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Mobile Phones Democratize and Cultivate Next-Generation Imaging, Diagnostics and Measurement Tools

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Abstract

In this article, I discuss some of the emerging applications and the future opportunities and challenges created by the use of mobile phones and their embedded components for the development of next-generation imaging, sensing, diagnostics and measurement tools. The massive volume of mobile phone users, which has now reached ~7 billion, drives the rapid improvements of the hardware, software and high-end imaging and sensing technologies embedded in our phones, transforming the mobile phone into a cost-effective and yet extremely powerful platform to run e.g., biomedical tests and perform scientific measurements that would normally require advanced laboratory instruments. This rapidly evolving and continuing trend will help us transform how medicine, engineering and sciences are practiced and taught globally.

The history of wireless phones dates back to the beginning of the 20th century. Even in 1940s wireless phones for automobiles were commercially available.[1] These earlier designs were much bulkier and power hungry in addition to being analog, making them quite far away from our modern digital cellphones that we carry in our pockets today. However, even then it was predicted that mobile phones will be widespread and carried by almost everyone. One interesting portrayal of this prediction was published in 1926 in a satirical magazine by Karl Arnold, a German painter, clearly showing that the idea of and the excitement around mobile phones have been out there for almost a century now (see Figure 1).[1–2] Of course, these previous discussions and demonstrations were mostly limited to wireless audio signal transmission and reception, and could not realistically portray the massive extent of today's "smart-phones" together with their computational power, various physical sensors including high-end imagers/cameras and the digital aspects of the "big" data that they can globally generate and share.[3–6] For sure, at the beginning of the 20th century it was extremely difficult, if not impossible, to predict the "internet" and without the internet it is very difficult to fully comprehend the smart-phone and what it globally enables.

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Conflicts of Interest Statement
A. O. is the co-founder of a start-up company (Holomic LLC) that aims to commercialize computational microscopy and diagnostics tools

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In this article, I will focus on some of the emerging uses of mobile phones for imaging/microscopy, sensing and diagnostics as well as general measurement science,[7–41] which will fundamentally impact the future practices and education of medicine, engineering and sciences globally. There are several aspects that make today's mobile phones rather unique for conducting sensing and diagnostic measurements/tests toward for example telemedicine, mobile health, point-of-care (POC) and environmental applications, among others, and below I will detail some of these distinctive features.

Massive Volume, Cost-effectiveness and Connectivity

Cellphones are cost-effective mostly due to their massive volume of users. We have approximately 7 billion cellphone subscribers in the world by the end of 2013, and this enormous volume makes the cellphone hardware and software extremely cost-effective and yet rather powerful and reliable, working almost anywhere in the world (see Figure 2). In terms of high-end consumer electronics devices, besides mobile phones there is simply no other platform that one can broadly rely on and cost-effectively utilize all around the globe. While a significant majority of these cellphones are not yet smart-phones, the penetration rates for smart-phones are constantly increasing worldwide (e.g., by the end of 2013 it has reached more than 55% per inhabitant in US),[3] and with the rapid accumulation of second hand phones one can expect further acceleration in adoption of smart-phones globally. These mobile phones, with their cost-effective and seemingly simple infrastructure provide data connectivity to >90% of the world population, which permits digital sampling, processing, reporting and sharing of the acquired information (whether it is an image, a sensor output, a diagnostic test result, etc.) both locally and globally.

High-End Components Embedded in Mobile Phones – The Building Blocks of Next-Generation Imagers, Sensors and Diagnostic Tools Running on Mobile Phones

In addition to their massive volume, cost-effectiveness, coverage and data connectivity, rapid improvements that we have experienced in cellphone related technologies and components over the last decade can provide important insights to some of the unique capabilities that our cellphones currently have (see Figure 3). One of the most interesting of these features/components installed on mobile phones that has been rapidly advancing is the opto-electronic image sensor. As a matter of fact, the mega-pixel count of cellphone cameras has been doubling almost every two years over the last decade, following the famous Moore's Law, and it has now reached to more than 40 mega-pixels (Figure 3a).

These advanced optical imagers on our cellphones provide various opportunities to utilize the cellphone as a general purpose microscope[7,9,10,12,14,16,19,27,35] that can even detect single viruses[29,38] on a chip. Microscopy is one of the most widely used tools in sciences, engineering and medicine, and the creation of high-end optical microscopy and imaging platforms that are integrated onto cellphones is rather important for not only telemedicine (e.g., telepathology, remote diagnostics), mobile health, POC and environmental monitoring applications, but also for the *democratization* of measurement science and higher education.

By creating cost-effective and yet powerful micro- and nano-imaging interfaces on the cellphone or using cellphone parts such as CMOS imager chips, researchers in the developing world can also find solutions to various measurement and testing needs of their research laboratories and higher education institutions. This has been the focus of some of the emerging efforts on creating e.g., lensfree computational microscopes on a chip,[14,27,29] where the spatial resolution and field of view are decoupled from each other so that improved resolution and higher-throughput can be achieved at the same time using some of these next generation image sensor chips that are installed on our smart-phones. This also means that such lensfree computational microscopes literally ride on the Moore's curve (Figure 3a), where their performance (e.g., space-bandwidth product) literally doubles almost every two years – a very interesting phenomenon that we have been experiencing for the first time in the history of optical microscopy.

Besides microscopy, these advanced imaging and opto-electronic or electronic sensing/sampling technologies embedded in our cellphones can also be utilized for various telemedicine, POC and mobile health related applications including but not limited to blood analysis and cytometry,[17,33] detection of bacteria or viruses,[22,34,38,39] diagnosis of infectious diseases,[24] monitoring of chronic patients (e.g., by testing urinary albumin,[30] cholesterol[40], etc.), sensing of allergens,[26] label-free detection of protein binding events,[36] ultra-sound imaging,[13] micro-NMR for molecular analysis of tumor samples,[18] electrochemical detection of parasites,[32] monitoring of electrocardiogram rhythms,[28] estimation of human eye refractive errors as well as detection of cataracts,[15,20] among many other applications as further detailed in reference 41. In most of these applications, sample preparation through smart microfluidic[42–49] chip designs is the key enabler for the success of mobile phone based sensing and detection platforms. In this regard, lab-on-a-chip research can be considered to be one of the core pillars for mobile micro-analysis, which provides cost-effective, field-portable and rapid solutions to complex sample handling, preparation and delivery steps, assisting with the specificity and sensitivity of mobile phone based micro-analysis, sensing and diagnostic platforms.

Some of the other key components and technologies embedded in mobile phones that we have seen dramatic improvements over the last decade include faster processors and higher bandwidth data transmission/receiver units (see Fig. 3) which altogether make the cellphone function as a portable *super-computer*, with ample opportunities for parallel processing of the acquired data even locally, at your palm. Obviously, the connectivity and the rapidly improving bandwidth of mobile phone telecommunication networks also enable data processing to be performed over remote servers through e.g., cloud computing, which might especially be suitable for lower-end cellphones, i.e., only the processed final results could be communicated back to the phone users. In any case, the cellphone with its core-processors, data connectivity and bandwidth brings a remarkable computational power to its users, which can be utilized for advanced imaging, sensing and diagnostics applications, among others. For telemedicine and field use of these cellphone based measurement/testing devices, this last feature is quite important and essential; however for POC and mobile health applications that involve e.g., home monitoring of chronic patients, other forms of data communication and signal processing methods that involve local PCs and/or tablets could also be utilized in addition to the cellphone processors or the cloud.

Cost-effectiveness of this data exchange between a cellphone based measurement tool and a remote server (e.g., for archiving of test results or for advanced signal processing and further analysis) is also an important parameter to consider. Fortunately, while the mobile phone data rates have been getting significantly faster (Fig. 3c), the cost of wireless data transfer has also been globally reducing as illustrated in Figure 3d. This trend is likely to continue within the next decade which will give us further opportunities for radical simplification of our measurement and sensing tools running on mobile phones and mitigating this simplicity with high-end computation that is performed on the cloud (in addition to the phone). This, I believe, will form an important step in the democratization and cultivation of next-generation sensing and diagnostics technologies globally.

The above presented summary of the unique features and components of mobile phones is not meant to be a comprehensive list, and in fact there are other important components, including for example the digital screen, accelerometer, IR sensor, projector, etc. that are also being used in innovative ways to convert the mobile phone into advanced sensing and measurement platforms.[15,41,50] All these emerging application areas of mobile phone based platforms in biomedicine and other fields of engineering and applied sciences create a set of exciting prospects in addition to challenges that await us in the future, some of which will be highlighted in the following sub-sections.

Big Data Created by Mobile Phone based Imaging, Sensing and Diagnostic Tools – The Internet of the Micro-World

In addition to various applications discussed earlier, these mobile phone based field-portable measurement tools are also digitally connected to each other, forming a rapidly expanding network. Based on the advances in the broad use of cellphones for micro-analysis, imaging, and sensing, within the next decades we can expect several orders of magnitude increase in the number of personal microscope and diagnostic tool users globally. All these cost-effective and ubiquitous cellphone enabled devices designed for field-portable imaging, sensing and testing would generate high quality, sensitive and specific data from wherever they are being used, forming a global network, which I term as the micro-Internet (i.e., *μ-Internet*). This reminds me of the transformation that we have experienced from PCs to the internet: once made cost-effective and compact enough, PCs were connected to each other through telecommunication protocols, creating the backbone of the modern internet. Together with crowd sourcing and social networks, today's internet can be considered as a highly sophisticated "living and learning" system, where we have more than 180 billion email messages every day, together with >850 million unique websites, with highly dynamic content.

Once fully scaled-up, this smart network of imagers, micro-analysis systems and diagnostic tools, i.e., the μ-Internet, might deliver a paradigm-shift for e.g., medical, environmental, and biological sciences, among others, through innovative uses of this network and its constantly expanding database. For instance, by creating massive libraries of various specimens (e.g., microbial communities, parasites, pathology slides, blood/sputum/pap smears etc.) we would be able to dynamically track both temporal and spatial evolution of different species, diseases or infectious outbreaks, and be able to better investigate and identify the cause-effect relationships of these spatio-temporal patterns at a much larger scale, providing an important tool for especially epidemiology. Such a robust platform could even lead to better policy making locally and globally for e.g., health-care and environmental issues.

While these opportunities are endless and all very exciting, there is also a major challenge which is related to the fact that our experts (e.g., medical doctors, diagnosticians, health-care technicians, micro-biologists, etc.) do not increase their characterization, diagnosis and labeling throughput as much as digital technologies increase their imaging/sensing and measurement throughput. As an example of the ultra-high throughput that some of the emerging mobile phone enabled technologies have, recently introduced computational on-chip microscopes can routinely generate images that have 1–2 billion useful pixels, where even single viruses can be detected over large sample areas of e.g., >0.2–10 cm^2[27,29] This throughput mismatch between emerging digital measurement tools and human expertise creates a bottleneck since more and more data that need to be classified/sorted and diagnosed will start to pile up as human expertise does not scale up as our digital tools do. This challenge, however, can potentially be mitigated by coupling μ-Internet database with machine-learning, crowd-sourcing and smart gaming strategies (see e.g., Refs. 51–52), which might lead to a self-learning hybrid network (machine + human) that gets much better in automated identification, classification and diagnostic analysis of new generated data of various specimen, whether it is e.g., a bodily fluid, a histopathology slide or water/food sample. Once successful and scaled-up, this self-learning network of cellphone enabled micro-analysis tools and its constantly expanding database could be a priceless global asset for a variety of medical, environmental and biological applications for both the developed and the developing world.

The Future of Moore's Law and Standardization of Mobile Phone based Diagnostic and Measurement Tools

The Moore's Law at its origin is related to the dimensions of a transistor in an integrated circuit. Since we are approaching the physical limits in terms of the size that can still govern reliable switching operation in a transistor design, there are heated debates on how long more the Moore's Law can effectively continue. This technical discussion is beyond the scope of this article, and as far as this manuscript is concerned, we are broadly using the term Moore's Law to refer to the rapid advances in digital technologies, even extending it to for example the mega-pixel count of mobile phone cameras as depicted in Figure 3a. For us the important and relevant question is: *Can this rapid trend and its impact on different components in consumer electronics devices including cellphones continue in the next decades?*

There may not be a clear and globally correct answer to this question covering all the embedded technologies/components in mobile phones and other electronics devices. However, the consumer electronics market has been one of the main drivers and the economic forces behind the Moore's Law and its direct impact on the rapid evolution of mobile phones. Therefore, with the increasing buying power globally, a continuing growth in the number of mobile phones in the world can be expected, which will also create a very large pool of second-hand phones (see e.g., the global evolution of mobile phone sales reported in Figure 2, which illustrates that since 2000, approximately 15 billion mobile phones have been sold). All of these factors will most likely continue to lower the overall costs for mobile phone based technologies, despite the major technological improvements that they go through almost every year.

On the other hand, this rapid pace of advances in consumer electronics market also creates major challenges for standardization of mobile phone based imaging, sensing and diagnostics tools and technologies. Considering the fact that the regulatory approval processes in biomedical device industry are rather cumbersome, costly and time consuming, these rapid changes in the hardware and/or software of our mobile phones can become a major limitation for commercialization efforts toward e.g., telemedicine, POC and mobile health related applications of cellphone based tools. This obstacle can be potentially addressed by new business ideas that turn the challenge into an opportunity; for example a consortium that is formed to provide the industry with standardized and regulated supply of certain mobile phones and/or mobile phone components could be a possible solution. Another potential solution toward this challenge could be the systematic development and standardization of open software and hardware platforms for mobile phones, such as the Android OS and the recently announced Project Ara[53] (through the collaboration of Motorola and Phonebloks[54]), respectively.

Wearable Computers

In addition to mobile phones, other emerging consumer electronics devices, especially wearable computers such as Google Glass, Samsung Smartwatch and others, might also play important roles in the future practices and designs of next-generation mobile health, telemedicine and POC tools. Most of these wearable computers and telecommunication devices will share similar embedded components and technologies as found in our smart-phones. However, their user and data collection/sharing interfaces might provide new prospects that mobile phones do not currently have. One such example is Google Glass (Fig. 4), where its hands-free augmented reality environment can be explored in various biomedical and/or environmental imaging and sensing applications including e.g., pathological investigation of samples. One of the first examples of this exciting opportunity has been recently demonstrated through the use of Google Glass for digital reading and quantification of nanoparticle based immunochromatographic diagnostic tests where a custom-written Glass application was created to image one or more of these diagnostics tests labelled with Quick Response (QR) code identifiers using the hands-free and voice-controlled user interface of Google Glass (see Fig. 4). The acquired Glass images are then transmitted to a server for rapid digital processing and quantification of test results with e.g., a few parts per billion (ppb) level of detection limit.[56]

As another possibility, in addition to the medical expert's professional opinion, computer vision and machine learning tools running on Google Glass platform can create real-time digital “flags” or “virtual maps” on the sample (e.g., a pathology slide or live tissue) field of view assisting and guiding the medical personnel in their routine practice, making them more efficient and accurate in their professional assessments. Likewise, the same interface provided by Google Glass or similar wearable computers could also be utilized for real-time sharing of and consultation on medical images, along with additional related data, with other experts for remote diagnosis and telemedicine. These emerging opportunities provided by wearable computers could be quite valuable for e.g., surgeons (during surgery), pathologists, microbiologists, diagnosticians, among other professionals.

In addition to experts, such wearable computers could also create new interfaces for individuals to self-monitor or routinely test/measure their own health status, behaviour or the environmental conditions (e.g., pollution). In this regard, I highly value all of these recently emerging smart consumer electronics devices, following the successful footsteps of mobile phones, since they will continue to bring highly sophisticated digital technologies to masses within cost-effective and compact platforms with the potential to radically transform the future practices of medicine, engineering and sciences globally.

Democratization of Science, Engineering and Medical Research and Education

As detailed earlier, the use of cellphones for the development of next generation imaging, sensing and diagnostics tools opens up numerous opportunities and new applications, partially bringing the functions of advanced laboratory instruments to field conditions, resource limited settings and even to homes within compact and cost-effective embodiments. While this is very exciting, another major impact that this direction will generate is the democratization of science, engineering and medical research and education. Through these next generation technologies and measurement devices/tools that rely on mobile phones as well as other consumer electronics hardware and/or software, researchers and educators will find new prospects to conduct scientific experiments that would normally be beyond their reach. This might result in better research outcomes in developing countries by empowering their research labs and institutions with much more cost-effective and yet quite powerful measurement and analysis tools. Furthermore, the same consumer electronics driven cost-effective scientific measurement modules could also assist educators to improve the quality of higher education by providing various hands-on learning experiences to their students, significantly enriching the existing curriculum. This might considerably boost the overall quality of the training and the education that the students in medicine, engineering and sciences receive in the developing world, potentially helping to democratize and cultivate research and education globally.

In summary, mobile phones will change the way that imaging, sensing and diagnostic measurements/tests are conducted, fundamentally impacting the existing practices in medicine, engineering and sciences, while also creating new ones. This transformation will also democratize high-end measurement and testing tools worldwide, which might significantly improve research and education institutions, especially in developing countries.

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Fig. 1.
A cartoon that is published in 1926 portrays the future use of mobile phones.[1–2]

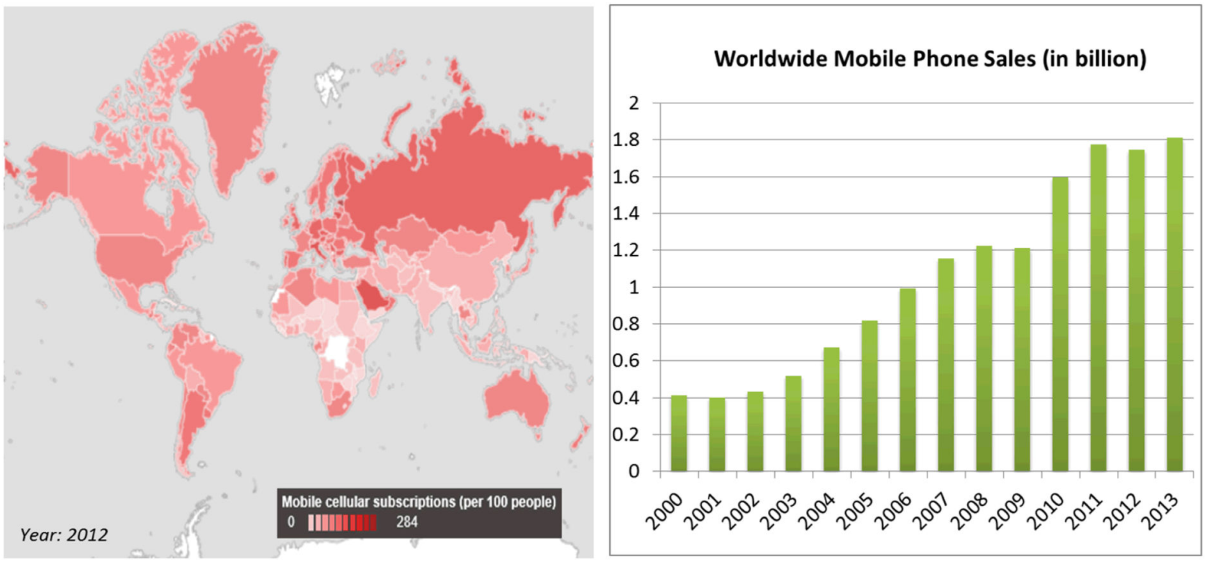

Fig. 2.

(Left) Mobile phone subscription rates (per 100 people) in the world. (Right) Mobile phone sales in the world as a function of time. Since 2000, approximately 15 billion mobile phones have been sold, which is more than 2 fold larger than the population of the world. Data sources: References 3 and 4.

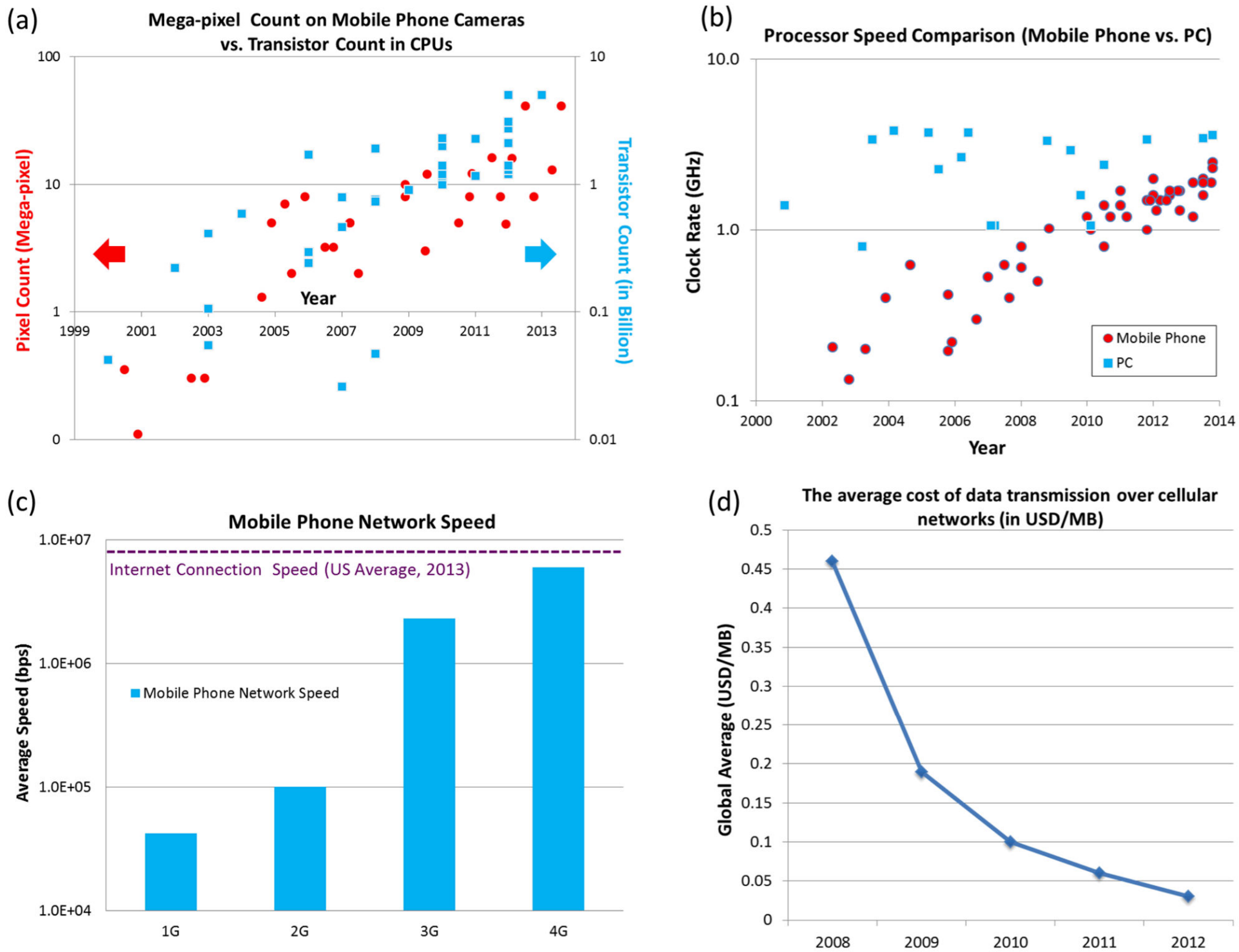

Fig. 3.

(a) A comparison of the mega-pixel count of mobile phones with the transistor count in central-processing-units (CPUs) of PCs. This comparison shows that the pixel count of cellphone cameras has been following the Moore's Law, i.e., doubling almost every 2 years. (b) The processor speed comparison between mobile phones and PCs. (c) Mobile phone network speeds for 1G, 2G, 3G and 4G networks are compared against the average internet speed in the US in 2013. (d) The global average cost of data transmission over cellular networks is reported as a function of time. Data sources: References 3–6.

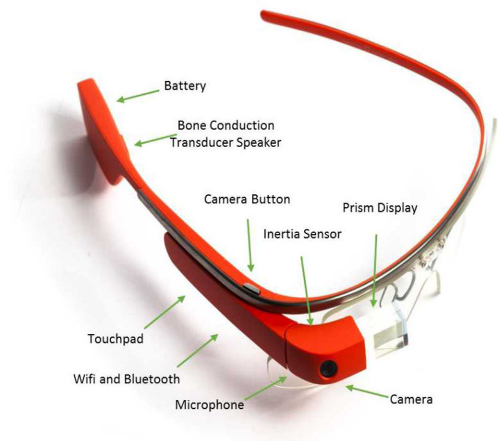

Fig. 4.

(Top) Components of Google Glass.[55] (Bottom) Google Glass based imaging and quantification of immunochromatographic diagnostic tests. For more details, refer to Ref. 56.