Digital Transformation in Healthcare

An IEEE Digital Reality White Paper

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Introduction

Healthcare costs are on the rise, and this is causing an increased interest in automation. However, it should be noted that in a few health care areas automation is sought to deliver better quality, like in pharmaceuticals or assistive automation in surgery which enables procedures that go beyond human abilities (micro surgeries among others). In surgery, there is a growing digital transformation, with diagnostic procedures generating data that are analyzed automatically, creating a model that is used for simulating procedures and eventually used by autonomous or semi-autonomous systems in surgery.

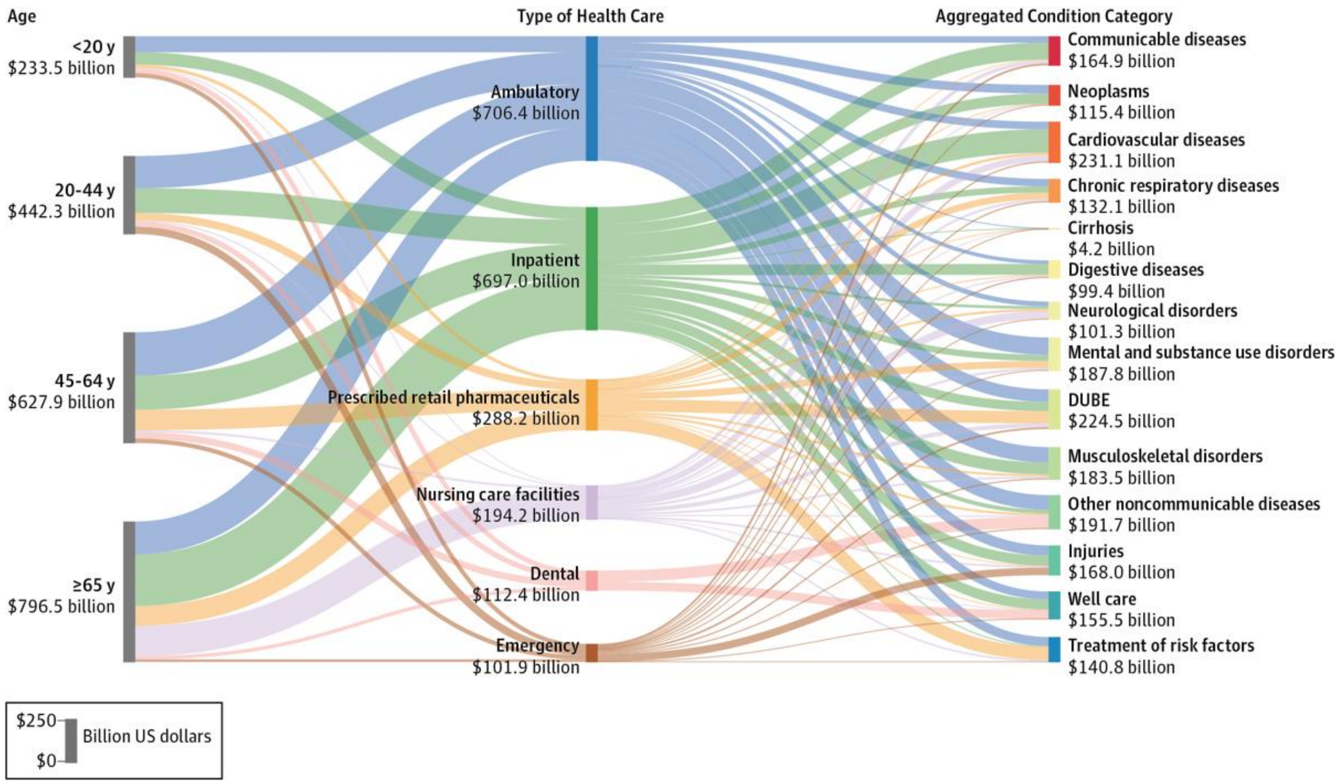

Figure 1 Differences in health care costs based on age range, type of resources and pathology. As expected, the lion's share of cost is fuelled by the elderly population as shown on the left hand side of the graphic. It is interesting to note that the biggest spending in healthcare support is in ambulatory and inpatient care, areas that are most likely to be affected by the digital transformation. Image credit: ***US Spending on Personal Health Care and Public Health, 1996-2013,*** *JAMA. 2016;316(24):2627-2646. doi:10.1001/jama.2016.16885*

The digital transformation in healthcare changes the whole landscape and is also changing the way people look at healthcare. Clearly, health care is also an area where symbiotic autonomous systems are making the first steps, mostly in terms of smart prosthetics.

This whitepaper presents several examples of autonomous systems applications clustered under the three main areas of disruptive transformation affecting health care that are deeply connected (in an increasing way from 1 to 3) to the digital transformation of this sector:

- **Delocalization**: health care can be delivered everywhere to serve patients in remote locations as well as to decrease cost and increase efficiency and convenience;
- **Personalization**: health care is shifting from the application of statistically certified paradigms (like drugs approved after extensive trials) to personalized protocols taking into account the patient (genomic) specificity;

- **Digitalization**: health care is exploiting data generated by a variety of monitoring systems (including wearables) and using data analytics on big data in community, country, or transnational ensembles.

Healthcare Delocalization

Autonomous systems are starting to play a role in the delocalization of care by providing on site assistance. Not surprisingly this has started in controlled environments such as hospitals and care facilities, but it is now extending to home-care.

Examples of autonomous robots include ones for preparing and bringing medicines to patients on a hospital ward and robots to disinfect rooms like the ones of Xenex that are used in hospitals and can be used in long-term care settings and at homes where there are debilitated persons that are not protected from infections.

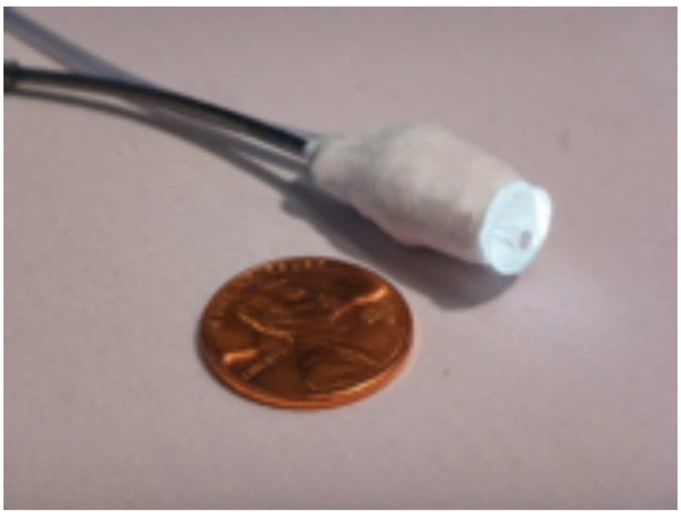

Figure 2 The tip of the robotic catheter developed at Boston Children's Hospital. Margherita Mencattelli. Boston Children's Hospital

In October 2019, ABB opened a research center on the premises of the Texas Medical Center Innovation campus in Houston. It is first focusing on development of autonomous robots to be applied to health care in a hospital environment. These robots are designed to be collaborative, called cobots, and to work autonomously as a team.

ABB already provides robots in the health care sector for preparing and delivering food. A new wave of companion robots are now on the market for elderly care, and significant improvement is expected in the next few years. Non-surgical robots used in health care are expected to grow to 60,000 by 2025 (there were 18,000 in 2018).

Fully autonomous robots able to perform surgery in remote locations are not operational although they are being studied in several research labs. Robots that have a limited range of autonomy that can be operated remotely are currently available. The next generation of communications network, 5G, has often been linked to enabling remote surgery using an onsite robot by taking advantage of its low latency that can support (to a limited extent) the use of haptic feedback. A few autonomous robot trials have been performed, like the one at the Boston Children Hospital where doctors have used an autonomous micro-robot to navigate inside the body to repair a cardiac valve (See Figure 2).

Suturing automation is another area being explored, and others are likely to come to the forefront in the next decade. In the last year there has been a growing use of artificial intelligence (AI), in its various forms, to provide surgical robots with advanced awareness and decision making capability. Clearly this is an area where legal issues are crucial, i.e., who takes responsibility for the autonomous decisions of a robot and of the outcome of its operation?

Healthcare Personalization

The sequencing of the genome is now a mass market reality. The cost had been decreasing but has remained stable at around $1000 since 2016. The cost is expected to start decreasing again in the next decade with more effective mapping technologies (leveraging machine learning, which is becoming more effective as more genomes are sequenced and mapped). Companies like Illumina (a market leader in sequencing), Nebula Genomics, Zenome, and DNAtix are applying blockchain to the mapping, making the genomic data accessible and will likely dominate in the coming decade decreasing the cost for top of the line services. On the other hand, other companies addressing the mass market today, like Ancestry, 23AndMe, are providing limited sequencing under $100, and they are expanding their capability in sequencing and mapping rapidly as they are growing the number of genomes sequenced. We can expect in the coming decade that these two forces, one from the top and the other from the bottom will dramatically change the use of genomics in healthcare.

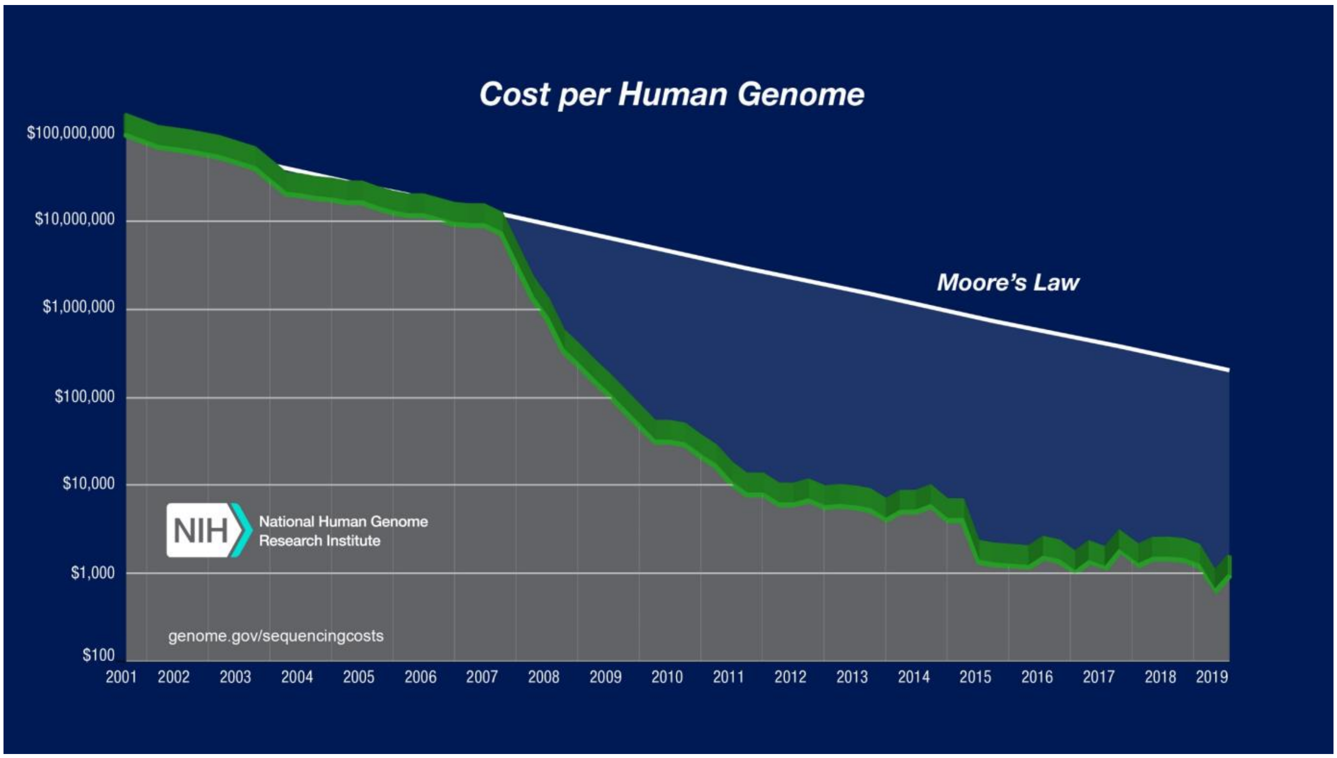

Figure 3 The decreasing cost for a full human genome sequencing. NIH – National Human Genome Research Institute

One of the problems today is confusion in the different numbers that are associated with genome sequencing, like:

- Storage required for a human genome: the figures go from 3GB (basically using one byte to represent each base pair) to up to 200 TB which is the monster data set coming out from the parallel sequencing of the million fragments of the DNA, with some intermediate figure in the order of hundreds of GB to keep the unmapped strings of DNA;
- Cost to make sense of the genome: as low as $850 for the sequencing, $3,000 for the mapping of the genome (moving from the strings of bases A-C-G-T to genes) to much more in order to understand the expression of genes;
- Cost to identify, or look for a specific gene (something becoming a standard protocol to define the way to cure a specific cancer): this cost can vary significantly (both in time and in

money) depending on the gene or mix of genes.

The combined forces of lower cost and increased data availability (fueling predictive analytics and enabling more sophisticated AI) are resulting in a growing interest on precision medicine (another way for saying personalization). The Obama administration launched the Precision Medicine Initiative which has now morphed into the All of Us initiative, which is aimed at at getting a genetic biobank[1]. France is actively working on the "France Medecine Genomique 2025" creating a genome bank growing by 235,000 Whole Genome Sequence (WGS) per year.

Personalized Healthcare / Digital Twins

Concurrent with the improvement of increased understanding and use of the human genome, companies like GE and Philips are investing in the creation of a person's digital twin as a way to support personalized medicine. Digital twins are already used to model processes, equipment and even hospitals but they are also being considered in the context of patients, more generally from a proactive medicine perspective.

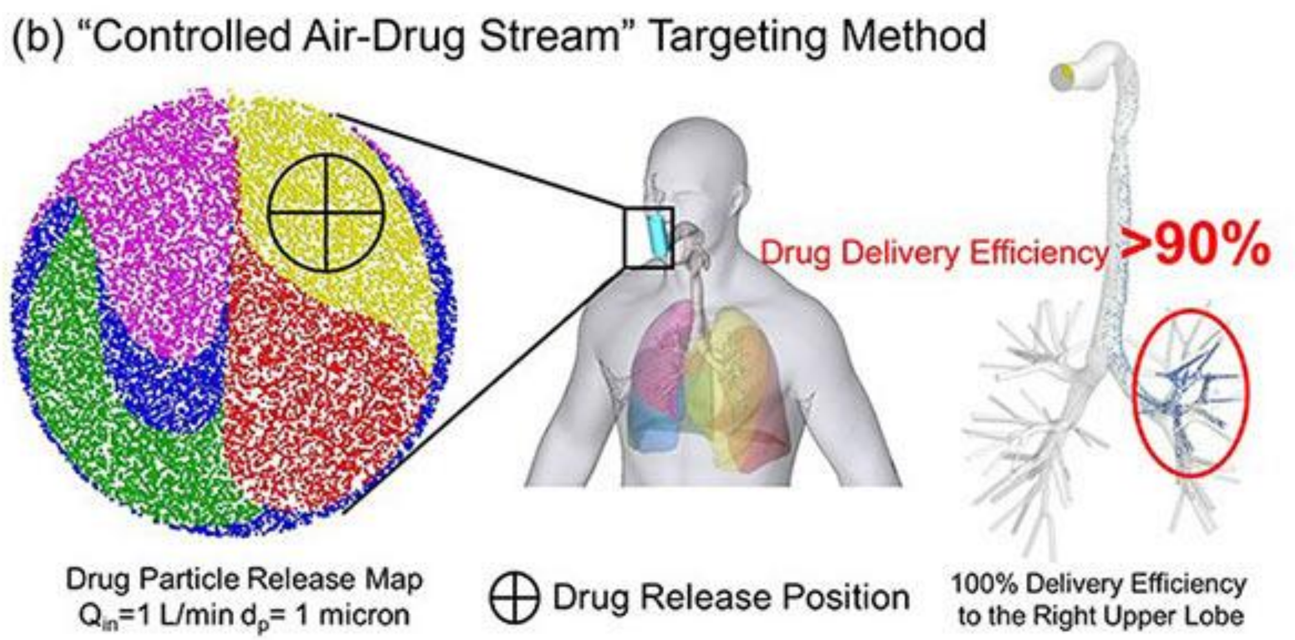

Figure 4 Digital Twins Deployed to Optimize the Aerosol Deposition of Medications. CBBL simulated the aerosol particles' movement through a digital twin of an adult's upper airway. The team then varied parameters like the diameters of the particles, inhalation flow rates and the initial locations of the medicine within the aerosol. The researchers eventually optimized the medical aerosol to have a delivery efficiency over 90 percent. Image credit: Oklahoma State University's Computational Biofluidics and Biomechanics Laboratory (CBBL).

Digital twins in personal healthcare are seen by the classic healthcare industry (such as GE, Philips, Siemens, Nokia) as a way to capitalize on data that are accrued through their equipment, fostering improved quality in healthcare and decreased cost. They are also seen, although this is not publicized, as a way to defend themselves from the competitive attack that is coming from companies that thrive on data and that see digital twins as a way to capitalize on their data and enter into the healthcare space. Google and Apple are at the forefront of this new breed of companies, with others already mentioned, like 23andMe, also trying to capitalize on the

[1] Interview with Dr. Francis Collins, Director of the NIH (interview starts at 7.53): https://www.youtube.com/watch?v=qjNnhdsgWsU&feature=youtu.be

availability of their data.

It is most likely that for the first part of the coming decade there will not be a clear winner (in the fight between the "incumbents" and the "data companies") but that the players will cause an acceleration of the adoption of digital twins.

An important aspect to mention is the expected evolution of digital twins to stage 4, a point where a digital twin may act as an autonomous system and roam cyberspace leveraging both data and services to provide a customized health guide to its physical twin. This development is not too far in the future; a few signs are already visible (the Apple Watch 5 is a step along this path although on a very tiny segment in healthcare). By the middle of the next decade, it is expected that digital twins in health care will become autonomous systems supporting advanced personalized cure.

Healthcare Digitalization – Leveraging Data

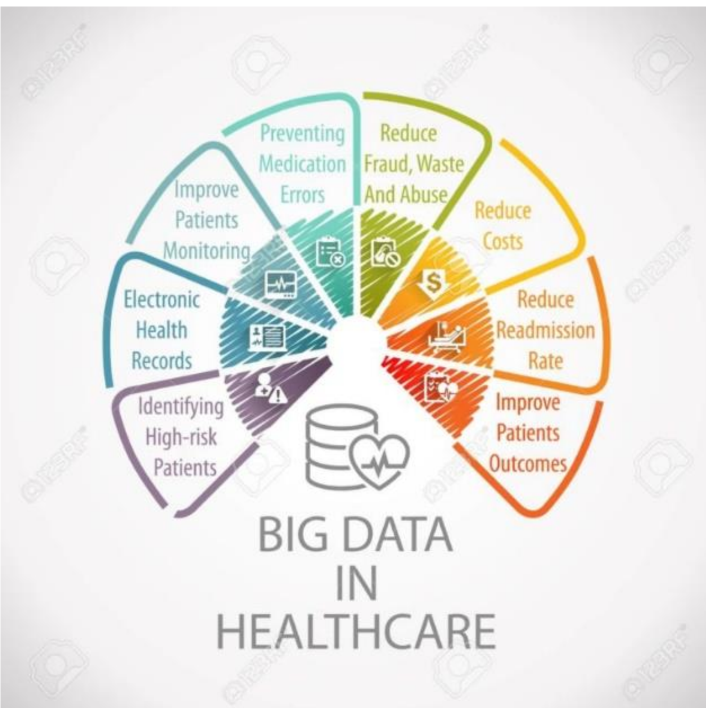

Figure 5 There are plenty of data in the healthcare space. The issue is how to leverage them, taking into account their sensitivity. Image credit: 123RF – Big Data in Healthcare Analytics Marketing Planning Wheel Infographic

In many countries, the whole healthcare process is now digital or it is in the process of becoming digitalized. However, in many cases, if not most, the digitalization is fragmented in digital siloes. Radiography is digital, as are blood testing results, but these data are not open, and it is often impossible to relate ones with the others. This is the biggest challenge facing healthcare digitalization: not to digitalize the various parts but to make all of them coalesce into a single whole. This is a technical or organizational issue. The second challenge is to make the analysis of data of different patients possible which needs to overcome privacy and legislation concerns. Yet, both challenges must be overcome if we are to exploit the digitalization of healthcare.

The scheme in data leverage is the same here as it is in any other areas:

- **What is happening?** The data gathered from the patient can include personal information like the genome, metabolome, the environment, the occupation, the activities and habits (including travel, frequency), the habits (smoker, drinker, vegan, suntan lover….), as well as patient data such as medical exams, use of drugs, data harvested from wearable devices. Correlating all of this information can help identify and explain the symptoms. All these person's data can be structured into the person's digital twin which can be the intermediary used by the doctor and by the healthcare system.
- **Why it is happening?** Similarly, those same data described above can be used to diagnose: is it a virus infection that is actually propagating among a community or something that has been acquired during a trip abroad, is it pollution in the air affecting the airways and stimulating an allergic reaction, is it the outcome of an ongoing cure that is creating undesired side effect, and so on.

- **What might happen?** Given the current ailment, or situation, and the patient history/specificity what would be the possible evolution if no action is taken? What could also be the effect on people in contact with that person? Usually in healthcare there is no single outcome, rather a slate of possible outcome that need to be evaluated. The probability of one versus the others depends on the patient and context. Control of possible epidemics is also a question to be evaluated under this "what might happen" and involves stepping back from the patient to consider a broader picture.
- **What can be done to change the outcome?** Here the point is find the best cure or the best preventive measures to avoid spreading. As previously noted healthcare is moving towards increased personalization and this obviously includes finding specific drugs that fit that particular person. Rather than going for "one size fits them all", which has been the approach to cure in the last century, based on years and years of testing of drugs on animals and then select patients through trials, healthcare is moving towards the design of specific protocols that are focusing on the specificity of the patient. Cancer cures are being explored in this way and become even more prominent in the coming years.

  This is likely to create a disruption among the big pharmaceuticals, since cures will no longer be tied to lengthy trials, rather to the specificity of a patient. This in turn generates the need for continuous, or almost continuous, monitoring. The former opens the door to many companies that can leverage the specificity of an area and whose excellence lies in data processing (machine learning and AI in general), the latter to technology companies creating wearables, implants and ambient monitoring systems.

Clearly data, harvesting, processing and applying the intelligence derived from data are going to be the foundation of healthcare in the coming decades. This video produced by Stanford Medicine provides a good look into leveraging big data for precision medicine.

Healthcare Digitization – Chatbots

The Electronic Health Record (EHR) which keeps track of patient data is now a reality in several countries. The European Community has adopted a recommendation for the exchange of EHR across Europe. Notice, however, that this recommendation allows a citizen of a European country to make his EHR available to any doctor or hospital in the EU in case of need. It is not intended to make the data available for research nor for intelligence.

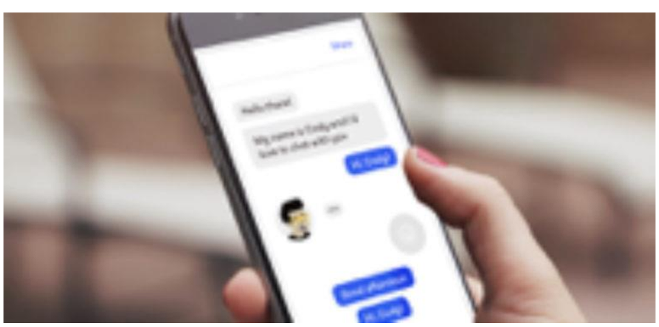

Figure 6 Chatbots are becoming widespread and are going to play a major role in healthcare, providing personalized doctor on demand services. Image credit: ISDDesign

In the US the situation is even more complex with some 700 different implementations of EHR, since there is no unified accepted standard and each type of EHR is tied to the specific vendor providing the software. In many cases there is not even an EHR but just an Electronic Medical Record (EMR) used by doctors in their practice to keep track of a specific aspect (for example, each specialist may have an EMR of a patient containing their specific information yet none of them has access to the EMR created by the other doctors).

A research project in Europe was funded by the EU to create a viable method of using health data for research, called Electronic Health Record for Clinical Research (EHR4C). The implementation is still complex, given the privacy concerns. At the same time there are bottom up approaches, like the one recently announced by Apple that may put pressure on governments to create and implement a top down solution for sharing data. There is no doubt in the scientific community that a full digital transformation making health data of hundreds of millions of people available would tremendously increase scientific knowledge and result in amazing advances in cures and the wellbeing of citizens.

The availability of people's health data can be exploited by an autonomous "bot" to:

- Discover patterns, like emergence of epidemics, noxious factors in an environment, long term effect of various ambient conditions, etc.
- Provide personalized consultancy services, "doctor on demand", through chatbots. Hospitals and insurance companies have started developing chatbots as interfaces for patients to access medical expertise, such as better understanding of symptoms (one example is YourMD chatbot, already installed in a few million smartphones), aiding in formulating a diagnosis (like Sensely chatbot designed as a service provided by insurance and pharmaceutical companies), or helping in remembering to take a pill (like the Florence chatbot) and others.
- Assist doctors in diagnoses and constructing a cure, like the services provided by Unanimous AI where bots are roaming the health knowledge space in the web providing up-to-date information to medical doctors.

It is interesting to notice that chatbots can boost healthcare in areas where healthcare service is limited by geography (remote areas) and resources. Clearly this can extend worldwide, but it there are possible negative aspects, as pointed out in *Cell* by Robin Cook[2], a medical thriller that describes the implication of chatbots on the medical profession and how these extend to medical insurance and pharmaceutical companies.

Augmented Reality in the Operating Room

Augmented reality is slowly, but definitely, entering the operating rooms in many hospitals around the world to help the surgeons and the operating team. Surgeons have used Google Glass (you can find a comprehensive review of their use here) and as technology evolves, both in terms of devices and software, additional applications are being developed.

Philips, a major player in the provisioning of advanced equipment in operating rooms, has teamed up with Microsoft to use their HoloLens 2 technology to assist and actually augment surgeons in the OR. HoloLens 2 supports multiple interactions, gesture recognition, voice control, and eye tracking, thus letting the surgeons' hands free. Interestingly, HoloLens 2 software supports cooperation among the surgical team by letting each team member see the same image. Actually, the team members can choose to see exactly the same image or different images of the same object from different points of view. When delivering information (data) it makes sense to present the same view to all members of the team but when layering images, like blood vessels, it makes much more sense to present each person with a view that is linked to that person's position. This requires intense software and sensors to determine the exact position of each person.

[2] Cook, Robin, *Cell*, Pan Macmillan, Feb 13, 2014

Actually, using AR in the OR is tricky because of optical constraints. Devices like HoloLens 2 are engineered to place the virtual image to a distance of about two meters, meaning that your eyes will be focusing at that distance. If at the same time you need to focus on a nearer field, because you are operating on a patient that is 50 centimeters from your eyes, or even closer, the two images do not match. Even by tweaking the focal point, parallax errors may possibly occur, distorting the impression of distance. Parallax errors are difficult to avoid since they require instantaneous tracking of the eyes, of the operating field, and the understanding of what the surgeon focusing on (is it at the edge of the surgical opening or five centimeters below where the heart is beating?).

Figure 7 The Augmented Doctor. Using HoloLens 2 Augmented Reality can help a doctor and a surgical team in the operating room. Image credit: Microsoft

Applying AR seamlessly in the OR is still a long way off. Current implementations, however, are already increasing the surgeon's performance making the whole procedure safer.

Reaching a truly augmented surgeon through AR will require few more years. For the time being AR and VR are becoming more common in medical training and in the preparation of surgery, letting the surgeon practice on a virtual patient that mirrors, accurately, the real patient.

Autonomous Systems in Healthcare

Autonomous systems are primarily robots (including autonomous implanted devices operating on sophisticated algorithms fed by local sensors data, like insulin delivery reservoirs), however there is a growing interest in soft robots (software systems) that can provide health care assistance. AI is a growing component in autonomous systems for the health care domain expected to lead to a global market value of $34 billion by 2025 ($2 billion in 2018); see Figure 8.

Autonomous robots in healthcare can be segmented into assistive, rehabilitation, humanoid, delivery, implanted, surveillance and security (these latter obviously apply to other sectors as well). The global assistive robot market value was $359 million in 2018 and is expected to reach $1.2 billion in 2024. A further expansion of the assistive robot market may come from humanoid robots, which so far is an area of research with several demonstrations, raising significant interest in Far East Asia. It is expected to reach a market value exceeding $5 billion in 2024. It is clearly a market dominated by AI, affective computing and autonomous systems whose uptake is rooted in a specific culture and that, if successful, will expand to other cultures.

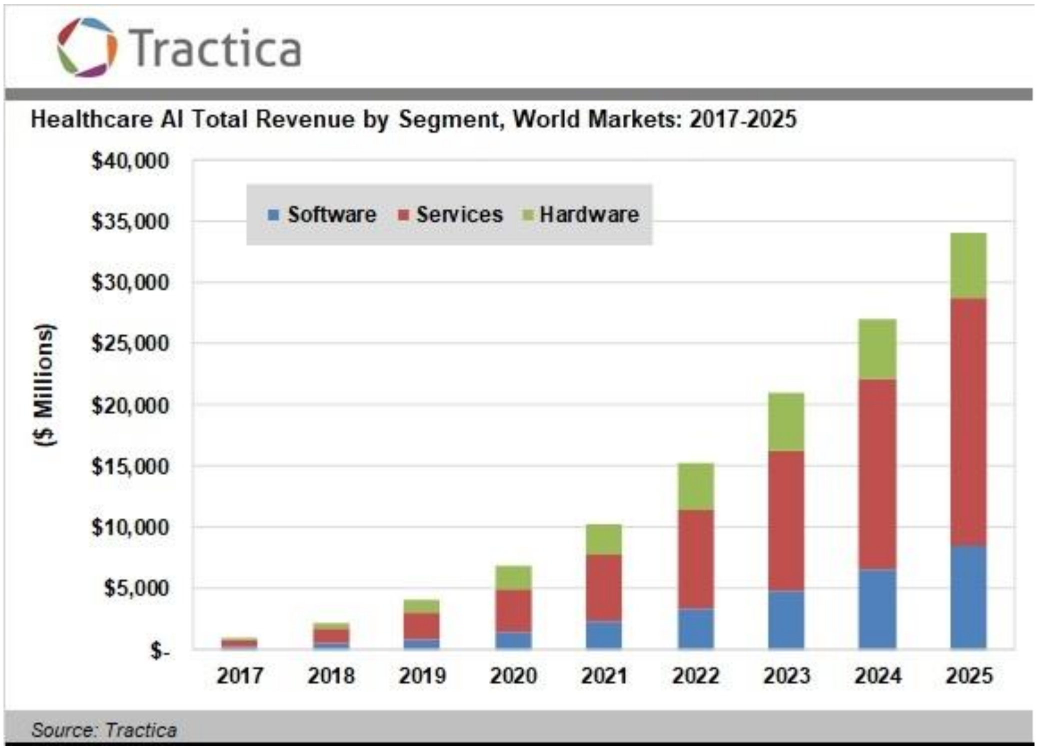

Figure 8 Raising market value of AI in health care, segmented in software, services and hardware, with services showing the highest growth. Source: Tractica

The global rehabilitation robot market, $641 million in 2018 (with cognitive and motor skill rehab having a $87.1 million market value in 2017), is expected to grow significantly reaching $6.4 billion in 2025 as autonomous robots are expected to replace part of the human therapist. A further push in this direction might result from the emergence of digital twins, mimicking the patient functionality "before" the pathology or trauma and with applications using that starting point to develop the customized rehabilitation protocol assisted by the robot.

These figures do not include exoskeleton based rehab ($130 million in 2018 including exoskeleton acting as prosthetics, with several, mostly US, companies on the market), that may also gain traction in the next decade. Most of exoskeleton market is focusing on augmentation (fatigue relief) in industry, manufacturing and maintenance primarily.

The market of non-surgery robots in operation in the healthcare sector is expected to reach 60,000 units by 2025, from 15,000 in 2018.

The implantable device market in healthcare is huge, expected to reach $49.8 billion in 2024 (from $34.7 billion in 2018). Clearly, many of these devices are not smart autonomous systems, but the general trend is to equip them with sensors and processing capability to support more sophisticated protocols.

AI in Healthcare

There is basically no segment in the healthcare area where AI is not expected to play a role, from genome sequencing to drug creation, from diagnosis to surgery, from patient care in hospitals to home care.

Yet the question of AI replacing researchers, nurses, or doctors remains quite open. It is a bit like saying that the screwdriver has become an essential tool in all domains where "hard" interaction with devices and machines is needed (and of course depending on the specific domain different types of screwdrivers are needed), but obviously the screwdriver did not replace the hand that is operating it, nor the "mind" pointing the hand to the right screw.

A recent article in IEEE Spectrum discuss the promises and the actual results of IBM Watson applied to the healthcare area. After winning Jeopardy, back in 2011, IBM started to reposition Watson to solve big issues and one of the biggest and most promising ones was healthcare (watch the clip). Worldwide healthcare in 2019 is a $7 trillion market (with the US market representing some 30% of it). An indication of the relevance in developed countries is that the Italian healthcare market represents 1.7% of the worldwide market while just having 0.7% of the world population, further demonstrating plenty of business opportunities. At the same time, the growing cost and the skyrocketing increase in potential knowledge, potential because it has become impossible for a single doctor to absorb and apply that knowledge in her practice, creates a gap that needs to be filled and technology, AI in particular, may provide an answer.

As described in the Spectrum article, AI is being applied in many segments of healthcare but as a flanking technology, not as a substitute. In most cases AI is actually increasing cost because it costs money in terms of much more sophisticated equipment that also requires skilled people to operate them, hence increasing training cost.

True, hospitalization time has decreased significantly as surgery has become less traumatic and better controlled procedures are available. At the same time technology is allowing the "healing" of many more pathologies, hence more surgeries are being scheduled. More surgeries are being performed than in the past.

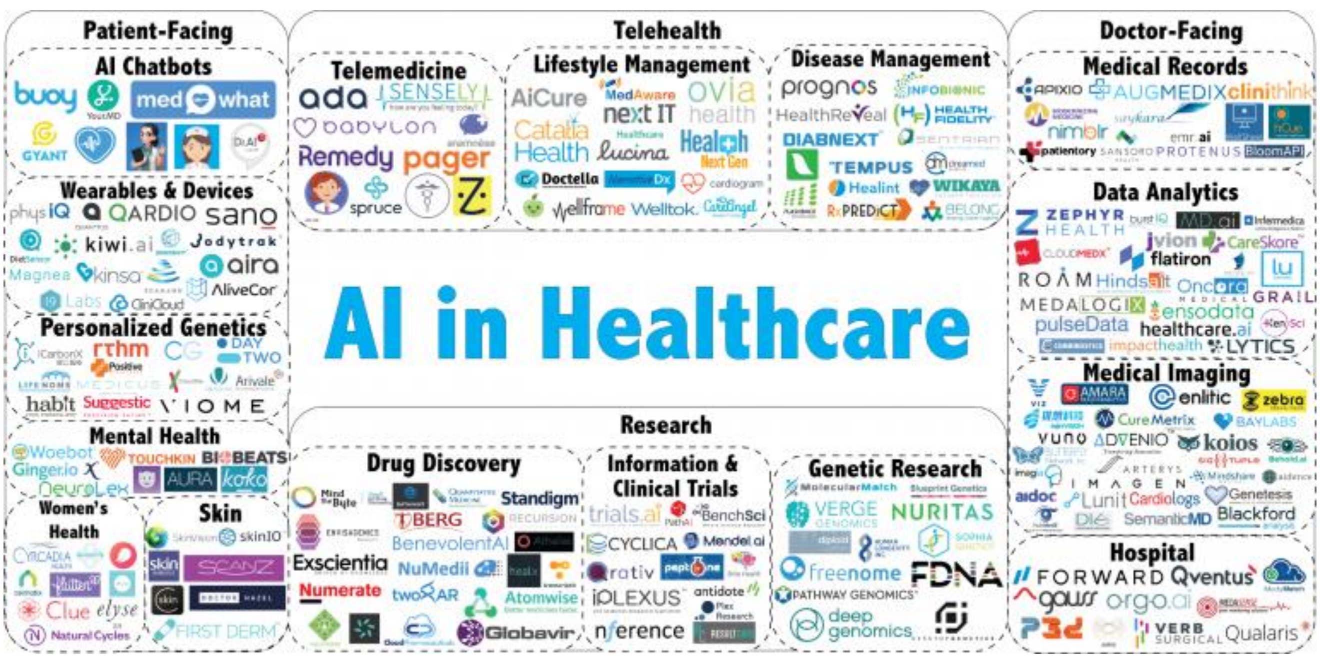

Figure 9 A (not exhaustive) industry landscape of AI in Healthcare. Image credit: Emily Kuo, Techburst

Technology keeps rapidly evolving but it is not substituting surgeons, although their role and the way they work keeps changing. Any new technological advance, particularly those brought by AI is just showing that much more can, and needs to, be done. Indeed, it looks like the pot of gold at the end of the rainbow. We see it, but as we move towards it the gold shift a bit further away.

Acknowledgement
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