Clinica Chimica Acta 462 (2016) 1–5

Contents lists available at ScienceDirect

Clinica Chimica Acta

journal homepage: www.elsevier.com/locate/clinchim

Smartphone monitoring of pneumatic tube system-induced sample hemolysis

Garrett R. Mullins [a,b,*], James H. Harrison [a,b,c], David E. Bruns [a,b]

[a] Division of Laboratory Medicine, University of Virginia School of Medicine, Health Sciences Center, Charlottesville, VA, United States
[b] Department of Pathology, University of Virginia School of Medicine, Health Sciences Center, Charlottesville, VA, United States
[c] Department of Public Health Sciences, University of Virginia School of Medicine, Health Sciences Center, Charlottesville, VA, United States

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 10 August 2016
Accepted 16 August 2016
Available online 20 August 2016

Keywords:
Pneumatic tube system, PTS
Hemolysis
Preanalytical variation
Smartphone
Lactate dehydrogenase, LD

ABSTRACT

Background: Pneumatic tube systems (PTSs) are convenient methods of patient sample transport in medical centers, but excessive acceleration force and time/distance traveled in the PTS have been correlated with increased blood-sample hemolysis. We investigated the utility of smartphones for monitoring of PTS-related variables.
Methods: Smartphones were sent through the PTS from several hospital locations. Each smartphone used 2 apps as data-loggers to record force of acceleration vs time. To relate the smartphone data to sample integrity, blood samples were collected from 5 volunteers, and hemolysis of the samples was analyzed after they were transported by hand or via 1 of 2 PTS routes. Increased sample hemolysis as measured by plasma lactate dehydrogenase (LD) was also related to the amount of transport in the PTS.
Results: The smartphones showed higher duration of forceful acceleration during transport through 1 of the 2 PTS routes, and the increased duration correlated with significant increases in hemolysis (H)-index and plasma LD. In addition, plasma LD showed a positive linear relationship with number of shock forces experienced during transport through the PTS.
Conclusions: Smartphones can monitor PTS variables that cause sample hemolysis. This provides an accessible method for investigating specific PTS routes in medical centers.

1. Introduction

Pneumatic tube systems (PTSs) are widely used for specimen transport in medical centers. They improve turn-around times [1] and provide an alternative to expensive satellite laboratories [2]. PTSs provide convenience, but preanalytical variation due to blood sample hemolysis has been related to excessive acceleration force and time/distance traveled in the systems [3–9]. In vitro hemolysis caused by PTS transport can lead to elevations in plasma potassium and lactate dehydrogenase (LD), among other preanalytical artifacts. As a result, it has been recommended that 3-axis acceleration (i.e. shock forces) experienced during transport be regularly monitored to ensure that transport is consistent with maintenance of sample integrity [6,8,10]. This is of particular importance when PTSs are adjusted or the PTS is modified as occurs during medical center renovations.

It is well known that blood samples can be centrifuged with a force >1100g for 10 min without showing significant hemolysis [11], which suggests it is not acceleration force alone, but rather rapid and large acceleration changes, or shock forces, that cause hemolysis during PTS transport [8]. Here we describe an approach to evaluate the 3-axis acceleration and "dose" of PTS transport by use of smartphones and data-logger apps that utilize smartphone accelerometers and chronometers [12]. We also investigate the ability of this approach to relate sample hemolysis, as indicated by the hemolysis (H)-index and lactate dehydrogenase (LD), to the sum of shock forces during real-world use of a medical center PTS.

2. Materials and methods

2.1. Description of the PTS

Pneumatic tube system transport was done through a Swisslog Healthcare Solutions TransLogic® PTS using EcoSeal® side-opening carriers (6-inch) and Standard Recessed Stations.

2.2. Volunteers

Healthy volunteers (n = 5) were recruited to donate blood for each experiment involving the transport and measurement of blood samples. Samples were drawn either in triplicate (for example, Fig. 5b and c) or in sextuplicate (e.g., Fig. 6) from each volunteer by venipuncture using BD

Abbreviations: PTS, pneumatic tube system; H-Index, Hemolysis Index.

* Corresponding author at: Department of Pathology, PO Box 800168, University of Virginia School of Medicine, Charlottesville, VA 22908, United States.
E-mail address: grm9yd@virginia.edu (G.R. Mullins).

http://dx.doi.org/10.1016/j.cca.2016.08.011
0009-8981/

Vacutainer® Push Button Blood Collection Set 21G into lithium heparin-containing tubes (BD Vacutainer® Plasma Separator Tubes) for analysis. All blood samples were drawn by a team of phlebotomists, with each volunteer's replicate samples drawn by the same individual. All tubes were filled to capacity before transport and analysis.

2.3. H-index and LD

For assessments of blood sample hemolysis and plasma LD activity, replicate samples were transported from patient-care centers to the testing facility by human courier (hand-delivered) or via one of 2 PTS routes. Samples were concurrently centrifuged (Druker Diagnostics, Horizon; 1200 $\times g$ for 10 min), then measured on the Abbott Architect *c* 16,000 clinical chemistry analyzer which provided a spectrophotometric index of hemolysis (H-index) and kinetic measurement of lactate dehydrogenase with lactate as substrate and readings at 340 nm.

2.4. Smartphones and apps

Three-axis acceleration (g) was measured at a rate of 30 Hz using 2 smartphones (both iPhone 5) and 2 different data logger apps (Sensor Kinetics Pro and VibSensor) during sample transport by human courier (hand-delivered) or 1of 2 PTS routes. Smartphones were wrapped in bubble wrap, placed in a PTS carrier, and sent through the PTS immediately after collection of iPhone data was initiated (Fig. 1a). Both smartphones were included in the PTS carrier with blood samples during the analysis of "dose" of transport (Fig. 6). To produce an audiovisual recording and capture still images of blood samples while traveling through the PTS, one smartphone was used to illuminate the sample in a carrier and a second smartphone was secured in place to record (Fig. 1b). All photographs were taken via smartphone (iPhone 5).

2.5. Data and statistical analysis

Data collected by smartphones were sent to a personal computer via email for analysis in Excel and/or GraphPad Prism software programs. H-index and plasma LD activity data were analyzed for statistical significance by one-way analysis of variance using Tukey's multiple comparisons test with human courier (hand-delivered) samples set as the control group. Data are expressed as mean $\pm$ SEM.

3. Results

3.1. Data from 2 smartphones and 2 apps correspond

As a means of evaluating the legitimacy of using smartphones and data logging apps for monitoring 3-axis acceleration and time spent under stress in the PTS, we tested 2 phones (both iPhone 5) and 2 apps (Sensor Kinetics Pro and VibSensor). The data obtained from the 2 phones and from the 2 apps agreed in both the magnitude of shock forces and temporal pattern while traversing through the same PTS route on multiple occasions (Fig. 2). In addition, the magnitude of force, at least 8g, was similar to previous reports where data was collected using specialized data loggers [8].

3.2. Smartphone monitoring of different PTS routes shows different temporal patterns and number of shock forces

To investigate a PTS route suspected of inducing sample hemolysis (defined here as Route 2) we used this smartphone method to assess the difference between 2 routes. Route 2 showed a longer temporal pattern (Fig. 3) and significantly more shock forces during transit ($p = 0.0006$) (Fig. 4). We also measured the 3-axis acceleration experienced when hand-delivering samples to the testing facility, which showed no shock forces exceeding 2g (Fig. 3).

3.3. Transport through the PTS route with more shock forces causes hemolysis and higher plasma LD

As longer time/distance traveled in a PTS has been related to increased sample hemolysis [3], we investigated whether sample transport through the tested PTS routes showed a difference in sample integrity. Upon visual inspection of replicate samples after transport and centrifugation, Route 2 showed evidence of hemolysis (Fig. 5a).

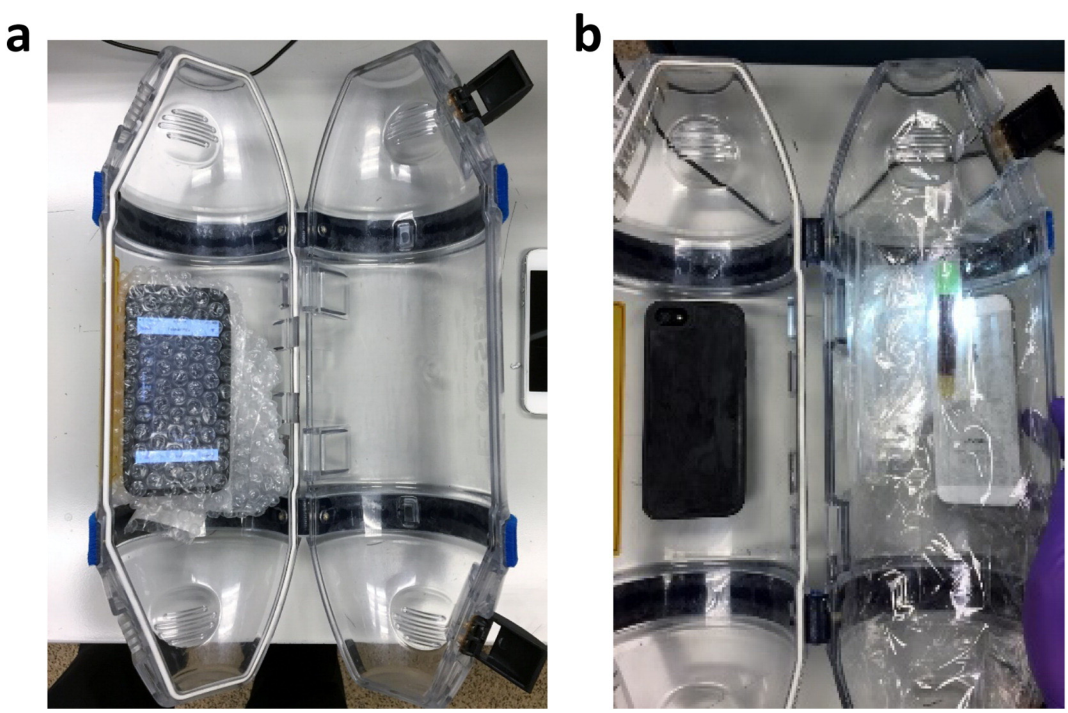

Fig. 1. (a) A photograph showing a smartphone (iPhone 5) wrapped in bubble wrap and placed in a PTS carrier just before being sent through the PTS to assess 3-axis acceleration. (b) A photograph showing the placement of smartphones and blood sample to capture images of a blood sample traveling through the PTS.