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Demonstrating the accuracy of an in-hospital ambulatory patient monitoring solution in measuring respiratory rate*

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Abstract— **This paper presents clinical testing conducted to evaluate the accuracy of Aingeal, a wireless in-hospital patient monitor, in measuring respiration rate via impedance pneumography. Healthy volunteers were invited to simultaneously wear a CE Marked Aingeal vital signs monitor and a capnograph, the current gold standard in respiration rate measurement. During the test, participants were asked to undergo a series of defined breathing protocols which included normal breathing, paced breathing between 8-23 breaths per minute (bpm) and a recovery period following moderate exercise. Statistical analysis of the data collected shows a mean difference of -0.73, a standard deviation of 1.61, limits of agreement of -3.88 and +2.42 bpm and a P-value of 0.22. This testing demonstrates comparable performance of the Aingeal device in measuring respiration rate with a well-accepted and widely used alternative method.**

I. Introduction

During the last century our understanding of human physiology and pathology has enabled many infectious diseases such as Small Pox, Leprosy or Polio, to be either completely eradicated or near eliminated from the list of challenges facing our populations. Coupled with rapid advancements in healthcare technology and delivery, global life expectancy has risen from 31 years in 1900 to 65.6 years in 2005, reaching over 80 in some countries. It is expected that by 2030, average life expectancy will be 85 years for females born at this time in countries such as the USA [1]. This shift in global trends brings with it new challenges that must be addressed. Rather than dying from disease, we are living with disease, and living longer. An aging population means healthcare must be adapted in order to meet changing needs. New approaches to healthier lifestyles, education on the consequences of smoking, alcohol abuse, poor diet and inactivity, and proactively managing wellness as opposed to illness can all help in the fight against chronic conditions such as Congestive Heart Failure (CHF), Chronic obstructive pulmonary disease (COPD) and Diabetes. Getting the message across is one of our new challenges. Delivering appropriate, effective and efficient care to patients currently with, or at risk of developing such diseases, is another.

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Part of this solution is presented by providing appropriate vital signs monitoring that is accepted by the patients being monitored, their families and the wider team of healthcare professionals providing patient care. In recent years the concept of wearable wireless monitoring solutions has undergone significant development with a wide range of solutions available for use in triage situations, the hospital environment, in the home and as patients go about their daily lives and normal routines [2-8].

II. In-Hospital Vital Signs Monitoring

It is well documented that patients exhibit changes in key vital signs ahead of experiencing clinical deterioration in the hospital ward environment [9]. Currently, focus is placed on intermittent manual measurement of vital signs that include pulse rate, respiration rate, blood pressure, blood oxygen levels, core temperature, responsiveness and urine output. These measurements are usually taken every 4 hours, with the frequency determined by the patient's current health status. If the information collected suggests that the patient is at risk of deterioration, or is deteriorating, defined pathways are followed until the patient has regained stability. The emphasis on using an approach such as this is to establish an Early Warning System (EWS) to help clinicians identify patients at risk and administer appropriate care [10]. The effectiveness of this approach is subject to much debate, with different versions of scoring scales used within and between facilities [11]. Limitations of the current process and remaining challenges are well reviewed by [12].

Providing clinicians with the tools to help automate the data collection process can provide more detailed trending information, can highlight specifically when predefined heart-rate or respiration-rate thresholds are exceeded, and when a key cardiac arrhythmia is detected. Appropriately processing and displaying the information via an intuitive central station can allow clinicians to see current health status of patients in the ward at a glance. Smart alarming and smart prioritising can allow clinicians to easily identify patients that require attention. This can ensure that the deteriorating patient is not overlooked if significant physiological changes occur within the traditional 4 hour intervals. This approach can also relieve nursing staff of collection of some vital signs information, reducing workload and associated stress, and reducing the impact of human error.

With a system such as this in place, the proportion of avoidable sentinel events may be significantly reduced, providing healthcare facilities with the potential to improve patient outcomes and safety and reduce costs. Data can also be easily integrated with existing electronic care records (ECR) to provide the clinician with a complete picture of the

patient's background medical history and current and previous hospital stays.

The importance of measuring respiration rate as an indicator of patient stability in the clinical setting is well understood. Despite this, evidence suggests that it remains one of the most under measured and incorrectly measured vital signs [13]. Manual measurement of respiration rate can be challenging when the working environment of the ward setting is considered alongside the time taken to accurately measure the parameter.

Providing a continuous reliable method of non-invasively measuring respiration rate that is acceptable to both patients and clinicians is discussed. Clinical testing undertaken to demonstrate the accuracy of a CE Marked and FDA cleared wireless vital signs monitoring solution in measuring respiratory rate is presented. Healthy volunteers were invited to take part in testing, where physiological data would be recorded simultaneously using the Aingeal device (designed and manufactured by Intelesens Ltd., Belfast, Northern Ireland) and a capnograph over a variety of breathing cycles.

III. The Aingeal solution

The Aingeal device has been designed to offer clinicians an affordable, miniaturised, body worn, wireless solution that can be used to provide a surveillance safety net for traditionally unmonitored hospitalised patients. The system measures heart rate, respiration rate, motion and skin surface temperature, providing trending information as well as alerts to a central station should any of the physiological values measured move outside of predefined limits. These limits can be defined on a per-patient basis. Arrhythmia detection algorithms also alert medical staff to the possibility of lethal cardiac arrhythmias being present, allowing clinicians to intervene sooner, and potentially resulting in fewer avoidable sentinel events. Arrhythmias detected include bradycardia, tachycardia, ventricular fibrillation and asystole [14].

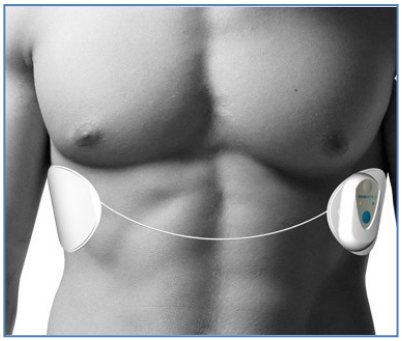

Figure 1. Aingeal device and location worn on the body

The Aingeal device derives respiration rate by measuring changes in impedance via patch-based electrodes applied to either side of the chest. The electrodes also measure electrocardiogram (ECG) signals from which heart rate is derived. A thermistor built into the electrode patch measures skin temperature. Physiological information measured by the device is recorded and communicated to a central station for review by medical staff via the hospital's existing WiFi infrastructure.

IV. Validating respiratory rate measurement

A. Overview of Testing

The investigation was designed to facilitate a comparison between respiration rate data measured using Aingeal and that measured using a Nellcor OxiMax™ N-85™ capnograph. Capnography was chosen as the comparative method as this is the current gold standard in respiration monitoring. A plastic cannula connected to the capnograph is worn over the nose and mouth. The amount of carbon dioxide in inhaled and exhaled air is quantified and respiration rate is derived.

Written informed consent was obtained from volunteers that agreed to take part. Screening ensured all volunteers met predefined inclusion and exclusion criteria. Demographic information relating to age, gender, height, weight, and BMI were recorded along with information relating to current medication and medical history, demonstrating that they were in good health at the time of testing.

An Aingeal patch electrode was applied to the volunteer and a live streaming version of the Aingeal device connected. A nasal/oral cannula connected to the capnograph was applied. The Aingeal device sent physiological information via a WiFi link to a PC for logging. The capnography data was logged to a PC via a wired Communications Adapter Kit specific to the device.

During testing physiological data were recorded simultaneously using both devices over a variety of breathing cycles. A clinician was in attendance throughout, and was asked to manually count respiration rates using a stethoscope over a duration of 60 seconds (s) at specific times during the test. The clinician was blinded to the visual aid used to help volunteers control their breathing rate (EZ-Air Plus developed by Biofeedback Federation Europe).

Once the test started, volunteers were asked to relax and breathe normally while data logging from both devices was initiated. After 2 minutes of normal breathing, the volunteer was asked to follow an on-screen visual aid to help control their breathing rate. This ranged from 8 breaths per minute (bpm) to 23 bpm over a 9 minute period. Following a break volunteers were asked to undergo a period of exercise using an exercise bike. When heart and breathing rates were suitably high, the volunteer was asked to return to their seat while they recovered. Once respiration or heart rates had returned to normal, or after 3 minutes of recovery time, the test was ended. During normal breathing and each paced breathing cycle a clinician measured respiration manually using a stethoscope.

At the end of the test all raw data files were checked to verify that the file name corresponded to the volunteer ID assigned to the volunteer. Data was then provided to an independent statistical analysis Company (Exploristics Ltd.) for analysis using SAS version 9.2.

B. Data Preparation

The Aingeal device samples at a rate of 120 /s and the capnograph stores values once every 5 s. As a result, there were many more measurements from the Aingeal device compared to the capnograph over the same observation period. Both methods of measurement stored a time stamp

for each sample taken. This allowed respiration rate data from both measurements to be aligned for comparison according to the time since the start of the observation period, as rounded to the nearest second. Measurements from the Aingeal device that did not align to the capnograph measurements were ignored for the purpose of the comparison between the two methods.

C. Comparison between measurement methods

As there were repeated measurements for each subject over each breathing cycle and over the entire observation period, the mean difference and variance in between two measurement methods was estimated using a random effects model. A model with the observed difference as the endpoint and participant as a random effect was fit to the data for all breathing activity cycles (except the exercise cycle). The estimated values for the intercept and variance then gave global estimates of the difference and variability of the difference over all observations and cycles and for each cycle. A similar model was fit to the absolute measurements for each method to give global estimates of the absolute counts.

The counts from each method were compared in a pair-wise manner using the approach of Bland & Altman [15]. This involved plotting the difference in count against the mean of the two absolute counts. The 95% limits of agreement, equivalent to 1.96 times standard deviation were plotted. The standard deviation was calculated based on both the total variance and the between-subject variance. The impact of increasing count on the bias and variability of the differences was assessed. The impact of the breathing cycle on that comparison between Aingeal and the capnograph was also assessed by including the breathing cycle at a categorical variable in the repeated measures model.

V. RESULTS AND DISCUSSION

A. Participants

Data was recorded from 19 healthy volunteers (10 male and 9 female) aged between 21 and 61 years (with a median age of 37 years). 4119 data points were used to facilitate a comparison between respiration rates measured using Aingeal and those measured using the capnograph. No adverse events took place during the course of the study or afterwards as a result of the study.

TABLE I. SUMMARY OF STATISTICS FOR VOLUNTEERS

Statistic	Demographic Information			
	Age	*Height (m)*	*Weight (kg)*	*BMI*
Mean	37.6	1.76	76.6	24.7
SD	NA	0.10	13.7	3.87
Max	61	1.97	109.4	32.1
Median	37	1.75	76.2	23.9
Min	21	1.60	55.1	18.2

B. Accuracy of the Aingeal device at measuring respiration

Table 2 shows the summary statistics for each breathing cycle undertaken during testing to include: Mean Respiratory Rate for capnograph and Aingeal; Difference between the two measurements; standard deviation (SD) of the difference; and the upper and lower limits of agreement (+/- 1.96SD). The table also shows the P-value from an analysis of variance to evaluate the impact of breathing cycle which covers the variation in breathing over the low, normal and high respiration cycles recorded.

TABLE II. STATISTICAL ANALYSIS SUMMARY

Breath-ing Cycle	Statistical Analysis						
	Mean Diff	*SD*	*Upper 95% Limit*	*Lower 95% Limit*	*Mean Ang. RR*	*Mean Cap. RR*	*P-value*
Start	-0.73	1.9	2.96	-4.42	13.40	14.10	.
PB=8	-0.14	2.0	3.81	-4.09	9.82	9.97	.
PB=11	0.67	1.0	2.72	-1.38	10.60	9.92	.
PB=14	0.11	1.0	2,14	-1.92	13.20	13.10	.
PB=17	0.15	0.8	1.70	-1.40	16.30	16.20	.
PB=20	0.25	1.6	3.38	-2.88	19.50	19.30	.
PB=23	-0.19	1.4	2.63	-3.01	22.10	22.30	.
Recov	-0.01	2.0	3.81	-3.83	16.80	16.80	.
All	-0.73	1.6	2.42	-3.88	13.40	14.10	0.22

In general, there is very good agreement between the respiratory rate measured by the Aingeal system and the capnograph over the range of rates observed in the study. On average, the differences are less than 1 breath per minute. The limits of agreement (95% Upper and Lower limits) confirms that over the entire test, the Aingeal system measured respiration to within +2.42 and -3.88 breaths per minute in comparison with the capnograph.

The P-value was not significant, indicating that there is no evidence that the breathing cycle has any impact on the comparison between Aingeal and the capnograph.

The mean difference remains fairly constant over all breathing rates except for the fast paced breathing.

The plots in Fig. 2-5 show the graphical representations of the Bland-Altman analysis conducted for the whole test and for each section of the test for all volunteers. It can be seen that variability exists between volunteers during the test, particularly during the paced breathing phase. This phase was undertaken using a visual aid to help volunteers breathe at consistent rates for a period of time. It was recorded in test notes and in volunteer feedback that some volunteers had difficulty breathing in time with the visual aid, particularly during lower and higher breathing rates. This may explain why the differences between Aingeal and capnograph respiration rates are smaller within the mid-range of paced breathing. The best comparison between the two devices is therefore during the normal breathing phase undertaken at the beginning of the test, and during the mid-range breathing rates during the paced breathing phase. This could be because of the more natural relaxed breathing undertaken by volunteers during these times.

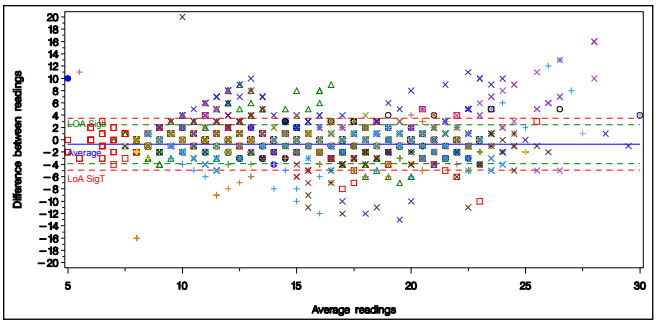

Figure 2. Bland Altman Plot for All Cycles

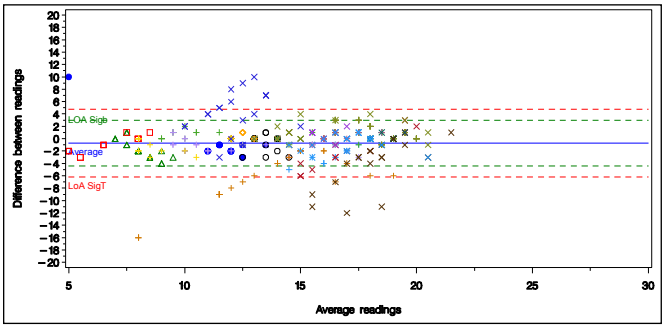

Figure 3. Bland Altman Plot for Start

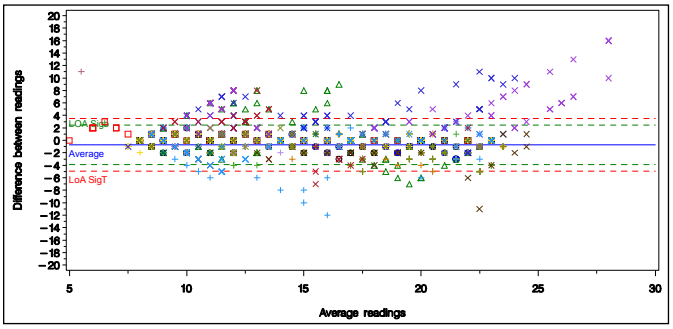

Figure 4. Bland Altman Plot for All Paced Cycles

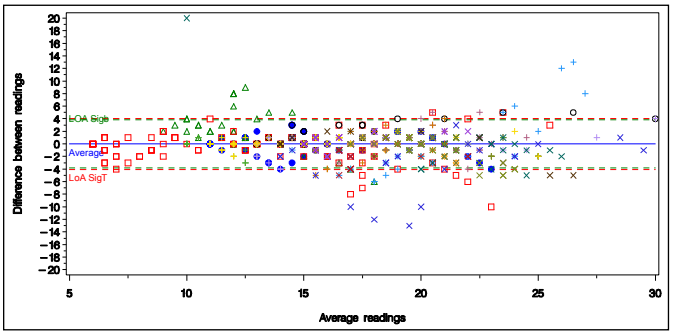

Figure 5. Bland Altman Plot for Recovery

As can be seen from the plots, 95% of all differences are typically within +/- 4 breaths, i.e. the Limits of Agreement. On average, differences are less than 1 breath per minute. The breathing cycles had no significant effect on the difference; however, it was observed that the differences tended to be higher under normal breathing, and for fast or slow breathing. The difference between the two measurements is smallest in the middle range of paced breathing cycles.

Outlying data points are to be investigated further using raw waveform data to analyse the root cause of the error. By definition, approximately 5% of all data points shall lie outside of the limits of agreement. However, in some instances the outliers are noted to be more the 3 standard deviations outside of the accepted limits of agreement. These instances will be explored in more detail in order to further improve the accuracy of the device.

Fig. 6 shows an example of all data recorded during the test for one of the volunteers. This shows the beginning of the test as the volunteer relaxes, the beginning of paced breathing, the period of exercise and the following period of recovery. Respiration rates measured manually by the clinician are represented by green points at the start and at each paced breathing interval. Instances where high or low alarm conditions were met are indicated by the line at the bottom of the graph.

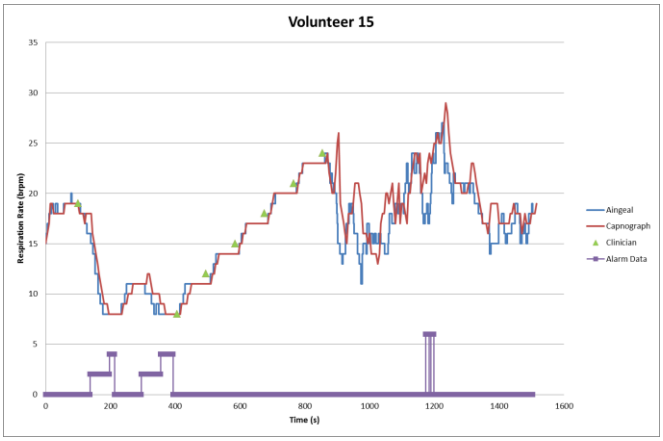

Figure 6. Direct comparison plot between Aingeal, canograph and clinician respiration rate measurements for V15.

C. *False Positive Rate*

Ensuring a low rate of false positive alarms is key to building confidence and acceptance of the technology among clinical staff. For this reason, the number and type of respiration-based alarms generated by the Aingeal device during testing were determined and assessed for validity.

The Aingeal device had been set up to alarm if respiration rates fell below 10 bpm or if they rose above 25 bpm. Sustained low and high respiration alarms were raised if the respiration rates remained consistently outside of the thresholds for 60 s or more. Each alert generated was evaluated in line with the respiration rate measured by Aingeal, the corresponding data recorded by the capnograph and any comments made by researchers during the individual test as appropriate. The data collected during the volunteer test indicated that with regard to respiration thresholds being breached, Aingeal has a false positive alarm rate (FPR) of 10 false alarms per patient per day. This figure has been calculated based on 3 false alarms generated in 7 ¼ hours of data, while 19 volunteers undertook different breathing cycles, and making the assumption that a patient will be monitored for 24 hours. Further investigation into how the respiration detection algorithm performed during the portions of the test when the alarms were generated

highlighted opportunities where algorithm improvements could be implemented. Once the changes were verified, the dataset was rerun using the updated algorithm, providing a revised FPR of 0. The output of the revised algorithm within the intended clinical environment will provide further confidence that the device performs acceptably.

D. User Acceptance

Volunteers were asked to complete a follow-up questionnaire in order to provide information on the acceptability of the Aingeal device and the capnograph device. Fig. 7 shows the average level of acceptance reported by volunteers in relation to the following areas:

- Comfort of Aingeal electrode / capnograph cannula
- Comfort of Aingeal electrode removal
- Discreteness of Aingeal / capnograph
- Preference of wearing Aingeal / capnograph while in hospital

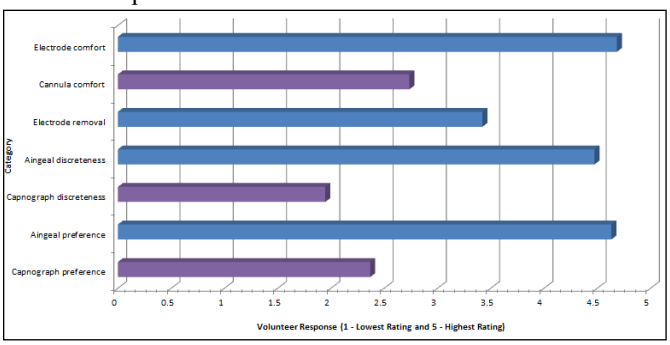

Figure 7. Feedback received from volunteers who took part in testing

The questionnaire was not designed to facilitate a direct comparison between the Aingeal and capnograph devices, but to gather information relating to the acceptance of each device individually. The feedback received indicates that most volunteers would be happy to wear the Aingeal device while staying in hospital and that there is a high level of acceptance of the system, with minimal discomfort experienced during removal of electrodes. There was less satisfaction recorded in relation to acceptance of the capnograph monitor, with volunteers less inclined to want to wear the monitor during a hospital stay.

Although a useful tool for gauging user feedback, this data should be considered in light of users wearing both devices for approximately only 30 minutes. This can therefore provide a high level indication of acceptance. Data collected from intended patient populations wearing the device in its intended environment would provide information on which stronger conclusions could be made.

VI. Conclusion

The statistical analysis of the comparative data collected during volunteer testing has shown very good agreement between the Aingeal device and the capnograph in measuring respiration rate. How the Aingeal and capnography devices measure respiratory rate must also be considered in that differing methods of measurement will of course result in different outputs. What this initial work has shown however, is that the output of the Aingeal device in measuring respiration is comparable to a well-accepted method of measuring respiration rate. Using the device in its intended clinical setting will provide information that can facilitate evaluation of acceptable clinical performance and acceptance by patient and clinician users. Further work is currently underway with a larger number of patients receiving care in a general ward environment, in a respiratory ward and in a post-surgical orthopedic setting.

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References

[1] World Health Organisation, "Health, History and Hard Challenges: Funding Dilemmas in a Fast-Changing World." *World Health Organisation Website*: http://www.who.int/global_health_histories/seminars/presentation07.pdf; August 2006 [Accessed 23/01/2013]

[2] T. Gao,. et al. "Vital signs monitoring and patient tracking over a wireless network." *Johns Hopkins APL Technical Digest* 2006: 27(1); 66-74

[3] P. Insom, "Implementation of a human vital monitoring system using Ad Hoc wireless network for smart healthcare." *Biomedical Engineering International Conference 2011* 2012: 76-81

[4] A. A. Soomro, "System and method for highly reliable delivery of life-critical alarms through shared wireless channels." *U.S. Patent 20130015966*, March 03, 2011

[5] P. Pawar, et al. "A framework for the comparison of mobile patient monitoring systems." *Journal of Biomedical Informatics* 2012: 45(3); 544–556

[6] N. Wickramasinghe, et al. "The Benefits of Wireless Enabled Applications to Facilitate Superior Healthcare Delivery: The Case of DiaMonD." *E-Health and Medical Communications* 2012: 3(4);

[7] J.S. Choi and D. Kim, "Design and Implementation of Wireless Patient Monitoring System for Postoperative Patients on General Care Floor." *Informatics for Health and Social Care*,2012: 37(3); 141-158

[8] G. D. Clifford and D. Clifton, "Wireless Technology in Disease Management and Medicine." *Annual Review of Medicine* 2012: 63; 479-492

[9] Kause J, Smith G, Prytherch D, Parr M, Flabouris A, Hillman K, Intensive Care Society (UK), Australian and New Zealand Intensive Care Society Clinical Trials Group: A comparison of antecedents to cardiac arrests, deaths and emergency intensive care admissions in Australia and New Zealand, and the United Kingdom—the ACADEMIA study. *Resuscitation* 2004; 62:275– 82

[10] Prytherch DR, Smith, GB, Schmidta PE, Featherstone PI. ViEWS – Towards a national early warning score for detecting adult inpatient deterioration. *Resuscitation* 2010:81; 932–937

[11] Smith GB, Prytherch DR, Schmidt PE, Featherstone PI. A review, and performance evaluation, of aggregate weighted "track and trigger" systems. *Resuscitation* 2008;77:170–9.

[12] Taenzer AH, Pyke JB, McGrath SP. A review of current and emerging approaches to address failureto-rescue. *Anesthesiology*. 2011 Aug; 115(2):421-31.

[13] Parkes R. Rate of respiration: the forgotten vital sign. *Emerg Nurse* 2011;19(2):12-7.

[14] Donnelly N, et al. "Development of a ubiquitous clinical monitoring solution to improve patient safety and outcomes" *Conf Proc IEEE EMBS 2012*; 2012: 6068-6073.

[15] Bland JM, Altman DG. "Statistical methods for assessing agreement between two methods of clinical measurement." *Lancet*, 1986; i; 307-310