Opinion Paper

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Digital transformation in healthcare – architectures of present and future information technologies

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Abstract: Healthcare providers all over the world are faced with a single challenge: the need to improve patient outcomes while containing costs. Drivers include an increasing demand for chronic disease management for an aging population, technological advancements and empowered patients taking control of their health experience. The digital transformation in healthcare, through the creation of a rich health data foundation and integration of technologies like the Internet of Things (IoT), advanced analytics, Machine Learning (ML) and Artificial Intelligence (AI), is recognized as a key component to tackle these challenges. It can lead to improvements in diagnostics, prevention and patient therapy, ultimately empowering care givers to use an evidence-based approach to improve clinical decisions. Real-time interactions allow a physician to monitor a patient ‘live’, instead of interactions once every few weeks. Operational intelligence ensures efficient utilization of healthcare resources and services provided, thereby optimizing costs. However, procedure-based payments, legacy systems, disparate data sources with the limited adoption of data standards, technical debt, data security and privacy concerns impede the efficient usage of health information to maximize value creation for all healthcare stakeholders. This has led to a highly-regulated, constrained industry. Ultimately, the goal is to improve quality of life and saving people’s lives through the creation of the intelligent healthcare provider, fully enabled to deliver value-based healthcare and a seamless patient experience. Information technologies that enable this goal must be extensible, safe, reliable and affordable, and tailored to the digitalization maturity-level of the individual organization.

Opportunities and challenges in healthcare

We live in exciting times. On the one hand, medical and technical advances are driving better healthcare for humanity across the globe, whereas on the other escalating costs are a big concern for all governments, healthcare providers and patients [1].

Global healthcare spending is projected to reach a staggering \$8.7 trillion by 2020 [2], mainly due to inefficiencies in care delivery and the cost of drug development (\$2.6 billion per newly launched drug) [3]. As the global life expectancy rises, the demand for better elderly healthcare and specialized care programs increases (e.g. senile dementia, Alzheimer’s disease [4]). Another key factor is the increasing occurrence of chronic and lifestyle-related disorders. In 2015, 70% of all global deaths were attributed to noncommunicable diseases (such as stroke or diabetes [5]). This highlights the urgent need for strategies around prevention, diagnosis and optimized care.

Empowered patients put further pressure on the system, as the consumerization of healthcare leads to the patients’ desire to be actively involved in the treatment decisions, for more convenient point-of-care options, value-added services, home diagnostics and health information sharing [6]. Human lives are at stake, and regulation and compliance requirements, therefore, play a big role in drug development and treatment. Yet, these requirements also carry additional cost and efforts – which potentially hamper the speed of digitalization in the healthcare industry [7].

Nevertheless, a “Gutenberg moment” in healthcare is quickly approaching, as technology continues to progress at a rapid pace. Technology is increasingly creating information parity between patients and physicians. The cost of sequencing a human genome has dropped by a factor

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of a million in about 15 years. Smartphones contain more data than ever before and are considered by many as mini-medical devices, capable of high-speed monitoring and analytics. Technology has the potential to democratize healthcare to such an extent that it will allow physicians to spend more time with patients that truly need support, and other care might be handled virtually and semi-autonomously. The physician will become the teacher of the computer system and delegate tasks [8].

Data and analytics challenges

Although the digitalization of healthcare has been progressing slowly, the amount of usable patient-level data has increased dramatically over the last decade [9]. Without doubt, the conglomerate of health-related industries is a true big data sector; as much as 30% of the entire world's data volume is generated in the healthcare industry (on the yottabyte $\sim 10^{24}$ gigabytes scale [10]). A patient typically generates 80 megabytes each year in imaging and electronic health record data [11]. However, the challenge in health is not simply data volume. The variety of data types is the bigger challenge. This includes patient demographics, encounters, diagnosis, pathology, laboratory tests, medications, radiology, radiation treatments, surgical treatments, post-therapy care, notes and documents, operational, financial and insurance information, and provider characteristics. The biggest data sources are images (used for diagnosis), omics data (such as complete genomes sequences data) and proteomics information. Per patient, thousands of data fields and files can be collected, all of which describe the health status. In addition, the challenge of veracity, a typical big data issue, must be addressed. Proper quality of information is key to ensure sound clinical decision-making as it directly impacts patients' lives.

With advancements in IoT, sensors and mobile technology, additional diagnostic information from connected medical devices, electronic Patient Reported Outcomes (ePROs) from smartphones and medical-grade wearables can be collected and interpreted. Three hundred and twenty-five thousand mobile health apps were available in 2017, growing by 25% year-on-year [12]. Smart phones and fitness trackers are in many cases already perceived as medical devices, but the majority lack appropriate testing and regulatory authorization. Because of these challenges, healthcare data remains highly siloed, and the value largely untapped.

Medical devices typically deliver patient data in structured formats. This content can be mined by software in

a relatively straightforward manner. However, the data available in Electronic Medical Record (EMR) systems allows mining to a lesser extent, as this patient data is only partly structured. Most of the data used to treat cancer is unstructured, and thus the real challenge lies in patient information that is only available as free text, e.g. within doctor letters [13].

Healthcare providers are struggling to turn these challenges into an opportunity. The degree to which these data assets are digitized and analyzed, can improve productivity. Unfortunately, healthcare has the lowest level of digitalization, usage and digital innovation adoption compared to other industries like media, finance and insurance and retail leading to limited labor productivity growth [14].

All these challenges and escalating healthcare costs underscore the critical need to identify the right incentives and business models to ensure sustainable business innovation and quality of care. The lack of interoperability in healthcare systems, for example, is a problem which is straightforward to solve with existing technologies, but the incentive on solving it is still missing. Recent initiatives around meaningful-use guidelines such as Blue Button or Argonaut partly address the problem but not the root cause [15]. The crux of the challenge is that providers are currently mainly paid by the volume of services. There is a lack of value-based "competition" and risk-sharing, leading to inefficient utilization of healthcare services and resources and poor patient outcomes. In many other industries, value is created at lower cost, as such industries compete based on value [16].

Payers and policy makers are thus seeking ways to reimburse healthcare providers through measuring the value of care, with a strong focus on improving patient outcomes and optimizing cost. Ultimately, innovation pathways in healthcare will be driven through systemic changes to the economics of care.

This advancement is happening at widely diverse speeds, depending on the location, size and strategy of the organization. In a healthcare provider setting, four maturity levels of digitalization can be recognized.

- Level I. Patient data is captured in a **paper-based** fashion. This greatly constrains useful analytics of the information, limits productivity and efficient use of resources for high-value tasks.
- Level II. Only in the next phase, when the data is **digitized**, is it possible to start to reap benefits from the data, and to gain deeper insights. Although EMR systems have accelerated health data digitalization, they are still largely a digital remake of the traditional paper-based systems, with limited ability to mine and analyze information.

- Level III. Once digitalization is fully implemented, the organization can become **intelligent**, applying next-generation data management, analytics and Machine Learning (ML)/artificial intelligence (AI) technology, as well as new service models to the challenge of improving business performance [17, 18].
- Level IV. Systems of intelligence are now the core-enabler for **value-based healthcare**, the delivery model in which providers, are paid based on patient health outcomes (in contrast to a fee-for-service or capitated approach, based on the amount of healthcare services delivered) [19].

Possible solutions – digital transformation accelerators

The cost explosion leads to an increased willingness by all stakeholders to jointly consider value-based models, utilizing transparent indicators relevant for patient outcomes. Global health leaders have stated the following five strategic priorities [20]:

- Improve the organization's operational efficiency to augment resources for innovation and better care
- Optimize outcomes for each individual patient
- Apply data-driven innovations and use evidence-based decision making to guide caregivers and researchers
- Enhance overall experience to meet the needs of all healthcare consumers
- Empower healthcare workers to perform at their best

Therefore, it becomes crucial to achieve greater collaboration within the healthcare ecosystem, full systems connectivity, and complete access to data, and strong predictive analytics capabilities (e.g. intelligent real-time, in memory computing) to derive greater value from that data. This can be realized through digital transformation and embedding systems of intelligence within business processes. Furthermore, recent analyses [21] revealed that six areas related to affordability, access and quality in healthcare received 73% of investor funding in 2016. These areas were: provider efficiency (\$1.2 billion), virtual care/coordination, wearable devices, personalized medicine, enhanced diagnostics, and big data and analytics.

To tackle the challenges mentioned in the previous sections, a Logical Data Warehouse must be created that should address the five big Vs of big data analysis: Velocity, Volume, Value, Variety and Veracity [22]. In-memory

database technology and real-time insights for advanced predictive analytics play a large role in realizing these five prerequisites.

Gartner [23] describes such a system with “Jobs to be Done:”

- Job 1 is taken by the analysis of structured data.
- Job 2 addresses the addition of little- or even non-structured data, and
- Job 3 is taken by the integration of new and old data analysis engines.

This phased approach helps to overcome the biggest challenges in care [24] and help healthcare stakeholders to:

- gain access to real-world data;
- unlock, assemble, and privacy preserving analyze patient medical records;
- allow physicians to identify an adverse set of events in patients (such as specific drug usage or combinations that had an unexpected detrimental outcome)
- provide guidance by identifying the best, evidence-based course of care;
- measure and benchmark the quality of care;
- uncover patterns to generate knowledge.

This knowledge leads, for example, to the development of better therapies with existing drugs (also known as repurposing through label extensions) or better non-invasive methods for monitoring disease progression (also known as biomarkers).

Mainstream adoption of standards can help address some of the challenges around data sharing and communication between disparate systems. For example, Fast Healthcare Interoperability Resources (FHIR) [25], a standard defined by HL7, is rapidly being adopted by the industry. FHIR describes data formats and elements (“resources”), and an Application Programming Interface for exchanging electronic health records.

Intelligent, adaptive, learning clinical information extraction and high precision rule-based systems are needed to turn unstructured information into semantically standardized, structured data sources [26]. Clinical data warehouses must be augmented to fully-fledged knowledge discovery systems, relying on ontologies, not only for codification and code translation (e.g. ICD, SNOMED CT, LOINC [27]) but mostly for semantic reasoning approaches that lead to hypothesis generation and knowledge discovery. Instead of simple analytical reporting, predictive analytics is key. Care givers must evolve their skills and become (at least partially) clinical knowledge miners and trainers of machine learning systems. In addition, knowledge systems need to rely heavily on ontologies: grouping

of diseases or other medical principles according to similarities and differences, and codification services.

Many organizations are currently turning their attention to ways of saving costs. The creation and maintenance of on-premise instances of data and software may be perceived as the right choice to ensure data control and security. The reality might be different with cloud systems offering compelling advantages [28]. Easier archiving and use of patient records and medical images, less storage costs, faster innovation cycles, easier collaboration, improved telemedicine capabilities; these are some of the promises of cloud computing in healthcare. Taking into account the four phases of digitalization (above), the adoption of cloud in healthcare will be handled at different speeds. As a result, the technology will continue to be consumed in different flavors; some on-premise, others in the cloud. Therefore, hybrid systems that can seamlessly connect these data worlds need to be fully supported.

Applying AI and ML on big data holds additional promise [29] for operational intelligence, optimizing business processes, improving the quality of care and obtaining cost efficiencies. Recently, an AI algorithm was approved by the FDA for diagnostic purposes [30]. Applications of machine learning include:

- Chatbots and digital assistants that will redefine patient interactions and provide healthcare professionals with more flexibility to spend time on complex tasks [31]
- Clinical decision support that will become a crucial component in guiding and supporting decision making for healthcare professionals [32] and predicting multiple medical events like mortality, readmissions and length of stay [33]
- ML enabled NLP that will suggest a patient translation of documents to simplify scientific terms into layman's terms [34]
- ML enabled clinical information extraction systems that will learn from the hospital in which they are installed, and that will deliver high quality knowledge from medical narratives
- Automated and more accurate billing and invoicing that will make claims processing faster and potentially prevent fraudulent activities.

Vision for intelligent healthcare enterprises

Over the last 50 years, the IT industry has played a pivotal role in generating business value for users. Mainframes and PCs (in the 1960s and 1970s) drove industrial automation followed by client-server architecture and the Internet (in the 1980s and 1990s), which led to business process automation. Since 2000, technology advancements in cloud computing, mobile, big data and social networks accelerated digital transformation through the creation of digital data platforms. The rise of intelligent technologies such as advanced analytics, ML, AI and the Internet of Things (IoT) will enable the creation of the intelligent enterprise (see Figure 1).

Spending on AI and ML is projected to grow from \$12 billion in 2017 to \$57.6 billion by 2021, according to the International Data Corporation (IDC) [35]. As other industries move towards adopting systems of intelligence, the healthcare industry is still grappling with digital transformation and these new trends. The main barriers are

Figure 1: Evolution of Information Technologies (IT) from digital era into the intelligence era.

data privacy concerns (to also be addressed through privacy-preserving knowledge mining systems), the need for secure systems landscape [36], compliance with often incomplete regulatory guidelines [37], and lack of stable and widely accepted standards. On the IT side, investments in legacy systems, and short-term programming and systems-architecture decisions, compound the “technical debt” – the price needed to pay for a course correction, which impedes the ability to scale innovation in the digital era. One strategy for global healthcare leaders to future-proof their enterprises is “digital decoupling”. This requires decoupling data from legacy systems by creating “data lakes”, decoupling applications from legacy systems and business processes, and utilizing digital platforms to ensure maximum value is still derived [38].

Adopting intelligent technologies will require healthcare leaders to not only reimagine operational and clinical processes around care delivery but also embed these technologies within existing core business processes to reap the benefits. This will also ensure care givers’ focus on high-value tasks and outcomes such as better patient outcomes and strategic planning to accelerate the delivery of innovative solutions that provide an engaging and seamless patient experience, without disrupting their core business processes. All of this should be based on a data foundation capable to handle big data and deliver real-time processing (see Figure 2).

By viewing business processes and innovation solutions holistically and putting fundamental patient needs at the core of the healthcare enterprise strategy, the long-term impact of intelligent technologies to accelerate delivery of value-based care will be a game-changer for the healthcare industry. This will change the very nature of patient-doctor relationship – from **reactive health** (a paternalistic approach to diagnosis and treatment in response to signs and symptoms) to **proactive health** (personalized patient interactions and care delivery based on early warning signs detection complemented by passive data capture and relevant biomarkers, predictive models connected to epigenetic predispositions and continuous monitoring from multiple connected data sources) [39].

Several initiatives exploring digital transformation and advanced technologies have evolved from a purely academic exercise to a more real-world clinical care setting. As an example, the American Society of Clinical Oncology’s (ASCO) [40] ambition is to build a real world, big data learning system far beyond a growing network of 100+ community oncology practices, academic institutions and major health systems, and to offer a representative, holistic view of the cancer patient’s voyage, to support quality improvement and discovery. The created system (CancerLinQ) taps into information that exists beyond the cohort of data within traditional clinical trials and the lens of medical oncology. CancerLinQ engages with the broader oncology community beyond ASCO’s

Figure 2: The Intelligent Healthcare Enterprise framework.

Three key components are needed to enable the intelligent healthcare provider: 1. fully digital platform with optimized data management preferably in a cloud system, 2. advanced technologies like AI, ML, IoT capabilities and real-time, in-memory analytics embedded within business processes; that then facilitate the creation of 3. an intelligent and innovative healthcare application suite.

membership to incorporate the integral perspectives of the entire oncology care team, to create one of the largest, most robust sources of Real-World Evidence (RWE) in oncology.

Researchers at Flatiron, in collaboration with the FDA, used EMR data collected at point-of-care clinics to examine the demographic and treatment characteristics of metastatic non-small cell lung cancer (NSCLC) patients treated with nivolumab and pembrolizumab in routine clinical care vs. clinical trial cohorts [41]. Insights showed differences in the two cohorts and revealed the need to collect further RWE in underrepresented groups to inform immunotherapy treatment decisions and optimize care in a real-world setting.

In addition, several translation research platforms integrating complex clinical and omics data (genome, transcriptome, epigenome, proteome and interactome) enable rapid exploration of patient data to accelerate personalized medicine. Notable ones include BRISK, caTRIP, cBio Cancer Portal, G-DOC, iCOD, iDASH and tranSMART [42].

Outlook

Intelligent enterprises and intelligent healthcare providers effectively used advanced IT systems and data assets to achieve their desired outcomes faster, and with less risk. Responding to individual patient/customer needs, engaging talent in new ways, and creating disruptive business models are critical business imperatives – also (or perhaps especially) for health-related industries and healthcare providers. Although many healthcare organizations have initiated digital transformation projects, very few have reached digital maturity. As technologies like ML, AI, IoT, big data and advanced analytics become more mainstream, organizations must adapt to reap their benefits [43]. Global healthcare leaders will need to factor in long-term technical debt and adopt a “digital decoupling” strategy to ensure a scalable, flexible and resilient enterprise IT.

Eliminating data silos and automating data wrangling and integration, as well as recognizing unseen patterns, and providing new intelligence to service patients and care-givers, will offer value across the care continuum. There is a relentless need to direct limited resources to areas where they will have the greatest impact. Simulating the outcome of potential treatment options is imperative. Healthcare providers and other healthcare organizations need agility to improve patient outcomes and control costs, but in many cases also to disrupt and outmaneuver competition. As a result, it is key to build flexibility and insight

into business processes through digital transformation, to rapidly respond to change, pivot towards the right outcomes, and ensure sustainable competitive advantage [43].

This can only be achieved through digital transformation with intelligent, integration-ready applications and platforms that help to manage patients, networks, employees, and core processes. These must be easily extensible and offer a consistent and intuitive user experience. Going forward, healthcare organizations will consume and experiment more with technologies such as ML, AI, IoT, big data and advanced analytics, so that they can drive ongoing innovation. Applications with embedded intelligent technologies will be crucial for success.

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