While digital transformation is widespread in industry, healthcare has only started to follow a similar path in the last few years, with COVID-19 leading to rapid acceleration. With the rise of the Internet of Medical Things, integrated care networks and connected healthcare, new opportunities emerge.

Is healthcare ready for a digital future?

By GUYLIAN STEVENS, KOEN DE BOSSCHERE and PASCAL VERDONCK

The rise of integrated healthcare networks, connected healthcare and the Internet of Medical Things (IoMT) has led to a huge and rapid expansion in the volume of data generated. The current fragmented structure of the healthcare landscape is not fit to manage, or make the most of, this vast amount of information. In a world where data has become currency and sensors are continuously generating new data, we are no longer able to process this continuous inflow. Therefore, a computational approach to analyzing and visualizing this data is needed to prevent healthcare systems and providers from drowning in an overwhelming lake of 'useless' data.

Novel microchip developments are finding their way into healthcare. Whereas until now, mostly wearables have been in use, new developments are now opening up the path to in vivo sensing devices, "insideables". This will lead to personalized healthcare and a resulting explosion of the volume of data. Is healthcare ready for this?

Key insights

- Healthcare is evolving from a centralized institution-based structure into a decentralized network-based structure founded upon increasing value for both patients and healthcare workers. This leads to the emergence of **value-based**, **integrated** and **connected** care.
- The Internet of Things, integrated care networks and connected care have led to the creation of an overwhelming volume of data, causing an overload for both clinicians and decision makers. **Collection, transmission, protection** and **processing** are the four key components of this data network. AI-based algorithms will be necessary to process this data into a form useful for clinical, financial and ethical decisions. A clear vision on how to store and analyze this data – ranging from edge devices to data centres – needs to be developed.

Key recommendations

- Computational healthcare will include a wide variety of domains: ranging from artificial intelligence in **decision support systems** over **computer-aided diagnosis** and data collection, transmission and security of wearables and insideables to manufacturing applications in **3D printing** and **computational modelling**.
- Future healthcare will require advanced cyber-physical systems with high quality of service and low latency.
- Insideables and bioelectric devices will require ultra low-power computing. nteroperability that allows security and privacy to be preserved will be a key requirement of the move to the cloud.

From healthcare to health

In 2010, the European Commission defined the primary goal of healthcare policy as that of maximizing the health of the population within the limits of the available resources, and within an ethical framework built on "equity and solidarity principles". This goal encompasses three pillars of major importance: maximize health, with limited resources, in an ethical framework. Over the last decade the goal to maximize health has not changed, however the limitations and the framework surrounding this goal have changed significantly [1].

Various frameworks aiming to redefine healthcare have been developed. A clear shift from individual and sporadic one-on-one care to a network-based continuous care is emerging. An early example was initiated by the ministry of health of Singapore. It describes three "moves" to implement better care (Figure 1).

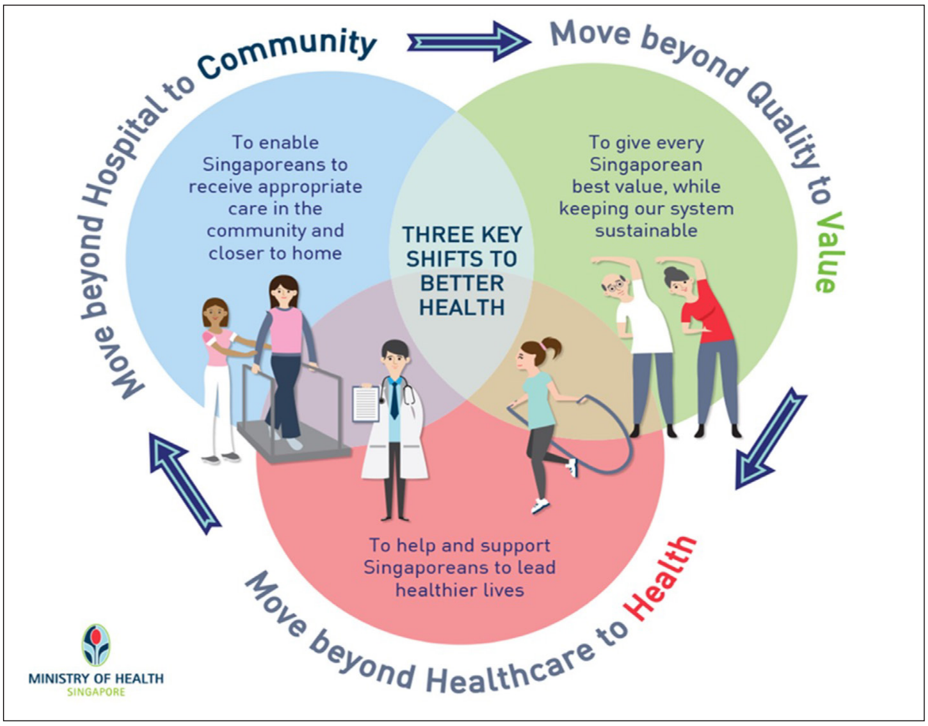

Figure 1: Framework healthcare Singapore [2]

The first move goes beyond the concept of hospital to the concept of community. This allows patients to receive good and appropriate care within their own community and thus closer to home. This does not mean that the hospitals become redundant, but that they organize care close to or in the comfort of the patients' home. This could include telemedicine, chronic care management, patient remote monitoring, patient self-management with or without coaching, etc. This is not only more comfortable and more affordable for the patient: it is also essential in areas where people do not have easy access to advanced medicine and hospital care. The second move is to go from quality to value, and to offer every patient the best possible value he or she can get. The last move is from healthcare to health, meaning caregivers would not simply act in the healthcare process but in fact intervene in the prevention and pre-care process to enable better and healthier living conditions for their previous, current and future patients [2].

This move from healthcare to health shows similarities with the health continuum plan proposed by Philips. This continuum describes how clinicians should not only focus on diagnosis and treatment but also get involved across the patient care spectrum, in healthier living, prevention and home care. This starts from the idea that citizens are in a continuous loop.

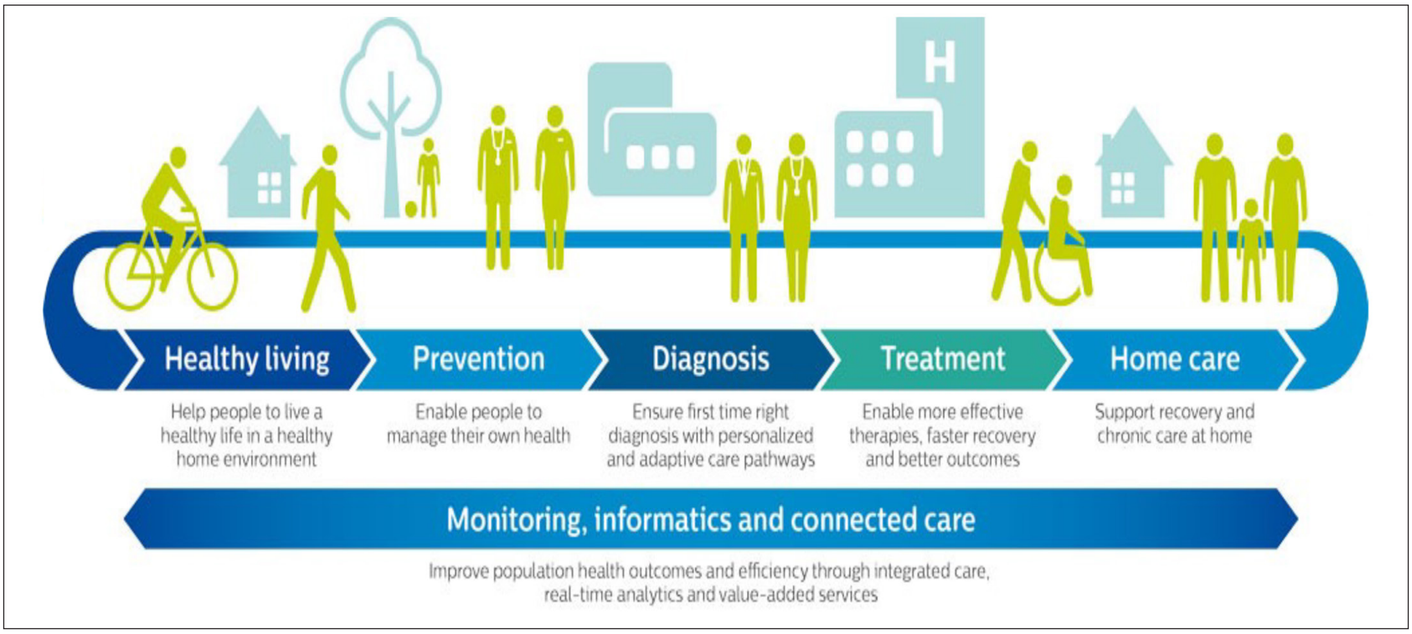

Figure 2: Healthcare continuum Phillips [2]

When citizens are treated and receive home care, they are treated as patients. Once they are fully recovered, they go back to being citizens. However, chances are high that if no change in their way of life is initiated, they will quickly return to being patients in the diagnosis phase. As citizens are either future or past patients, it is logical that healthcare practitioners are connected to both citizens and patients. As can be seen in Figure 2, this injects into the cycle several additional actors and information that can only be coordinated well if a foundation of monitoring, informatics and connected care-giving is established [3].

Towards value-based, integrated and connected care

Within these frameworks, three healthcare concepts play an important role: value-based healthcare, integrated healthcare and connected care. The idea of value-based healthcare is that the goal and purpose of healthcare in general is to improve the value for patients. Value is the product of the patient's personal experience with his or her outcome divided by the cost to achieve this outcome.

As M. E. Porter said, the only way to unite the interests of all participants in the healthcare system is by using value as a goal. Value is created by caring for a patient's medical condition over the full cycle of care. The improvement of the outcomes are the most powerful single lever in order to reduce costs and improve value [4].

The second concept is **integrated care**. Integrated care brings together inputs, delivery, management and organization of services related to diagnosis, treatment, care, rehabilitation and health promotion. Nowadays, a hospital or an individual healthcare professional can no longer operate in isolation. All of these individuals are integrated into one or more healthcare networks. Once a patient consults a healthcare worker of a certain network, he or she automatically becomes part of this network, of course with the liberty to leave or change as it pleases [5,6].

The last concept is **connected care**. We are increasingly confronted with smart environments. Wearables, smart cameras, ambient technology, connected equipment, etc. are embedded in a world where the Internet of (Medical) Things is growing exponentially and everything and everyone is becoming connected. This connection can be seen at different scales, going from on-body to in-home to community, in-clinic or in-hospital settings. When a patient is treated with a certain device or undergoes a certain examination, digital data will be generated, stored and used by other devices, people, institutions or environments in order to improve the value for the patient [7].

Towards a data framework turning data into value

Value, integration and connection are based on data. Without data that measures a patient's outcomes and costs, the value to optimize the healthcare process cannot be calculated. Without efficient data exchange, healthcare networks described above cannot operate and healthcare staff would once again work on their own isolated islands, leading to redundant examinations and consultations.

The healthcare of the future will generate massive volumes of data. Connected devices, healthcare workers and patients

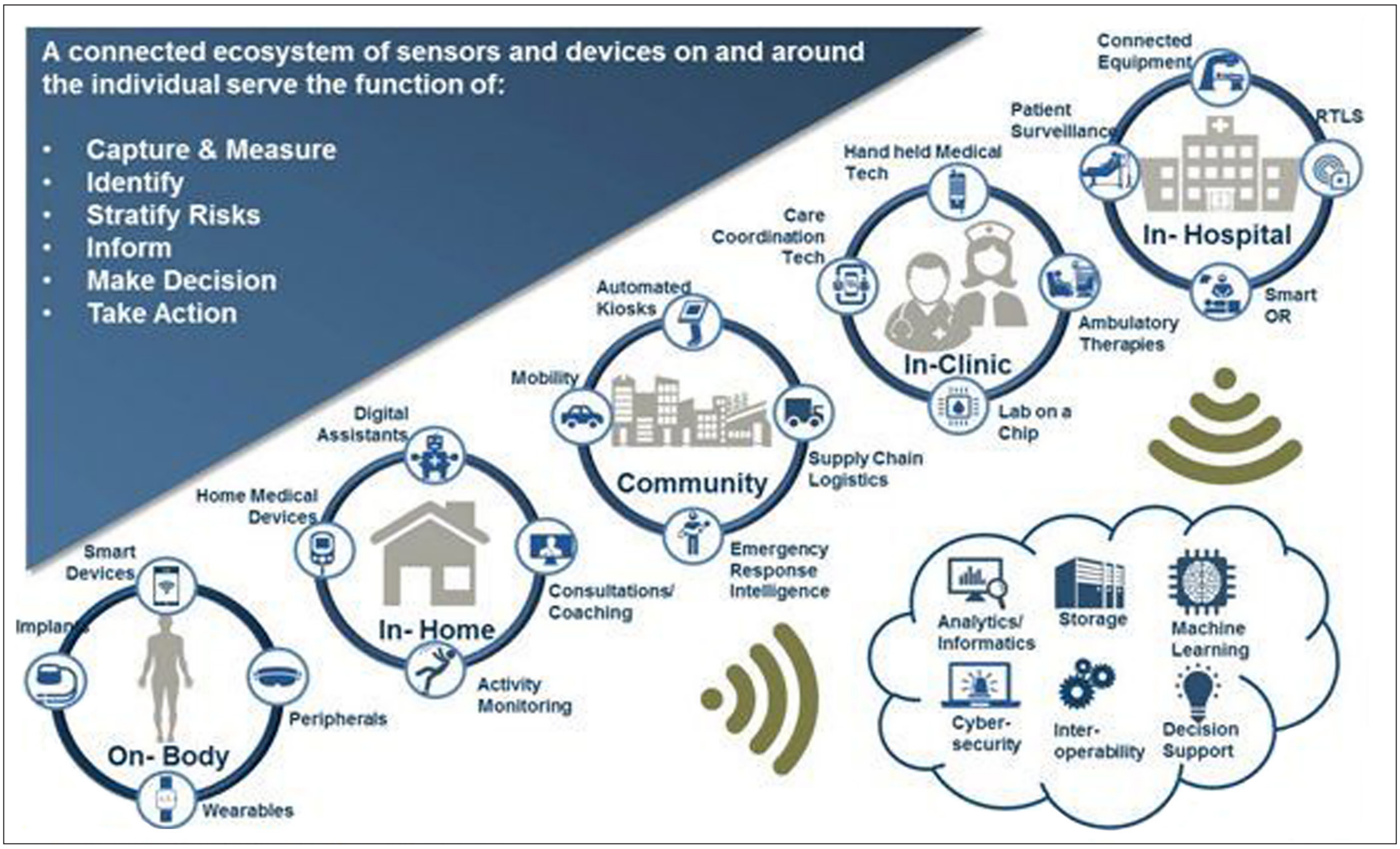

Figure 2: Connected care in 2025 by Frost & Sullivan

will create a lake of data. Sensors will perform the data collection from health, activity, location, emotions, parameters, etc. They will be the well of the data lake. One should not only think of wearables or insideables that monitor parameters of the patient but also the external ambient sensors that measure humidity, temperature, weather, pollution, etc. Measuring the living environment of a patient is something that is already done with a technique called ambient intelligence. Ambient intelligence creates a digital environment that is aware of the individual's presence and context, and is sensitive, adaptive, and responsive to their needs, habits, gestures and emotions. Combining these measurements with the patient-specific data allows for a more patient-specific approach. This data, used as **currency** in the network, can take many forms, ranging from personal to population or environmental data and will be transferred between a variety of interested parties [10].

Different communication protocols can establish a connectivity (**data transmission**) between all those different parties in this integrated and connected care network: Wi-Fi, Bluetooth, cellular (3G, 4G, 5G), LoRa, etc. Of course, merely collecting and transporting data will not be enough. This continuous flow of data collection will outgrow the storage capabilities of modern-day healthcare infrastructures, and the IoMT and decentralized healthcare will only increase further the demand for storage space.

Physical examinations will be partly substituted by a flow of digital information. Such a huge volume of data could easily overwhelm healthcare workers, leading to a situation in which value and patient outcomes no longer improve. The amount of non-processed data might lead to a decrease in efficiency and poor use of time, and thus also to a worsening of patient outcomes.

Therefore, next to collection, currency and transmission, **intelligence** needs to be introduced into the data framework. This intelligence, when done by computers is called artificial intelligence (AI) and can be a great asset to healthcare teams. AI is able to analyze data in order to provide insights that can inform the actions of healthcare staff, decision makers or the patients themselves. Signals that would otherwise go unnoticed or reacted upon too late can now be detected by the AI to trigger alarms directly to the responsible party.

The use of this artificial intelligence in healthcare can be put into three categories: knowledge-based decision support systems, data-driven clinical decision support systems and computer-aided diagnosis.

This third category has been particularly rich in development of new applications within the last couple of years. For example, the University of Pittsburgh has developed an algorithm that can identify prostate cancer with near-perfect accuracy. During tests, a sensitivity of 98% and specificity of 97% was demonstrated [26]. Another example is found in the domain of deep learning and neural networks. A collaboration between MIT and the Massachusetts General Hospital trained neural networks to automatically administer anesthetics during a surgery, based on the monitoring of the patient's vital parameters [27]. The universities of Melbourne and Otago have trained a neural network to predict the risk of cardiovascular diseases by gathering information from the retina of the eye [28]. As one can see, without this computer-aided intelligence, the data would still be available but would still require processing by individuals. With the current volume and complexity of such data, this wouldn't be achievable in practice.

Last but not least, an important aspect of data is **security**. With the new GDPR regulations of 2018, data protection has gained a tremendous importance over the last two years. This, in combination with a huge volume of generated data, leads to the necessity of rethinking the concept of data protection as a whole. Figure 4 represents the five discussed aspects of data: collection, currency, transmission and intelligence all protected within a shell of security. Each of these elements is essential and the loss or weakness of one would undermine the potential and capabilities of the others.

Nowadays, data is typically spread over different entities: central servers of hospitals, decentralized personal computers of

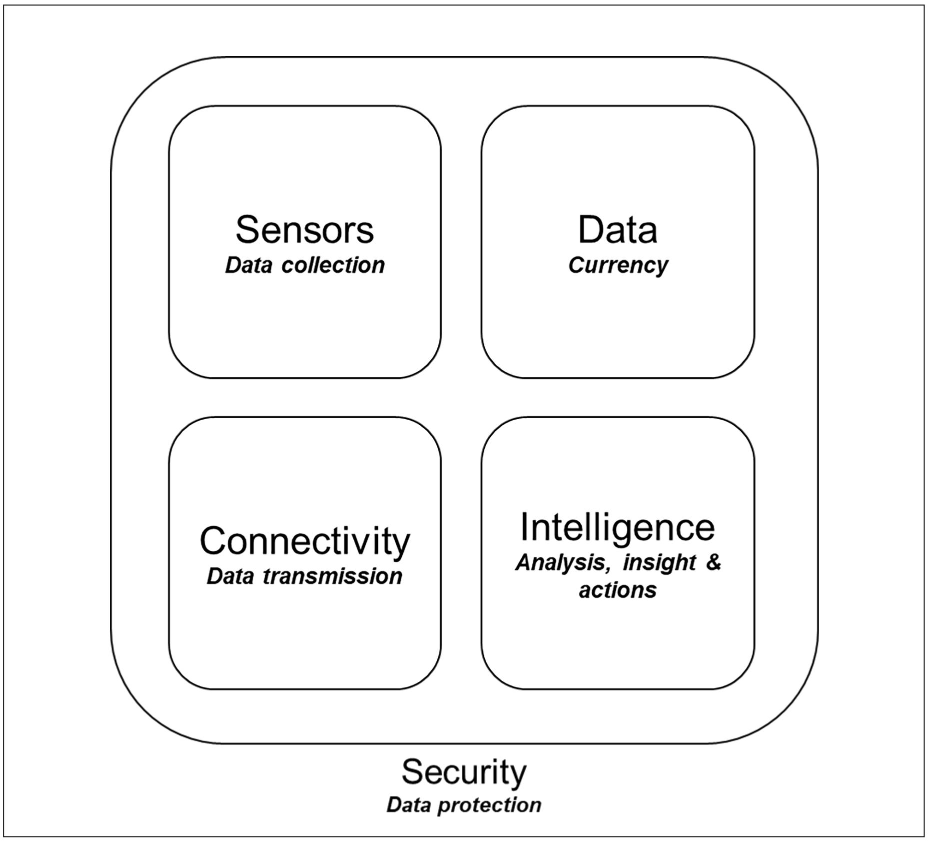

Figure 4: Aspects of the data framework

general practitioners, and centralized cloud servers of medical and non-medical apps. This is an obstacle to the introduction of connected and integrated healthcare. New concepts of connecting all these data sources in a decentralized network of data will be required. Technology like blockchain can control who has access to which data and could be the foundation on which to create these decentralized networks. Full Homomorphic Encryption allows the processing of information in encrypted form on untrusted servers. The possibility to use this data in a secured and effective way will lead to an increase of the future value of healthcare. As EY [8] reported in 2019, the future value will be equal to innovation to the power of data. Hence, without data, innovation will not create any value or vice versa.

From hospital servers to the cloud

As described above, healthcare is evolving into an integrated, connected care network. There are many different players involved, including healthcare practitioners, hospitals, governments and technology providers, all of whom play a role and have a stake in creating optimum value. The fundamentals of this evolution will be collection, transmission, sharing, analyzing and protection of data.

Data analysis will be the greatest challenge in the short term. The need to process this continuous dataflow will force healthcare systems to innovate and upgrade their IT infrastructure continuously, with more computational power, more storage and more network capacity. It will be necessary to transform massive amounts of data into information. To achieve this, a digital transformation is already taking place in healthcare. Computers are used to store and organize electronic medical records, for diagnosis, to administer medication, in operating rooms, for off-site care, for telemedicine, for machine learning, for clinical decision support systems, for clinical assisted diagnosis systems and so on.

Regarding the processing of the data, the way the data is stored leads to three processing techniques. When all data is stored locally in a database server, High Performance Computing (HPC) and quantum computers can be used to perform computationally intensive tasks and large analyses. At the moment, HPC systems are used in a good number of healthcare applications ranging from computational biology and chronic disease recognition to big data analyses and artificial intelligence. Quantum computing can open up new possibilities in healthcare in terms of drug design, in silico clinical trials with virtual humans simulated "live", real-time whole genome sequencing and analytics, the achievement of predictive health, or the security of medical data via quantum uncertainty.

Hospital servers are cautiously being replaced by cloud servers. Today, healthcare decision-makers remain skeptical about cloud computing due to its vulnerability to hacking, tampering and data leaks. However, with the rise of the IoMT, apps, wearables and ambient intelligence, cloud computing in healthcare will have to become mainstream, and technical and legal solutions will need to be found so that necessary levels of trust in the cloud can be achieved.

Figure 5 shows a conceptual scheme of the computing techniques of present and future.

Robots, AI and 3D-printing

Another major application of computing in healthcare is robots. Robots can be employed in several parts of the health continuum (prevention, treatment, diagnosis, aftercare). A primary application would of course be in the operating theatre (treatment). In surgery, many operations are already carried out by robots, operated by a specialized surgeon. Such robots are safety-critical cyber-physical systems with high reliability requirements. When used for telesurgery, the robot and the surgeon have to be connected via a fast and reliable low-latency network. Based on data from surgical robots, (parts of) some operations might in the future be carried out by autonomous robots.

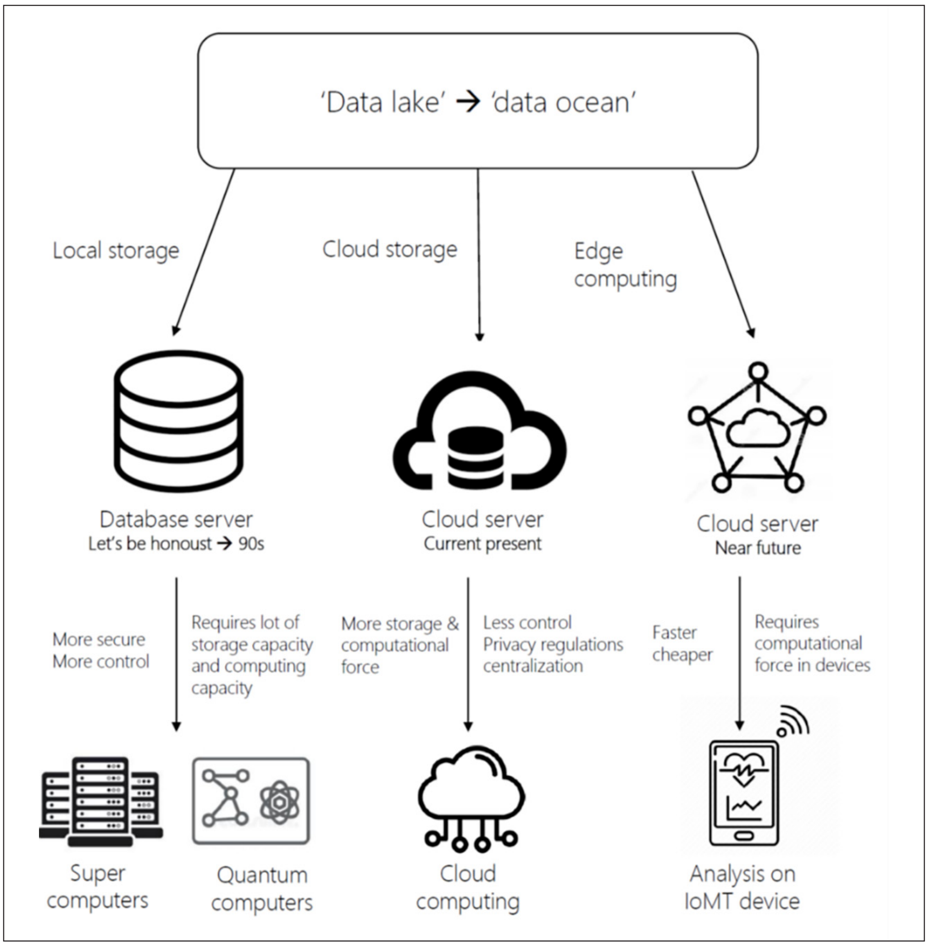

Figure 5: Concept scheme of computational data flows in the present and future healthcare institutions

However, the application of robots in healthcare goes beyond the operating theatre: think of their usability as a chat function, in which they can support patients by addressing misunderstandings and concerns about a procedure, delivering information in a responsive, conversational way over email or text. The general idea is that in the future, **these talking or texting algorithms might become the first contact point for primary care**. Patients will not automatically get in touch with physicians or nurses or any medical professional with every single health-related question; instead, they will turn to chatbots first. This chatbot function can be performed by an online platform or executed more physically in the form of a real humanoid robot, giving company to children or elderly people who would benefit most from this (prevention and aftercare) [20].

Other applications in which computers and robotics have proven to be great assets are logistics, assistive technologies (daily activity tasks, mobility, smart prostheses, etc.), revalidation (physical as neurological) and training or education.

Medical diagnosis is another field in which computers can play an important role. Take the IBM Watson technology: it was able to pass first year medical school exams but failed in the more practical tasks of the following years. Furthermore, Watson for Oncology did not deliver on its promises because the data it had to work with contained too much ambiguity. Watson for Genomics seems to work at least as well as humans when searching for mutations and proposing relevant drugs and clinical trials. In some cases, it has spotted important mutations overlooked by a human doctor. But there is no proof yet that it led to a better outcome. Watson is however very much appreciated as a smart librarian suggest the relevant studies [31].

In radiology, clinical decision support systems can support radiologists with routine tasks, improving their productivity and increasing the quality of their work, leading to better patient outcomes. The software will not take over the radiologists' jobs but will support them in such a way that they can focus more on the specific cases (diagnosis) [22].

A last important innovative domain within computer technology in healthcare is situated in the field of 3D printing. The combination of this additive manufacturing technique with software that can transform medical images into computer models (e.g. Mimics, 3-matic of Materialise) opens up a new range of possibilities within different hospital departments. Nowadays, 3D printing is used for computer-assisted and image-based patient-specific implants in orthopedics and maxiofacial surgery as well as for didactic communication between radiologists and organ specialists. Therapeutic 3D printing of cells with the use of bio printers for use in vivo and for regenerative medicine are still a dream for the hospital of the future [29, 30].

Microchips and insideables

Development of new materials and new chip manufacturing techniques have led to very small microchips with promising applications on and inside the human body. One of the first widely adopted applications is the use of microfluidics and with it the creation of lab-on-a-chip (LoC) devices. LoC allows the integration of several laboratory operations such as PCR (polymerase chain reaction) and DNA sequencing into a single chip on a very small scale [11]. This technology has seen spectacular growth over the last few years with applications including diagnosis of infectious diseases, handheld diagnostic devices and detection of analytes. In a recent project, researchers have developed a smartphone attachment that can detect multiple infectious diseases in a few minutes from a single drop of blood. Detection zones in a tiny cartridge present in the phone detect antibodies in the blood that enters the cartridge, thus detecting a disease. This device was field-tested by researchers in community clinics in Rwanda and was used to screen 96 patients for HIV and syphilis. The results had an accuracy level of 96% in detecting various infections when compared to those of standard lab tests [12, 13].

Another application of microchips is a human computer tag, called the VeriChip. It can be compared to a kind of wireless barcode or dog tag for humans. The VeriChip is a radio-frequency identification (RFID) tag produced commercially for implantation in human beings. Its proposed uses include identification of medical patients, physical access control, contactless retail payment, and even the tracing of kidnapping victims. In healthcare settings, the VeriChip can help identify a "Jane Doe" or "John Doe," that is, an incapacitated or disoriented patient whose identity is difficult to establish [14].

Of course, the functionality of microchips as being small computers for insideables brings with it a new dimension for consideration, which spans safety, reliability, efficiency, etc. Requirements can be functional (e.g. sensors, computational unit, telemetry), environmental (e.g. biocompatible, biostable, no biofoulding, limited heating, etc.) specific for device-tissue interaction (e.g. miniaturization, biomimetic, flexible, stretchable) or risk assessment-based (e.g. redundancy in hardware and software). Regarding the safety issues, biocompatibility and biostability are the key focus. This requires new techniques for chip production that will allow safe contact between the chip and biological tissues depending on the application. Innovative manufacturing techniques in chemical, physical and atomic layer deposition need to be supported. They need to be smaller, integrate more sensors and process the measurements in a meaningful stream of data – in other words, they need to become smart. This requirement will of course go hand in hand with higher energy consumption. To counter this problem, innovation in batteries (e.g., lithium-iodine, lithium-manganese dioxide), remote powering (e.g., telemetry, inductive coupling, ultrasound powering) and internal energy harvesting from sources in the body (e.g., temperature differences, bio-fuel cells, piezo-electric conversions) are the main focus. In Belgium, imec is currently one of the more advanced developers in medical microchip technology [25].

Imec and Ghent University have collaborated on the production of smart contact lenses developing a lens that can mimic the human iris to combat eye deficiencies (Figure 6). The iris aperture is tunable

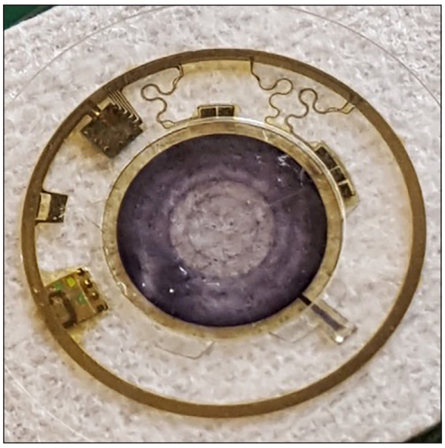

Figure 6: Smart contact lens by imec and Ghent University

through concentric rings on an integrated liquid crystal display (LCD). The smart contact lens is designed to operate for an entire day thanks to an ultra-low power design, offering a practical solution for people who suffer from deficiencies of the eye such as aniridia, high order aberrations like keratoconus, and light sensitivity or photophobia. The artificial iris lens is capable of dynamically changing the pupil size, bringing back two levels of functionality of the eye: light adaptation and expanded depth-of-focus [15].

Last but not least, neural probes seem to be the major future application for microchips in healthcare. This so-called bioelectronics will open up a completely new dimension of computing: the human-computer interface. Whereas, at the moment, people decide on how a computer device should react, neural probes will enable computers, and thus also robotics, to react directly to the neurological behaviour of the human. This can open up possibilities in terms of robotic prosthetics, allowing paralyzed people to speak again or control their automated wheelchairs just with their thoughts. Besides assistance, neural probes might also contribute to brain mapping, nerve stimulation, restoration of neuronal functions, and investigation of brain disorders [16, 17, 18]. In this domain, imec has created a neural recording and stimulation probe, implanted into the peripheral nerves. This research was carried out in collaboration with DARPA to research the opportunity of controllable prostheses for army amputees. The technology works with an in vivo CMOS chip and computational electronics that regulate the external control unit of the bionic prosthesis [15].

Market

The medical technology market in Europe was worth €120 billion in 2018, which makes it the second biggest global market (27%) after the United States (47%). Germany, France and the UK own more than 50% of the European market. The biggest export market is the US (41%) followed by China (10%). The total employment in the medical technology industry in Europe is almost 700,000. Europe has 27 000 medical technology companies, 95% of which are SMEs. The medical technology industry is a research-intensive industry, which reinvests 6-10% of its annual sales in research. With a global market share of 27%, medical technology is an important economic sector in Europe, and a position that is worth defending. Given the rapid digitization of medical technology, it is also an important market for the European computing industry.

New competitors have recently arrived on the medical technology market. Big tech companies like Google and Apple are investing heavily in the healthcare market. They currently limit themselves to consumer-based non-clinical applications and wearables. It is clear that they are focussing on the medical market too. Apple has already launched the Apple Health record and equipped their Apple watch with a single ECG measuring sensor. With its health kit, the company is able to report trends taken from other health apps and wearables. Furthermore, they have created a platform on which third parties can create pre-approved medical apps that can simply connect to the Apple health ecosystem. This will allow healthcare providers and insurance companies to create custom apps to use in their practices [23].

Google is also investing in the healthcare market. A recent joint venture between Google and Johnson & Johnson has led to Verb Surgical Inc. Verily (an Alphabet company) brings its expertise in data analytics, visualization and machine learning to the Verb Platform. Johnson & Johnson and Ethicon bring their deep knowledge of surgery and expertise in surgical instrumentation to this partnership. As they say themselves: "In the future, our actions will connect surgeons to an end-to-end platform for surgery, including pre-operative planning, intra-operative decision making and post-operative care." [24] Besides this venture, Google has bought Fitbit in order to launch new platforms and wearables onto the medical market as they are aiming for FDA approval in due course. It has also created a platform to support healthcare application builders in the development and implementation of new healthcare apps.

Roadblocks: smart infrastructure and new competencies

The implementation of integrated and connected healthcare will require an infrastructure upgrade for fast and stable connectivity through the widespread implementation of 5G wireless networks. The speed and bandwidth of this network will allow the creation of a speedway for data transmission and analysis. At the moment, 5G is being rolled out in Europe. A stable network with very high levels of coverage will be essential, along with suitable solutions to the possible issues of data security and privacy, for the next steps in the future of healthcare to be taken.

Given that cloud storage decreases control over stored personal and medical data, it will be vital to check if providers are completely compliant with the GDPR. Beside safe storage and transfer of data, the interoperability between the devices generating this data and the electronic patient records will also be of major importance. Without this integration, healthcare professionals will hesitate to use this large source of information and data will be lost.

Another hurdle is the urgent need for new competencies in healthcare leadership in general, in particular in hospitals. There is a growing gap between healthcare management competencies and capabilities that are acquired, and those that are now needed in the changing technological landscape. New computer technology can be embraced in order to reduce expenditure and help healthcare provision to adapt to changing social values [19].

Conclusion

In healthcare, data has become the currency of healthcare professionals, patients, governments, hospitals and decision makers. In the bigger picture of integrated and connected care, value-based healthcare can only be achieved if this data can be collected, transmitted and analyzed. In order to do this the computational landscape is shifting from a local data storage model to a cloud storage model. However, due to the fear of tampering, hacking and loss of data, this transition is moving slowly when compared to other domains. The greatest challenge will be the transformation of data into actionable information. Artificial intelligence, combined with increasing decentralized computational power, will play a key role in this. With current and future developments of insideables and bioelectronics, the data stream will only increase. This requires support and encouragement for continuous innovation in computational healthcare.

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