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Invited critical review

Clinical laboratory data: acquire, analyze, communicate, liberate

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A R T I C L E I N F O

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A B S T R A C T

The availability of portable healthcare devices, which can acquire and transmit medical data to remote experts would dramatically affect healthcare in areas with poor infrastructure. Smartphones, which feature touchscreen computer capabilities and sophisticated cameras, have become widely available with over billion units shipped in 2013. In the clinical laboratory, smartphones have recently brought the capabilities of key instruments such as spectrophotometers, fluorescence analyzers and microscopes into the palm of the hand. Several research groups have developed sensitive and low-cost smartphone-based diagnostic assay prototypes for testing cholesterol, albumin, vitamin D, tumor markers, and the detection of infectious agents. This review covers the use of smartphones to acquire, analyze, communicate, and liberate clinical laboratory data. Smartphones promise to dramatically improve the quality and quantity of healthcare offered in resource-limited areas.

Contents

1. Introduction

Cellphones are becoming an integral part of everyday life. Recent statistics showed that cellphone subscriptions reached about 6.8 billion, accounting for almost 96% of the world's population [1]. In 2012, developing countries had cellphone subscriptions of approximately five billion [2]. Currently, there are more than one billion smartphone users worldwide and they are expected to reach 5.6 billion by 2019, representing a penetration rate of about 60% [3]. Smartphones are characterized by high processing power. For example, Nexus 5, one of today's fastest smartphones, is supplied with Qualcomm Snapdragon ™ 800, a quad-core 2.26 GHz processor [4]. High performance computing provided by such processors allows smartphones to operate several sophisticated software applications. In addition, most

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smartphones as well as many conventional cellphones are equipped with high resolution cameras e.g. Nokia Lumia 1020 has a 41 megapixel (MP) camera [5]. These features along with many others qualify smartphones for several applications that are not restricted to telecommunications.

Cellphones have been used in plenty of health-related applications. Technologies used to enhance healthcare include text messages (SMS) [6,7], cameras [8], cellphone applications [9,10], sensors [11] and internet accessibility [12]. These technologies have been used for health education, bringing awareness for better disease management, sending patient-related records and documented photos for current disease state and providing the appropriate physician feedback [13].

Laboratory medicine has encountered significant advances in the last few years [14]. Yet, the need for simple, inexpensive diagnostic solutions is still warranted. The application of smartphones in laboratory medicine aims to establish diagnostic facilities that can be easily used in rural and resource-limited settings. Typically, this will facilitate prompt diagnosis of diseases and allow timely treatment. There are a few reviews, which discussed the use of cellphones in medical diagnosis. For example, Gurol-Urganci and colleagues [15] reviewed the use of cellphone messaging for exchanging results of medical investigations, while Moore [16] discussed the use of cellphone-connected biological sensors in monitoring blood glucose level. Another review [17] identified and evaluated available smartphone applications for the use in radiology. This paper reviews studies, which utilized smartphones and smartphone-based technologies in different aspects of laboratory medicine and disease diagnosis. These include the use of smartphones in data generation, liberation, processing, and interpretation (Table 1).

Table 1
Studies exploiting cellphones for laboratory associated data generation.

Device	Technology	Use	Comments	Reference
Sony Ericsson i790	– 3.2 MP camera – Cellphone application	– ELISA detection of HE4 for ovarian cancer diagnosis	– Sensitivity 89.5% – Specificity 90%	[19]
– iPhone 4G – Sony Ericsson i790 – Blackberry Bold 9650 smartphone	– 5 MP camera – 3.2 MP camera – 5 MP camera	– ELISA detection of PSA for diagnosis of prostate cancer	– Detection limit 3.2 ng/mL	[20]
Sony-Ericsson U10i Aino™	– 8 MP camera	– Immunologic detection of *E. coli*	– Detection limit 5–10 cfu/mL	[21]
iPhone 4G	– 5 MP camera – iPhone app	– Immunologic detection of TSH concentration – Diagnosis of hypo- and hyperthyroidism	– Detection limit 0.31 mIU/L	[22]
iPhone	– Camera – iPhone app	– Immunologic detection of vitamin D	– Accuracy better than 15 nM – Precision 10 nM	[24]
Google Glass	– Camera	– Immunologic detection of HIV – Immunologic detection of PSA	– Qualitative and quantitative	[25]
iPhone	– Camera – iPhone app	– Detection of blood cholesterol level	–	[27]
Samsung Galaxy S II	– 8 MP camera – Android app	– Quantification of albumin in urine	– Detection limit 5–10 μg/mL	[28]
Samsung Galaxy S II	– 8 MP camera – Android app	– Detection of mercury in water	– Limit of detection ~3.5 ppb	[29]
iPhone 2G	– 2 MP camera	– Light microscope – Imaging peripheral blood smears of iron deficiency anemia and sickle cell anemia patients	– Up to 350× magnification	[30]
iPhone 4S	– 5 MP camera	– Light microscope – Image soil associated helminthes and their eggs	– Sensitivity ~70% for eggs – Poor species identification	[31]
Nokia N73	– 3.2 MP camera	– Bright-field and fluorescence microscope – Image peripheral blood smears of sickle cell anemia and malaria patients – Image fluorescently labeled TB	– Automatic counting of TB bacilli using ImageJ	[32]
Sony-Ericsson U10i Aino™	– 8 MP camera	– Fluorescence and dark-field microscope – Image white blood cells and *G. lamblia* cysts	– Resolution up to 10 μm	[33]
Smartphone	– Camera	– Fluorescent imaging of single nanoparticles and viruses	– Particles down to 100 nm can be detected	[34]
Sony-Ericsson U10i Aino™	– 8 MP camera	– Fluorescent flow cytometer – Count fluorescently labeled white blood cells	– Correlation coefficient with counts from hematology analyzer 0.93	[35]
Samsung Galaxy S II	– 8 MP camera – Smartphone app	– Fluorescent and bright-field blood analyzer – Count red and white blood cells – Calculate hemoglobin density	– Deliver results in 10 s for each image	[36]
LG 5200	– Cellphone battery – Cellphone application	– GlucoPack™, glucose meter – Monitor blood glucose level in diabetic patients	– Sends results to web server with secure access for patients and their physicians	[37,39]
Smartphone	– Capacitive touchscreen sensors	– Blood test for blood clotting agents	– Patent filed – Priority date: Dec 9, 2010	[40]
Windows Mobile 5 Smartphone	– Bluetooth connection – Smartphone apps	– Real-time display of ECG plot – Classification of ECG signals – ECG summary report – Diagnosis of four different arrhythmic beats	– Pop-up alarm with diagnostic arrhythmic beats	[41]
Android smartphones and tablets	– Bluetooth connection – Smartphone app	– Real-time EEG neuroimaging	– EEG sensor susceptible to environmental noise	[42]
– iPhone 5 – iPod Touch 4	– iPhone or iPod audio output – Smartphone app	– Pulse oximeter – Measure arterial oxygen saturation – Monitoring of infectious diseases e.g. pneumonia – During anesthesia	– Root mean square deviation <1% (ISO standard <4%)	[43]
Samsung Galaxy S II (GT-I9100)	– Built-in inertial sensors – Smartphone apps	– Monitor motion activities of the elderly – Fall risk detection	– Self-administrable at home	[44]

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