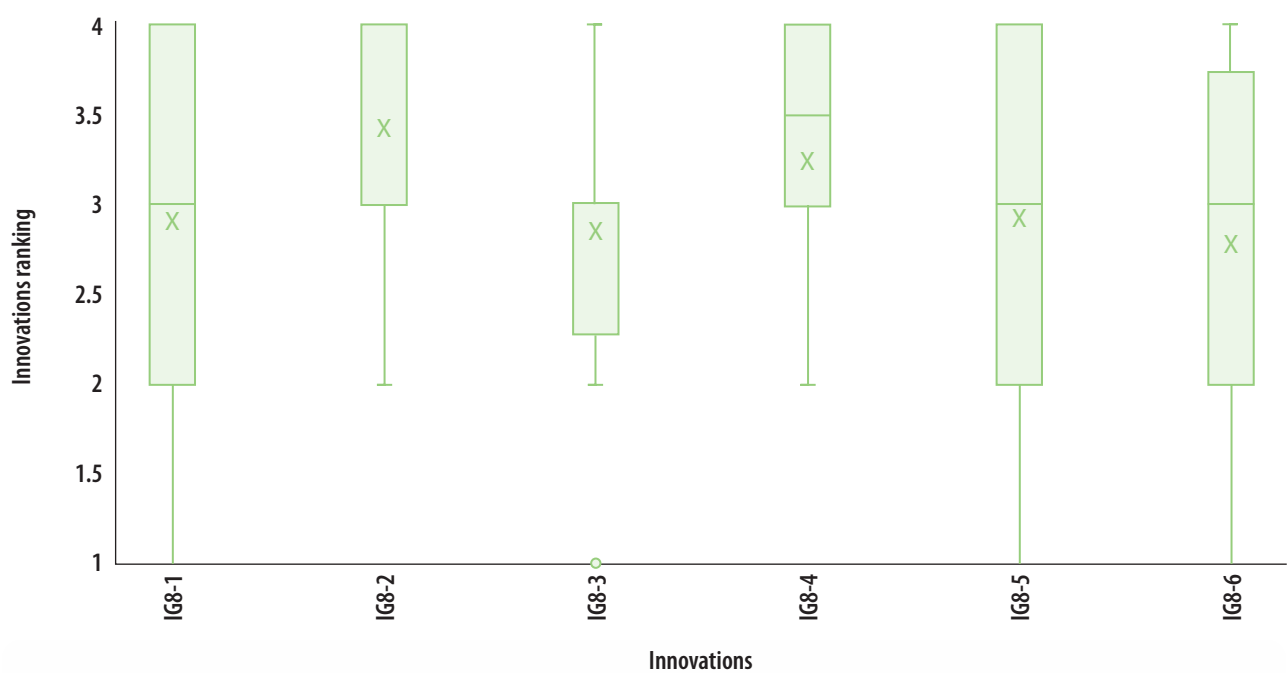
IG7-13 Using AI, natural language processing and other data science tools to analyse data on mental health conditions at individual and community levels

IG7-14 AI-enabled artificial organs

IG7-15 AI-assisted economic modelling and monitoring of health systems in low- and middle-income countries

IG7-16 Quantum-safe encryption for federated medical data-sharing

Innovation group 8. Materials and biomaterials, prosthetics



IG8-1 Diagnosis and monitoring through intelligent materials that can continuously sense, respond and adapt

IG8-2 Minimally invasive surgery or minimally invasive procedures that replace surgery altogether

IG8-3 Nanorobots in blood and tissues for diagnosis and microsurgery

IG8-4 New materials and prosthetics, such as artificial hearts, exoskeletons for spinal cord injuries, prosthetic fingers, arms, knee joint replacements, wide-range hearing aids, bionic eyes, electronic olfaction

IG8-5 Organ care technology and bioprinting

IG8-6 Tactile sensors (e.g. nanofibres), bio-integrated sensors

The Global Health Foresight function was established in the WHO Science Division to support WHO in remaining “ahead of the curve” in relevant areas of research, science and technology in order to proactively identify, anticipate and shape issues that hold promise for global health. This publication presents the findings of a global horizon scan of innovations in science and technology that could help solve global health challenges. An expert group scored over 100 innovations for their potential impact and the chance of wide adoption within 5, 5–10 or > 10 years. They also discussed enablers that would facilitate adoption of the innovations.

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