Goldman Sachs | Equity Research

5 April 2019 | 1:04AM EDT

The following is a redacted version of the original report. See inside for details.

Healthcare: Medical Technology

Digital Health: Sensor Technology and Disruption to the Patient-Provider Paradigm

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Sensors have the potential to advance some of the US healthcare system's most critical mandates: lowering costs of care, improving continuity, coping with the looming shortage of physicians and nurses, and bringing patient outcomes up to the standard set by other developed economies. Although these technologies have been around for decades, they have not yet reached broad adoption beyond early attempts at consumer wearables. We think the sensor story is starting now in earnest, as recent improvements in size, accuracy, and acceptance have paved the way for healthcare adoption and continued innovation over the next decade. We expect sensors' impact to be most material over this timeframe in four care areas: diabetes management, cardiovascular health, in-hospital monitoring, and remote patient monitoring. With their potential to generate new data streams for patients and providers, we expect sensors to have long-lasting effects on the Medical Technology industry's growth, profit pools, and competitive forces.

Key conclusions from our analysis:

1) **The sensor market could reach $30 billion annually.** Interest in the market has soared in recent years, with over 400 related venture capital deals closed in the last two years alone.

2) **MedTech companies are paying attention.** Nearly half of the companies we surveyed report having a senior executive focused on Digital Health.

3) **Sensors are already making strides in diabetes management**: A new market for monitoring disease with continuous glucose monitors (CGMs) that give diabetics real-time information on blood sugar levels has developed. These CGMs can also integrate with insulin pumps to form a "closed loop" system that can effectively function as an "artificial pancreas." Better/cheaper sensor technologies promise to bring these solutions to a broader group of the world's estimated 400mn diabetics.

We estimate that of the 8 million people intensively treated for diabetes globally, ~20% are treated with a CGM.

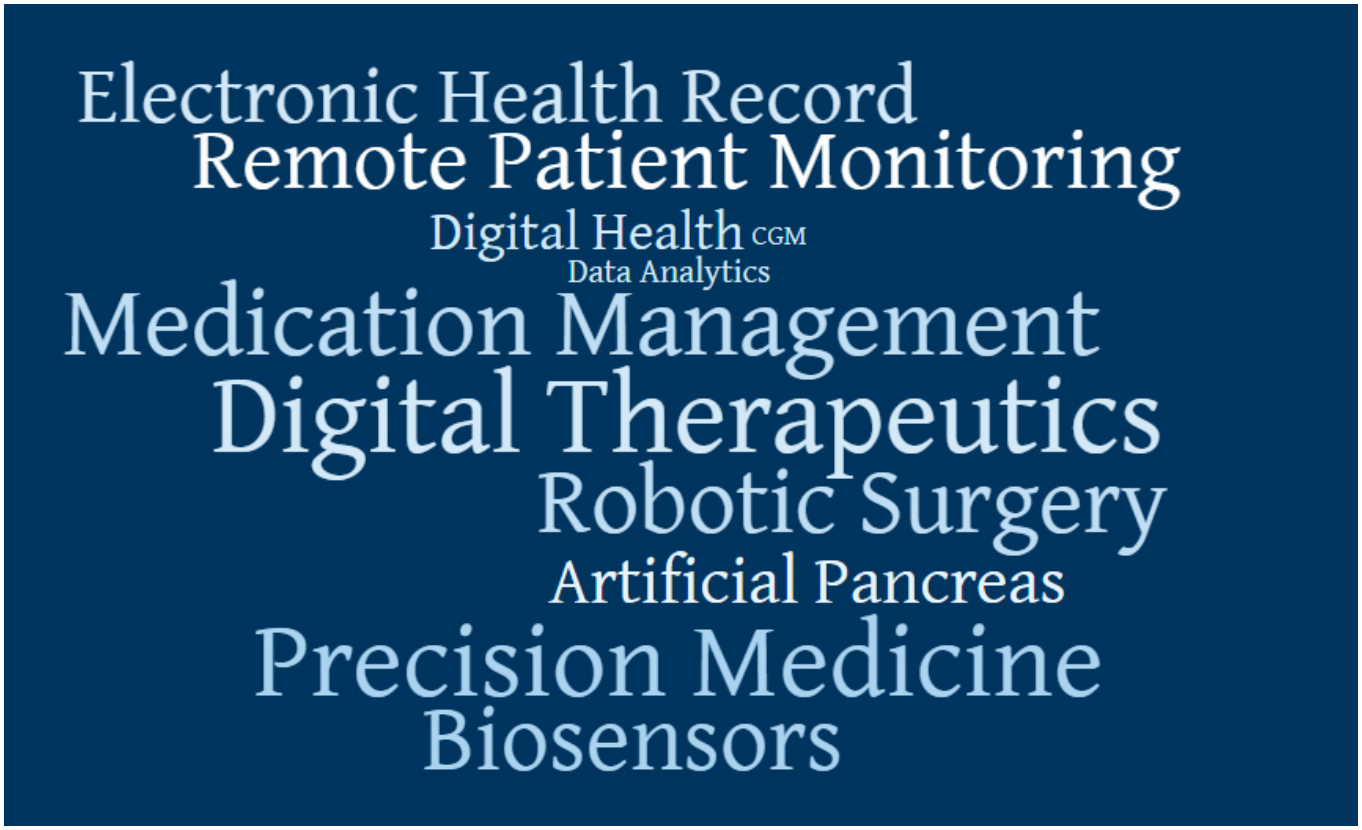
4) **Patient monitoring will soon become real-time**

5) **Cardiovascular opportunities are still early stage, but too large to ignore**: Could your Apple Watch save your life? The technology is nearing viability but still looks too early for mass market, and will likely to remain a complement rather than replacement for medical monitoring near-term.

Note: The following is a redacted version of "Digital Health: Sensor Technology and Disruption to the Patient-Provider Paradigm" originally published April 5, 2019 [35pgs]. All company references in this note are for illustrative purposes only and should not be interpreted as investment recommendations.

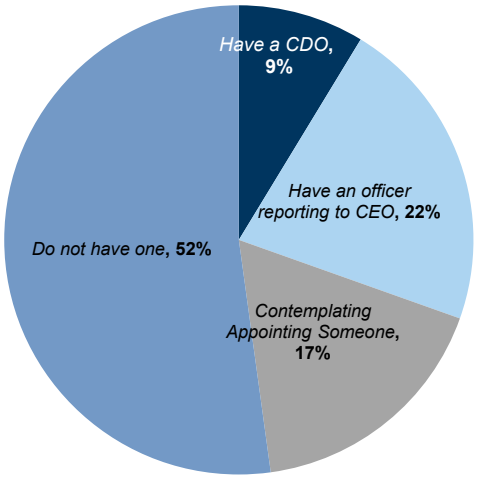
Sensors in Graphics

Exhibit 1: Interest in digital health (and sensors) is surging
Size of term reflective of growth rate of search engine mentions



Source: Google Trends

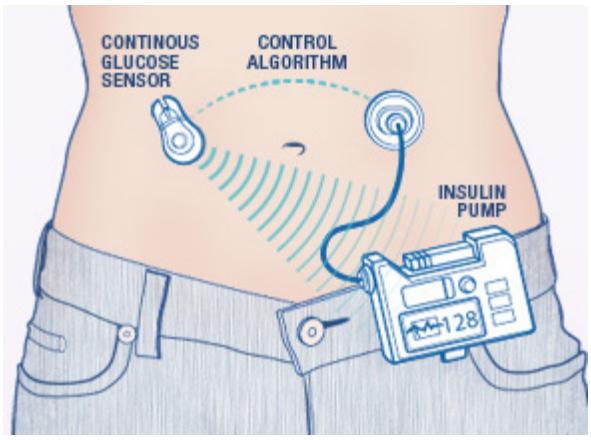
Exhibit 2: Almost half of surveyed Med Tech companies have hired or are thinking of hiring a senior executive focused on Digital Health



*23 Surveyed Med Tech companies

Source: Goldman Sachs Global Investment Research

Exhibit 3: CGM represents one of the most notable innovations in healthcare sensor technology.



Source: Goldman Sachs Global Investment Research

Sensors and the Healthcare Opportunity

Technologies like sensors represent one of the more promising tech-based cost-saving opportunities in an age of rising healthcare expenditures. In short, we think sensors have the capacity to be powerful mechanisms in healthcare whose benefits will accrue to a variety of actors. Augmented by other technologies such as artificial intelligence, we believe sensors can be at the core of a healthcare ecosystem that focuses on delivering increased value through a sophisticated end-to-end technologically intensive, cost-efficient model.

Defining Sensors

At its most basic level, **a sensor is a device that receives and responds to a signal.** The signal can be produced by a type of energy such as heat, light, motion, chemical, etc. Typically, the sensor will convert the signal into some sort of manifestation of the original input signal. This output can be either analog or digital. Needless to say, "sensor" is a broad term that can be applied to many different devices in many different industries.

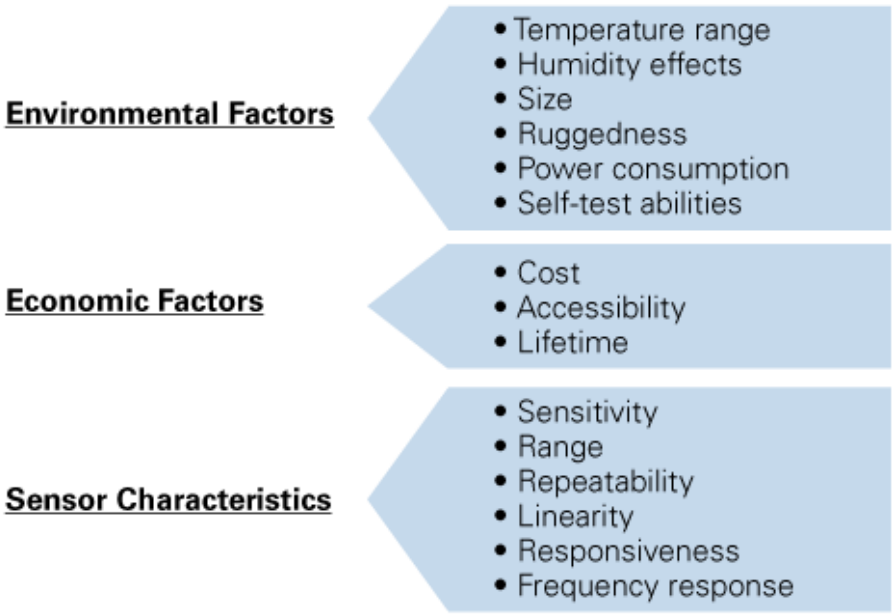
Recent advances in microelectronics, manufacturing, and data analysis have paved the way for new healthcare applications of sensor technologies. Formerly, sensors were generally too large to either wear or implant in order to gather data on an individual. This is no longer the case, as specifications such as miniature circuits, microcontroller functions, front-end amplification, and wireless data transmission systems are advanced enough to be used in digital health settings. Though certain types of sensors in healthcare are in many ways a nascent technology, the uses and potential uses for sensors are vast. **Sensors can be appended on garments, hats, wristbands, shoes, eyeglasses, and wristwatches. Ultimately, we think sensor technology will catalyze patients to take more ownership of their own healthcare decisions.** Increased involvement by patients should help address the looming shortage of physicians and nurses. Areas in which sensors are used include biologics, chemicals, electric, electromagnetic, temperature, magnetic, mechanical, optic, and radioactive.

Exhibit 4: Sensors by Stimuli

Stimulus	Detection unit
Acoustic	Wave, Spectrum, Wave velocity
Biological&Chemical	Fluid Concentrations(Gas or Liquid)
Electric	Charge, Voltage, Current, Electric Field, Conductivity, Permittivity
Magnetic	Magnetic field(amplitude, phase, polarization), Flux, Permeability
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque

Source: Goldman Sachs Global Investment Research

Exhibit 5: Choosing a sensor is an economic and engineering decision.



Source: NYU Engineering

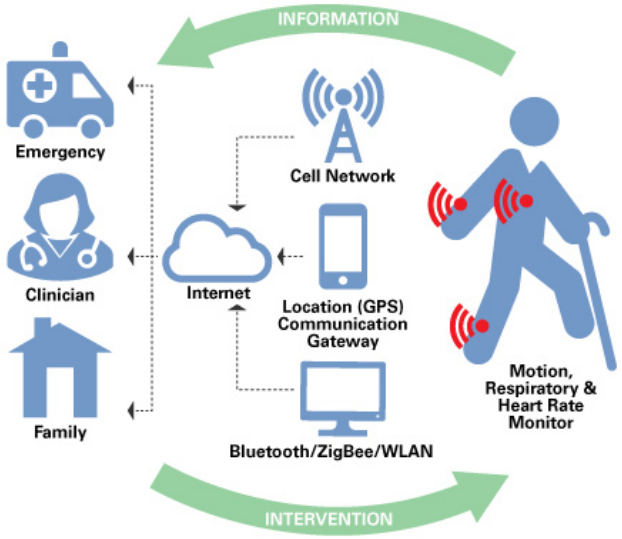
Improving Sensors

At this time, sensors are by no means perfect. One issue associated with sensors is energy consumption. Because the devices are often carrying out such robust functions, sensors may need to be recharged fairly frequently. This predictably negatively affects quality of compliance. Another potential issue with sensors is that of choice. With such a wide array of sensors available to people, **it can often be difficult to discern which type of sensor is most appropriate for the task at hand.** Conditions like submersion, extreme temperatures, and contaminants can have adverse effects on the abilities of certain sensors to carry out goals. Choosing the right environment for a sensor can also be a challenge for technicians. Often, the presence of certain materials can cause a sensor to erroneously detect something that is unrelated to the desired target. Contamination to the sensor is another common issue. If a sensor needs clean contact with another object, even a small amount of debris or dust can interfere with this task.

The Future of Sensors in Healthcare

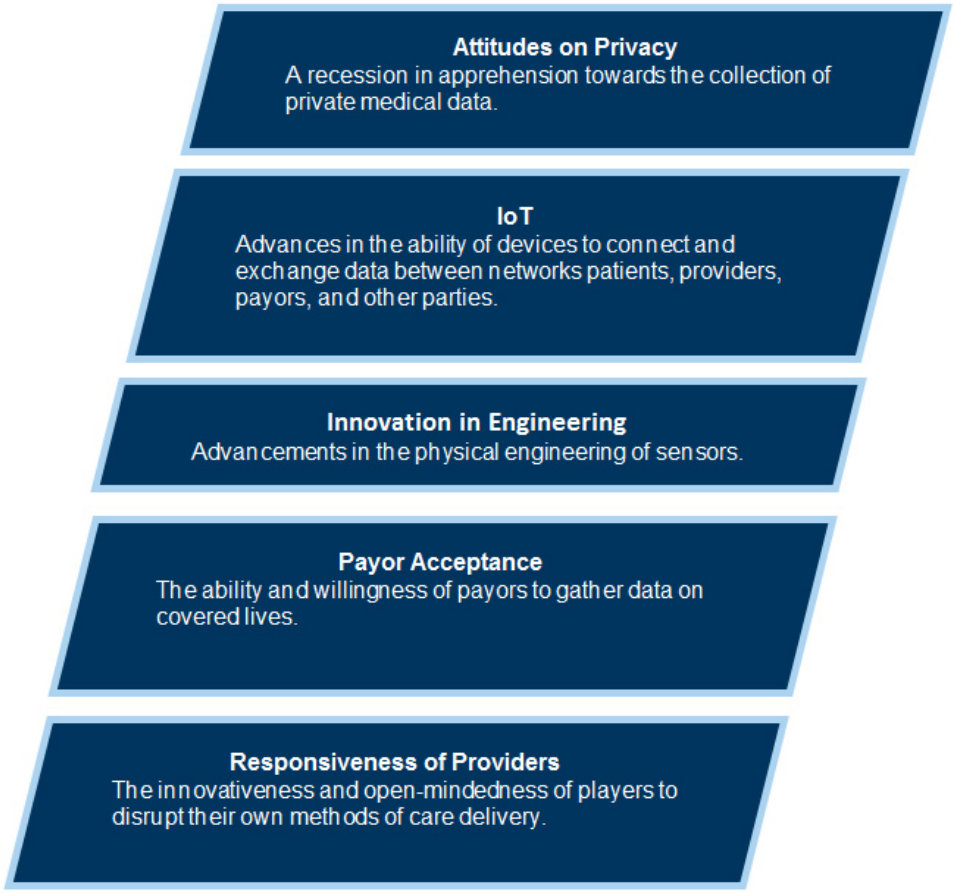
In the graphic below, we provide a structure for a healthcare ecosystem that is partly promulgated by an evolution in sensor technology. Often referred to as a "Healthcare Internet of Things" this system has the potential to enhance connectedness in the healthcare system between a variety of parties. Via sensors, troves of data can be collected on patients such as heart rate and blood glucose readings. **Using information stored in the cloud, clinicians can leverage patient data to recommend prevention or provide treatment.** Analyzing responses to treatment can increase the understanding of the clinician, creating a virtuous cycle in the healthcare system that can empower patients and endow providers/payors with access to data that is incomparable to the levels that have been available historically.

Exhibit 6: Sensors can help enable a new landscape in healthcare.



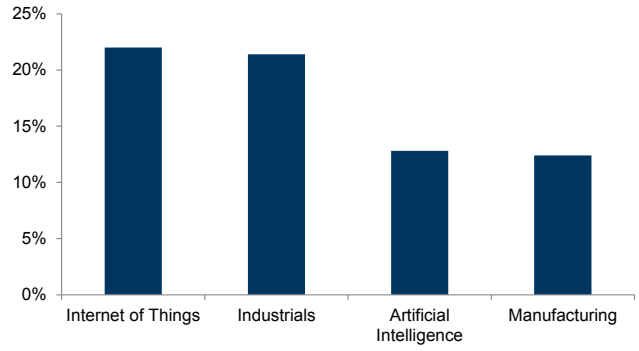
Source: Goldman Sachs Global Investment Research

Exhibit 7: Factors We Are Watching Driving Sensors



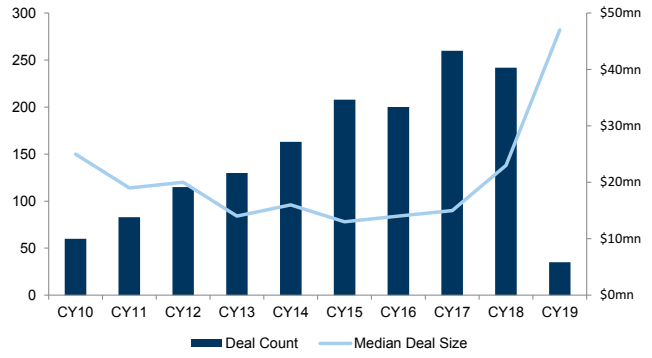
Source: Goldman Sachs Global Investment Research

Exhibit 8: Sensors are an area of VC interest across many categories.
Sensor Startups by Associated Vertical



Source: Company data, Goldman Sachs Global Investment Research, Pitchbook

Exhibit 9: The amount of capital deployed in sensor technology is ramping
Sensors - VC Deal Count and Median Deal Size



Source: Pitchbook, Company data, Goldman Sachs Global Investment Research

Sensor Types and Players

Classifying Sensors

There are **four classifications** in which one can think of sensors—measured property, measurement process, mobility, and connection. This taxonomy can be used to better understand the types of sensors in healthcare. The major goal in sensor technology is minimizing its user burden while maximizing the continuity of data collection. Current sensor manufacturers must work within the given constraints of the four categories.

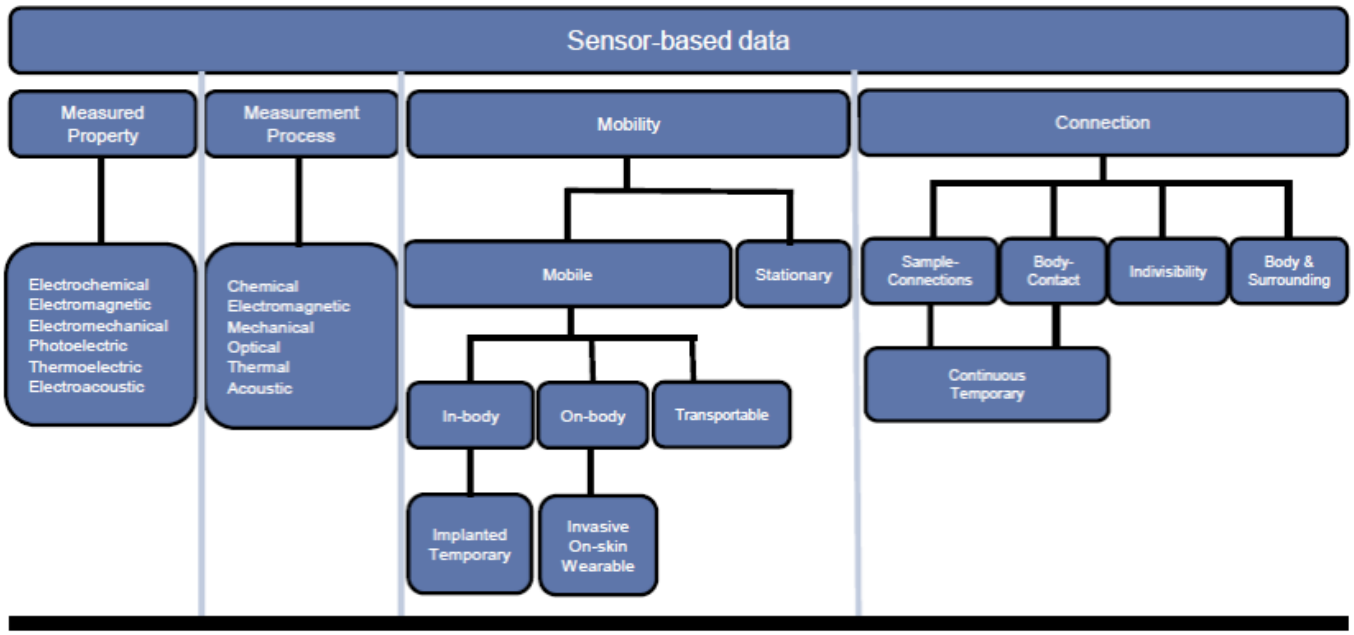
Exhibit 10: Sensor mapping by 11 technologies
Technologies are commonly used for Auto, Industrial, Consumers, and healthcare

Category	Physical										Chemical *see(10)
	Optical		MEMS							Magnetic	
	Optical	Image	Temprature (3)	Humidity(4)	Pressure (5)	Inertial(6)	Position/GPS	Sound/Ultrasonic	Gas(10)	Magnetic (11)	
Sensing technology (Example)	Infrared Radiation **(1)**	CMOS **(2)**	Negative Temperature Coefficient(NTC) thermistor	Capacitive	Strain gauge	Accelerometers	Capacitive	Microphone**(7)**	Semiconductor	Hall	Electrochemical(ceramic)
	IR LED	CCD	Resistance Temperature Detector(RTD)	Resistive	Capacitive	Gyroscopes	Magnetic	Ultrasonic Automotive**(8)**	Catalytic/ Pellistor	AMR	
		Vacuum tubes	Thermocouple	Thermal	Piezoelectric	Magnetometers	Inductive	Ultrasonic fingerprint**(9)**	Infrared(IR)	GMR	
		Flat panel detectors	IC	Gravimetric	Potentiometer	IMU	Potentiometer		Photo ionization	TMR	
Mainly detect	Image/Identity	Image/Identity	Temprature	Humidity	Force	Movement	Position	Distance	Gas	Motion	Gas
	Position	Position				Orientation	GPS	Identity		Current	
Future prospects	ADAS	ADAS	xEV BMS	Environmental	TPMS	ADAS	ADAS	AI speaker	Air quality sensing	Automotive TMR	Emission control
	Facial recognition	Machine vision	Factory automation	Industrial control	Touch sensing	Drones	Factory automation	Fingerprint sensing	Emission control		
Sensor name (Example)	Proximity detector	Photodetector	Temprature	Humidity	Force	Motion	Linear displacement	Microphone	Alcohol	Speed	Zirconia O2
	Lidar	Proximity detector		Moisture	TPMS	Vehicle Tracking	Proximity	ADAS sensing	CO2	Position	UEGO
	Facial recognition					Orientation	Rotary position	fingerprint	H2	Current	Nox
Automotive											
Communication											
Industrial											
Consumer											
Computers/IT											
Healthcare											
Others											

Major user | Marginal user

Source: Company data, Goldman Sachs Global Investment Research

Exhibit 11: The Taxonomy of Sensors



Source: NCBI

Developments in Sensor Technology

While we take no view on what exact types of sensors will be disruptive to healthcare in the intermediate and distant future, there are a few technologies worth keeping an eye on. First, **there is significant R&D investment in event driven sensors.** This technology is a sensor built to detect infrared light waves that are off until a certain event is triggered. The advantage is power savings that can be used in security applications. Also an interest of developers is piezoelectric resonators. Relevant applications include millimeter wave imaging and personal radar applications. Perhaps a longer term investment is a sensor that is able to use bacteria as an electron source. This could revolutionize power sources for temporary medical implants but is an early concept at the moment.

A blanket term applied to how the sensor of tomorrow may differ from the sensor of today is a **"smart sensor"**. The moniker applies to technologies that are equipped with a microprocessor that has the ability to customize outputs and provide interpretive data that improves the capability and performance of the system. This improved output with the goal of increased reliability and integrity is made possible by combining the sensor technology itself with a silicon microprocessor. **The smart sensor is comprised of a few main features: an onboard CPU, small size, wireless capability, and low cost.**

Sensors in Medical Devices

Though sensors are already fairly prevalent in healthcare, we think the next 5-10 years will be a period of accelerated innovation for sensors in healthcare. **Beneficiaries and users are numerous, from the newly born to the elderly, from the preventative to the acute, and from the patient to the surgeon.**

Sensor technology in a healthcare setting is often used for time-series monitoring of bodily conditions. **Glucose monitors, heart rate monitors, digital pills, medical beds, smart watches**, and other products all create value based on monitoring functions.

This is because the adoption of sensor technology can be justified in terms of (1) patient burden reduction and convenience, (2) high measurement and control accuracy, (3) acquisition of more measurement data than before, (4) lower cost than that of previous measurement methods, and (5) broad social cost reduction from preventive care.

We see the ultimate step as achieving a daily understanding and visualization of all changes occurring in the body using the lowest cost method.

Overcoming tail risk is key to expanding uptake

When looking at actual conditions, however, we see that the pace of sensor technology uptake in healthcare has not been that fast. Non-medical smart watches and other products have expanded quickly by providing services that help individuals manage and improve their health. However, we think medical applications require sensor devices to deliver a high level of reliability and performance due to the **question of who bears responsibility for complications in the event of misdiagnosis** (i.e., tail risk).

With devices becoming more and more interconnected, the necessity of robust cybersecurity controls also takes front stage. To point out a recent example, on March 21, the FDA issued a safety bulletin concerning communication between MDT's implantable cardiac devices, programmers, and home monitors that was not encrypted, possibly allowing for unauthorized individuals to access or manipulate the affected devices. Recent comments from the FDA suggest a push to allow public access to all medical device injury and malfunction data, reforming the legacy disaggregated reporting structure. Manufacturers of sensor-based medical devices and digital health platforms will likely need to invest heavily in protecting their products from unwanted incursion to protect from the risk of public disclosure of adverse events.

Types of Sensor Products

BrainWave - Electroencephalogram - Small bands that sit on your head that can track and record brain wave patterns. Can help diagnose disorders such as epilepsy or seizure disorders.

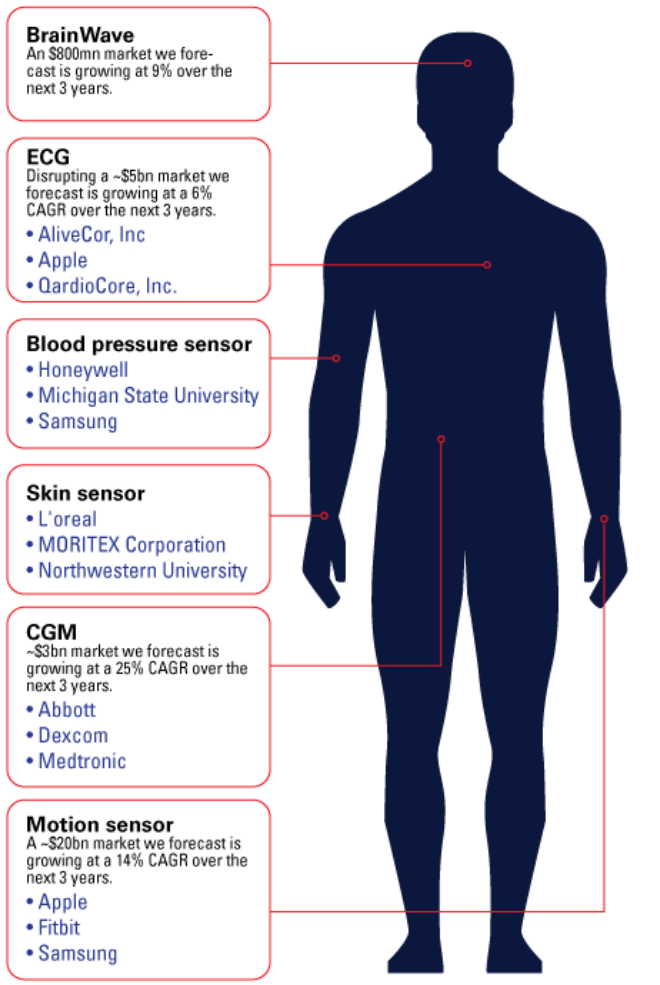
ECG or EKG - Electrocardiogram - Records electrical signals in the heart to gain insight on speed and rhythm of recorded heart beats.

Blood Pressure Sensor - Designed to measure human blood pressure and data points such as systolic, diastolic, and mean arterial pressure.

CGM - Continuous Glucose Monitor - Method to track glucose levels throughout the day that uses a sensor wire and an automatic transmitter with connectivity to a display device.

Motion Sensor - Primarily in wearables as they relate to healthcare, can give access to lab-quality data on walking speed, duration, and distance to provide feedback on performance.

Exhibit 12: Illustrating the Patient of the Future



Source: Company data, Goldman Sachs Global Investment Research

Diabetes: Using sensors to track and manage a chronic condition

Due to the CGM, diabetes care management has been the beneficiary of a tidal wave of innovation.

What is the CGM market?

Today, **we estimate ~700k people globally own a CGM system**. The CGM, or Continuous Glucose Monitoring System, is the foremost method of tracking glucose levels without the interruption of pricking one's finger and using a blood glucose meter. At regular intervals, the CGM will produce data readings generating direction and rate of change reports. Users simply insert a tiny sensor wire just under their skin using an applicator. A patch holds the CGM sensor in place so it can measure glucose readings. A transmitter connects to this sensor wire and sends readings to a receiver. The receiver can be a commonly owned device such as a smartphone or smartwatch. The receiver

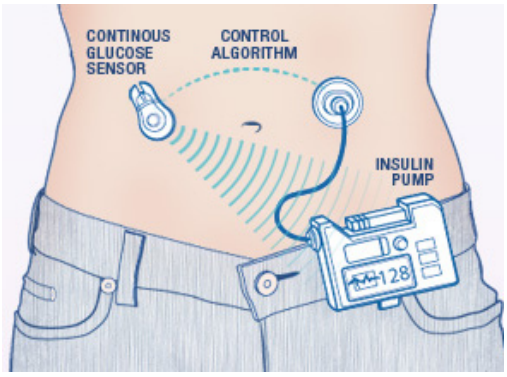
will display current and historical glucose levels. Looking forward, we are bullish on the prospects of CGM innovation to continue to evolve the way diabetes is treated.

Today, the CGM market is only increasing in competitiveness. Below, we illustrate the evolution of the CMG market along with our forecasts.

Diabetes TAM Among the Largest in Healthcare

Further down the road, we expect Med Tech companies to race towards the eventual possibility of the artificial pancreas. This solution is a system in which a CGM communicates with an insulin pump, allowing the pump to decide how much insulin ought to be delivered to the patient at any given moment in time. This would require improved capability in sensing technology and predictive analytics.

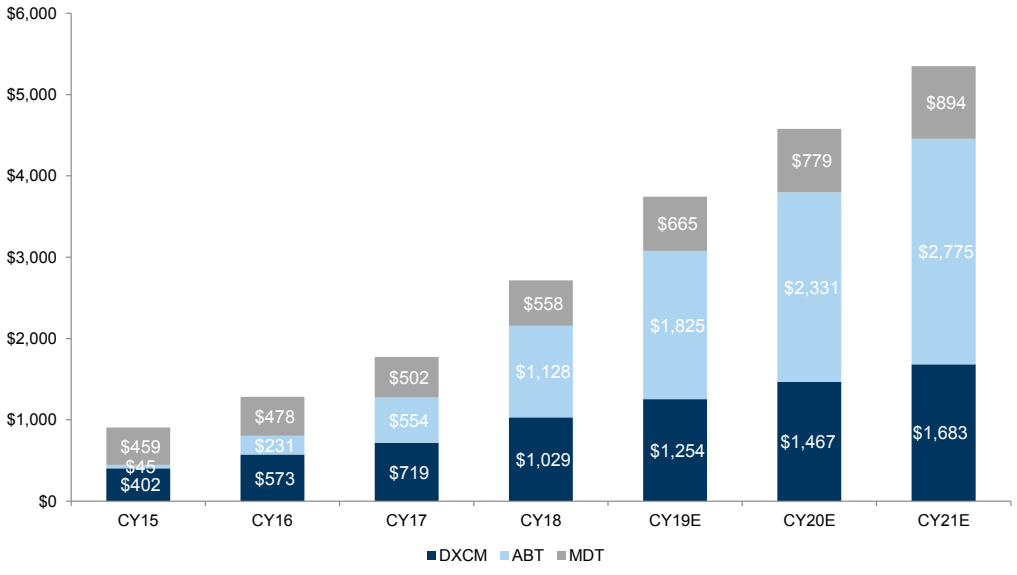
Exhibit 13: The diabetes care ideal is an integrated system that is both autonomous and predictive.



Source: Diabetes Council

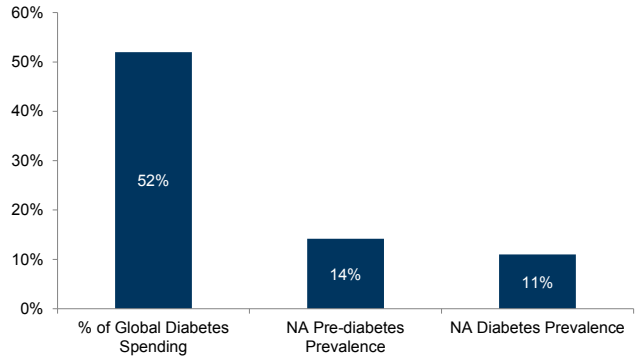
For context, according to DXCM, there are **about 3.2mn "core intensive" diabetics in the US and ~27mn T2 non-intensive patients in the United States.** Globally, **an estimated 9% of the world's population lives with disease**, and it is a leading cause of death linked to other harmful and expensive co-morbidities. **We estimate approximately $1 trillion in direct global cost associated with treating diabetes.**

Exhibit 14: We are modeling a ~$5bn market for CGM by CY2021
Global CGM Sales (Millions)



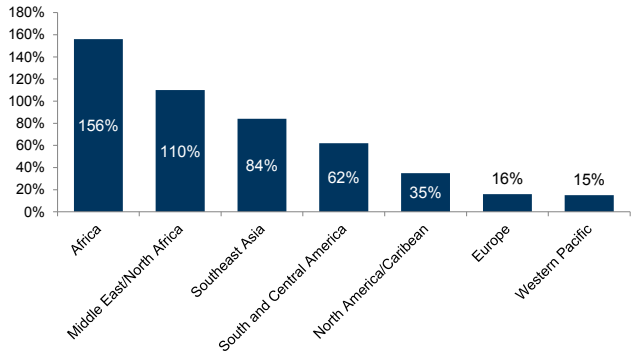
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 15: North America is currently the most penetrated market in diabetes, given relatively high rate of diagnosis
Diabetes by the Numbers in North America



Source: International Diabetes Foundation

Exhibit 16: Diabetes is increasing rapidly across the globe
Projected Growth in Diabetes Prevalence by Region (2018-2045)



Source: International Diabetes Foundation

Cardiology: Could your watch save your life?

Exhibit 17:

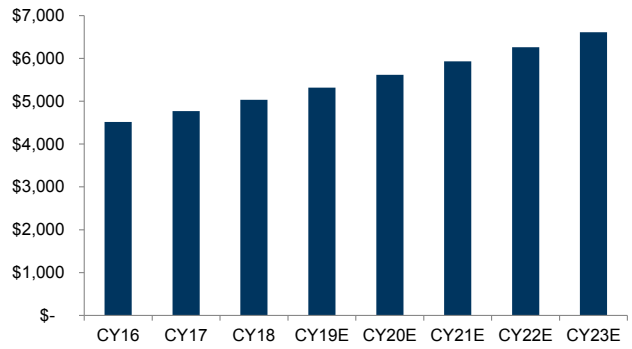
Wearables offer numerous areas for disruption to the healthcare system. An electrocardiogram, for example, is a test that measures the electrical activity of the heartbeat. An electrical signal causes first the top and then the bottom heart valves to squeeze in order to pump blood. Doctors examine the rhythm's movement to detect a wide range of problems that may or may not be present. EKGs can also identify enlarged or overworked areas of the heart. EKGs are traditionally performed in doctor's offices, clinics, or hospital rooms on electrocardiographs. Recent innovations, however, have introduced the possibility of a remote EKG.

Risks Going Forward

In general, we do not expect the industry's path to wearable health monitoring to be without challenges, however, patients' security concerns and their attitudes about data collection will likely remain top of mind for the foreseeable future. For example, the potential for unauthorized access to health monitors—and even implantables— will

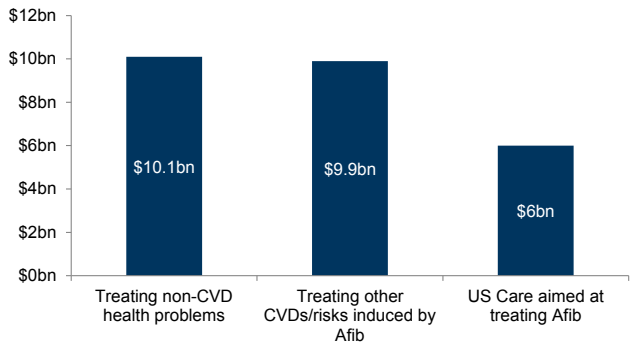
remain a major source of risk and potential liability for manufacturers of these products. It is our view that steps will be taken across the industry over the next few years to bolster protections around privacy and security.

Exhibit 18: The EKG market is set to benefit from tailwinds such as aging demographics and a rise in CVD incidence in the US
Size of the EKG Market (Millions)



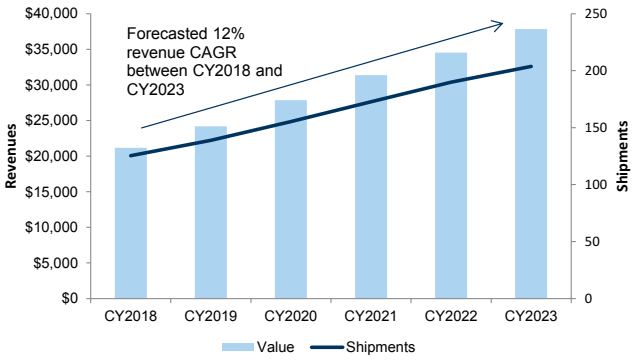
Source: Allied Market Research, Goldman Sachs Global Investment Research

Exhibit 19: AFib is a costly disease for the US healthcare system
US AFib Costs



Source: Company data, Goldman Sachs Global Investment Research, HealthLine

Exhibit 20: The market for wearables is a growing one with early but potentially promising investments in healthcare
Global Wearables Market Forecast (Mns)



Source: Company data, Goldman Sachs Global Investment Research, International Data Corporation

Patient Monitoring: Bed of the Future

A hospital bed may not, on the surface, be the first thing to come to mind when thinking of innovation in healthcare.

In reality, though, this is far from the case. The traditional hospital bed was, and in many cases still is, just a bed.

We believe sensors have a great deal of promise to increase the prevalence of in-patient monitoring. This technology is an integrated platform that gives clinicians immediate access to the patient's vitals and motion information needed to detect things like early deterioration, falls, and pressure ulcers. **The detection of these vitals is continuous in nature—tracking items such as heart and respiratory rate more than**

once per second. In this regard, sensors have the ability to both reduce adverse events and save on labor costs for staff that would otherwise need to be physically present in order to monitor.

The bed is just the entry point.

In the future of hospitals, we see sensors as value-enhancing to clinicians and IT teams looking to expedite solutions and execution in a hospital. Sensors play a highly important role in all of this, particularly those with predictive and artificially intelligent technologies. **If sensors and algorithms can together synergize and achieve high levels of prediction, the cost decreases and efficiency increases of having a refined system of matching nurses and physicians with ailing patients**—or not consuming resources on patients in an overly precautionary manner—could provide an attractive ROIC proposition on a bed.

Remote Monitoring: Tracking the patient everywhere

Most patients in and out of hospital go unmonitored

We estimate that the global in-hospital patient monitoring market - whereby patients are fitted with a wired sensor, which is connected to a bedside monitor - **is worth US$4bn today**. Yet continuous patient monitoring is only common in the ICU today, with **60% of all hospital patients not monitored continuously:** while these patients' vitals are checked regularly by nurses on the ward, this process is time-consuming, inefficient, and prone to error; this means patients outside of the ICU are effectively **unmonitored for 96% of their hospital stay (patients' vitals are normally checked once every 4 hours, ie 6x a day; this translates into <1 hour of monitoring time a day)**. This lack of continuous monitoring can lead to signs of complications going unnoticed for multiple hours, and therefore puts patients at increased risk.

Wearables: A new model for care delivery?

Remote patient monitoring will be a needed tool for providers to help mitigate the cost of treatment.

Another application for sensors are wearables. When leisure time comes at a premium, individuals often put their health on the back burner to make time for priorities such as labor and caring for children. A simple appointment with a doctor can be time-consuming. To make things worse, sometimes they can be overly expensive, as the patient may just be in need of a diagnosis, prescription, or treatment. Another reality in healthcare is that the lion's share of resources are going towards caring for sick patients—rather than to the prevention of getting sick in the first place. Sensor technology, in the form of wearables, offers promise in this area. Wearables could continuously monitor someone's health and provide real time insights across a broad range of parameters. Ideally, they could communicate this collected data to the patient's

physician. Analytics could be provided on fall risk, exercise, habits, and monitoring the elderly. Developments in this could even lead to an increased ability to help diagnose serious illnesses early in their stages.

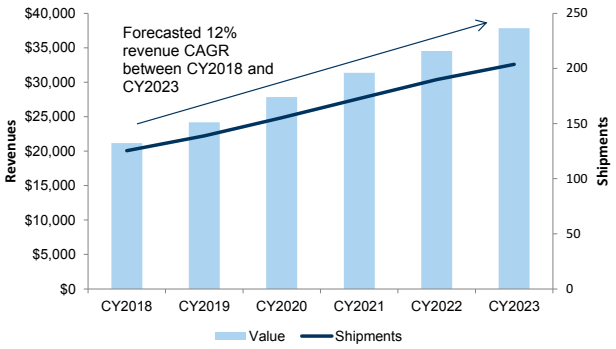
Drivers of Success: Accuracy, Payor Reception, and Attitudes

Going forward, we will be measuring the success of wearables through a few different lenses. First, current data, while useful, has not sufficiently proven it can be used for disease prevention. In order for this to happen, clinical proof that data from wearables can be leveraged to make diagnoses must emerge. For this to be the case, accuracy is crucial. As we generally are discussing a wearable as smart watch technology that sits on the wrist of an individual, it is at an obvious engineering disadvantage. Another question mark associated with wearables beyond accuracy becomes how to charge for the monitoring benefits it offers. Effective at the start of January 1st, 2018, CMS unbundled CPT code 99091 to enable clinicians to receive separate reimbursement for time spent monitoring remote patient data. We believe this to be a positive for implementation of remote patient monitoring solutions. Perhaps the biggest variable dictating the success of wearables in healthcare will be the trajectory of attitudes and policies dealing with data privacy. Over the long term we are constructive on the opportunity set despite the risk—given younger generations have typically shown comparatively more comfort with this risk than older ones.

Devices and Cyber Security

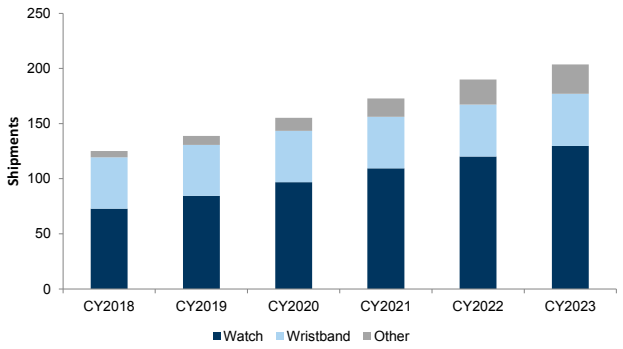
Another major area of uncertainty for wearable or implantable medical devices is their ability (or lack thereof) to quell potential cyber security threats. While historical examples of infiltration and malicious manipulation of medical devices have been limited, the frequency of security breaches reported by the media in other areas has certainly provided some reason to question the immunity of wearable and implanted devices to such activity.

Exhibit 21: The market for wearables is a growing one with early but potentially promising investments in healthcare Global Wearables Market Forecast (Mns)



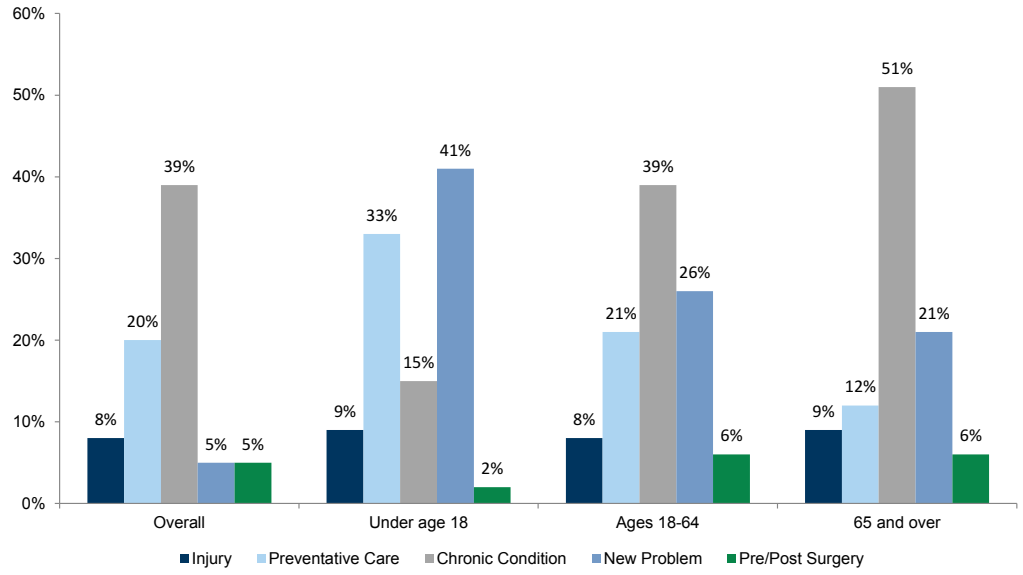
Source: Company data, Goldman Sachs Global Investment Research, Iinternational Data Corporation

Exhibit 22: The vast majority of wearables are either watches or wristbands Global Shipments by Product Type (Mns)



Source: Company data, Goldman Sachs Global Investment Research, International Data Corporation

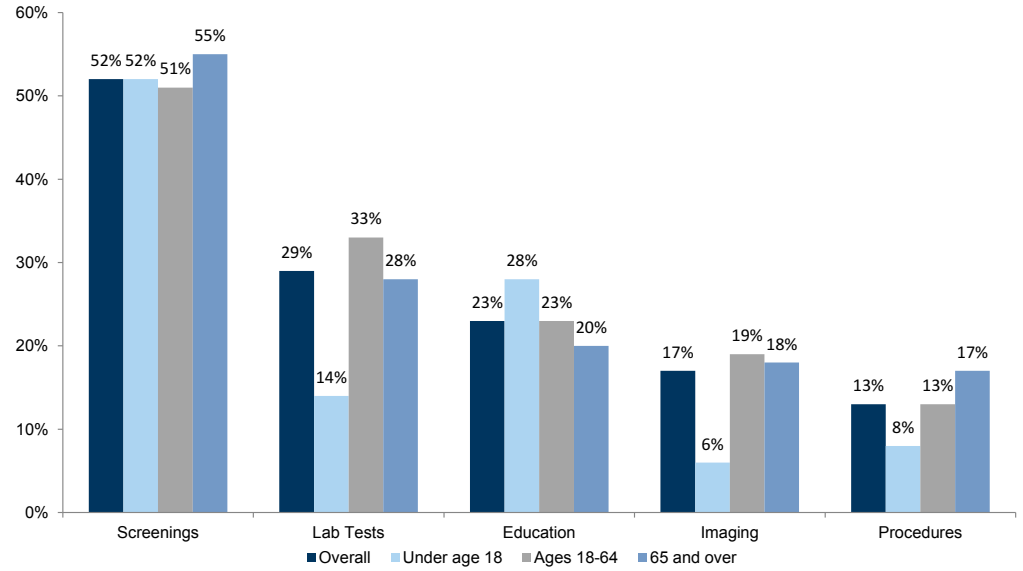
Exhibit 23: We believe sensors have the capacity to decrease the proportion of preventative visits to the physician's office.
US Reasons for Office-based Physician Visits



Data from 2015

Source: Centers for Disease Control and Prevention

Exhibit 24: Sensors have shown early potential to displace existing functions such as imaging and screening traditionally done in the physician's office.
US Selected services ordered or provided at office-based physician visits, by age:

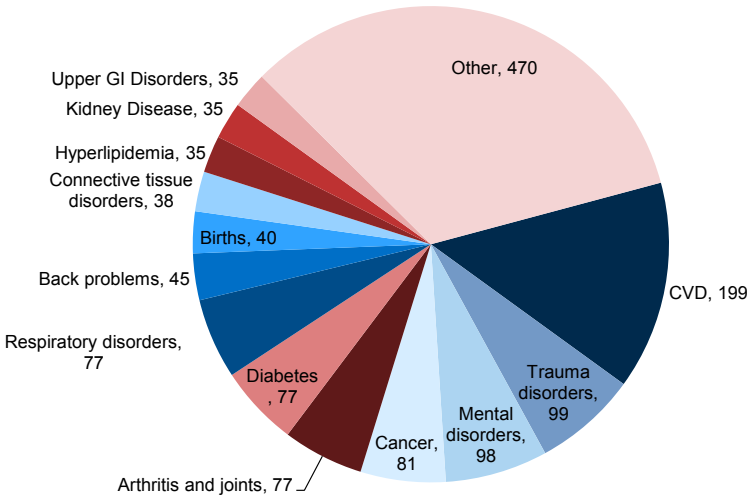


Data from 2015

Source: Centers for Disease Control and Prevention

Appendix: The Healthcare Burden & Other Applications of Sensors in Med Tech

Exhibit 25: Just 20 conditions make up more than half of healthcare spending in the US ($bn)
US Average Total Healthcare Expenditures 2013-2014



Source: HHS - Agency for Healthcare Research and Quality - Medical Expenditure Panel Survey - US - 2014

Exhibit 26: Cardiovascular disease represents the biggest disease area in the developed world—both in terms of financial cost and lives taken
US CVD by the Numbers

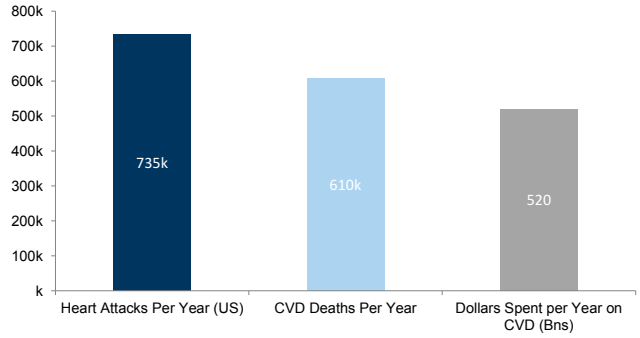
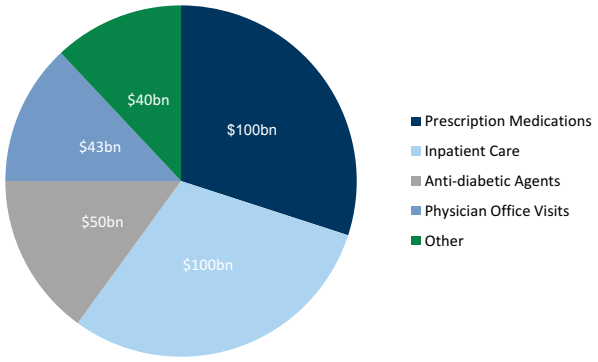
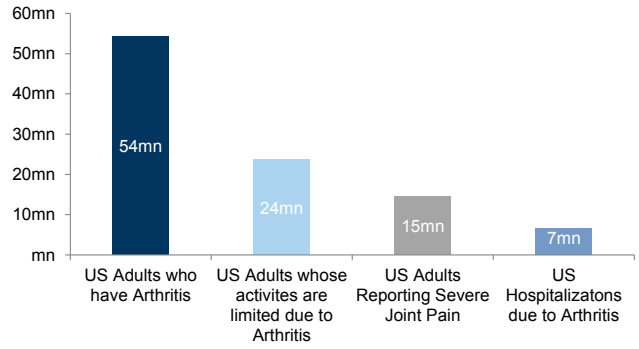


Exhibit 27: Diabetes is one of the largest and fastest growing disease areas; an estimated 1 in 3 Americans have diabetes or pre-diabetes
The Cost of Diabetes in the United States



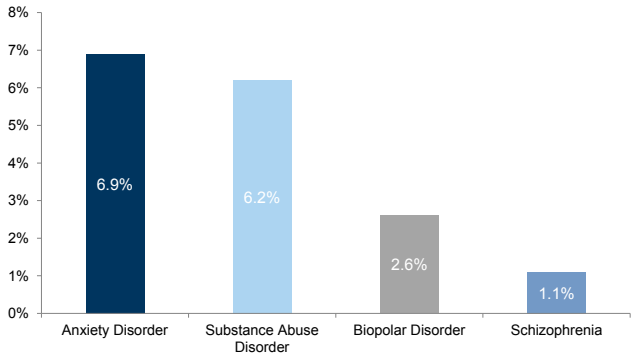
Source: American Diabetes Association

Exhibit 28: Joint pain is a ~$300bn burden in the US and strongly linked to other health conditions.
Arthritis by the Numbers



Source: Arthritis Foundation

Exhibit 29: ~$100bn in spending for mental health disorders; economic harm is exacerbated by lost earnings
% of Americans Affected by Mental Disorders



Source: Goldman Sachs Global Investment Research, Kaiser Family Foundation

Smart Clothing

In order to more frequently and accurately monitor vital signs, some companies have raised the possibility of body-worn smart clothing. These allow for signals containing various physiological indicators to be generated, collected, and then integrated into an infrastructure of smartphones, mobile applications, and big data. A solution like this seeks to address the problem of monitoring systems targeting too few physiological signals. **The utility of smart clothing comes from sensor placement that allows individuals to focus in on particular vital signs. We see sound design, high sensor quality, positioning, and comfort as integral to the user experience.** A few possible places/uses for smart clothing include the wrist/pulse, under arm/body temperature, left chest/myocardial, and tricep/blood oxygen. However, we believe smart clothing has many improvements to make before it can achieve even early signs of commerical viability, including cost effectiveness, customization, and computational intensiveness.

Haptic Feedback in Surgical Robots

Haptic devices are positioned as actuators rather than sensors, as they react physically, converting information received from sensors to movement.

Alps Alpine introduced the Haptic Commander as a haptic device in 2000. Haptic devices were first used in luxury cars made by BMW and other automakers to simulate the sensation of operating in-vehicle information systems using the sensitivity of the human hand (Haptic is a registered trademark of Alps Alpine in Japan, China, and Europe). Consumer products started using haptic devices from 2016, including Apple smartphones and the Nintendo Switch controller (released in March 2017). In automotive applications, haptic devices (incorporated in steering wheels) are being considered for use in measures to prevent drowsiness by controlling the frequency of vibrations.

Vibrations at many different frequencies can be produced by combining several haptic devices. Given that haptic devices are made with a combination of mechanical

components, the level of component processing precision and motion control technology are key points for reliability.

We have believed for some time now that robot-assisted minimally invasive surgery has tremendous potential to improve the accuracy and capacity of surgeons, while minimizing trauma on the patient. In order for robotic surgery to achieve further penetration, we believe sensors will need to play a big role—particularly in the area of haptic feedback. **By the term "haptic feedback", we are referring to a real and simulated touch that occurs between robots and humans in either real or simulated environments.** The essence of haptics is to allow the surgery to feel as natural and dynamic as possible. An everyday example of haptic feedback is the vibration on a video game controller when a character comes into contact with a particular object. This touch can be manifested in the form of distributed pressure, temperature, vibrations, and texture.

There are two major types of haptic feedback particularly worth mentioning. First, there is force feedback, which measures forces applied to a patient (typically by a surgical instrument). A common difficulty associated with building out force feedback mechanisms in the operating room is that it can be difficult to add force sensors to existing instruments. It is generally easier to integrate the capability of force feedback into the instrument. Much work has been done in the last few years to test the effectiveness of haptic feedback on patient outcomes. One particular study (Ortmaier, et al) found that haptic feedback does indeed reduce unintentional injuries in dissection tasks. Operating times, however, were lengthened. Though studies are far from conclusive, clinical studies have indicated superiority in palpitation tasks and tissue characterization in combination with visualization technologies. We believe that, down the road, sensors have tremendous potential to improve haptic feedback. In combination with virtual reality, haptic feedback offers a promising training opportunity for surgeons of the future.

Tactile feedback, an area that so far has not been studied as closely as haptic feedback, can detect properties such as compliance, viscosity, and surface texture. Tactile technologies ultimately have the goal of attempting to create the illusion that the surgeon is directly contacting the patient. As one can probably imagine, many see much of the capability of tactile feedback as a factor that can help make remote surgery a reality, so a physician can have an idea of what something feels like without being physically present.

Disclosure Appendix

Reg AC

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