

A model-based cost-utility analysis of an automated notification system for deteriorating patients on general wards

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1 Title

- 2 A model-based cost-utility analysis of an automated notification system for deteriorating patients on
- 3 general wards
- 4 Short title: Economic evaluation of an automated notification system for deteriorating patients on
- 5 general wards
- 6
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23 Abstract

24 Background

25 Delayed response to clinical deterioration of hospital inpatients is common. Deployment of an 26 electronic automated advisory vital signs monitoring and notification system to signal clinical 27 deterioration is associated with significant improvements in clinical outcomes but there is no evidence 28 on the cost-effectiveness compared with routine monitoring, in the National Health Service (NHS) in 29 the United Kingdom (UK).

30

31 Methods

A decision analytic model was developed to estimate the cost-effectiveness of an electronic automated advisory notification system versus standard care, in adults admitted to a district general hospital. Analyses considered: (1) the cost-effectiveness of the technology based on secondary analysis of patient level data of 3787 inpatients in a before-and-after study; and (2) the cost-utility (cost per qualityadjusted life-year (QALY)) over a lifetime horizon, extrapolated using published data. Analysis was conducted from the perspective of the NHS. Uncertainty in the model was assessed using a range of sensitivity analyses.

39

40 **Results**

The study population had a mean age of 68 years, 48% male, with a median inpatient stay of 6 days.
Expected life expectancy at discharge was assumed to be 17.74 years.

(1) Cost-effectiveness analysis: The automated notification system was more effective (-0.027 reduction
in mean events per patient) and provided a cost saving of -£12.17 (-182.07 to 154.80) per patient
admission.

46 (2) Cost-utility analysis: Over a lifetime horizon the automated notification system was dominant, demonstrating a positive incremental QALY gain (0.0287 QALYs, equivalent to ~10 days of perfect 47 health) and a cost saving of £55.35. At a threshold of £20,000 per QALY, the probability of automated 48 monitoring being cost-effective in the NHS was 81%. Increased use of cableless sensors may reduce 49 50 cost-savings, however, the intervention remains cost-effective at 100% usage (ICER: £3,107/QALY). 51 Stratified cost-effectiveness analysis by age, National Early Warning Score (NEWS) on admission, and 52 primary diagnosis indicated the automated notification system was cost-effective for most strategies 53 and that use representative of the patient population studied was the most cost-saving strategy.

54

55 **Conclusion**

Automated notification system for adult patients admitted to general wards appears to be a cost-effective
use in the NHS; adopting this technology could be good use of scarce resources with significance for
patient safety.

59

60 Keywords

economic evaluation, cost-effectiveness, cost-utility, patient deterioration, rapid response teams, acute
care teams, early warning score, automated monitoring, patient safety, vital signs.

63 Introduction

64

65 Clinical Background

66 Deterioration of patients on general hospital wards often goes unnoticed for prolonged periods of 67 time(1). This delay can result in otherwise preventable cardiopulmonary arrest and admission to the 68 intensive care unit (ICU)(2,3) even though, in most cases, measurable changes in vital signs (4) could 69 identify patients at risk. Such delayed or absent response to deterioration has been labelled as "failure 70 to rescue" (5). To decrease the incidence and consequences of such failure to rescue, many hospitals 71 have introduced rapid response systems (RRSs) (6) consisting of an afferent limb based on monitoring 72 of vital signs that triggers activation of the efferent limb, individuals or teams with training in the 73 management of critical illness. Even in hospitals with an established RRS, failure-to-rescue events 74 occur (7–9), mostly related to problems with the afferent (monitoring, identification, and rapid response 75 team (RRT) activation) component of the RRS. All these failings have in common the dependence on individual bedside staff to raise the alarm. 76

77

In contrast to human-based response, industrial high-reliability systems rely on redundancy to ensure that failure of a single part does not result in system failure(10,11). When this approach is applied to monitoring in health care, systems with automated notification can be deployed to notify remote and senior healthcare professionals or RRTs who are not at the bedside to respond to deterioration(12,13). Deterioration can be defined as a National Early Warning Score (NEWS)¹ of 6 or more (14). A score of 6 leads to the activation of a practitioner with critical care skills. The notification aims to prevent further deterioration to a degree that results in the need for admission to Intensive Care, death, or cardio-

¹ The National Early Warning Score is a score that summarises abnormalities in vital signs such as blood pressure, heart rate, temperature through a point system ranging from zero (all parameters normal) to 20 (all parameters maximally abnormal).

pulmonary arrest. This approach can be supplemented with continuous monitoring of selected vital
signs such as heart rate, respiratory rate, and oxygen saturation.

87

A prospective before-and-after study, 'Vital Signs to Identify, Target, and Assess Level of Care Study' 88 89 (short VITAL II, ClinicalTrials.gov, NCT01692847) investigated the use of conventional vital sign monitoring enhanced by automated wearable monitoring devices, automated calculation of Early 90 Warning Scores based on vital signs, and automated notification of clinical teams triggered by pre-91 92 defined changes in vital signs in all patients admitted to two clinical areas in a district general hospital in the UK (2139 patients before (control) and 2263 after the intervention). VITAL II concluded that 93 94 deployment of automated monitoring, and notification system was associated with a reduction in 95 mortality (8 vs 6%, p=0.042), cardiac arrests (0.7% vs 0.09%, p=0.002) and improved mortality for 96 those admitted to Intensive Care (45% vs 24%, p=0.04)(15), however, there was no health economic² evidence to assess the cost-effectiveness of this intervention. 97

98

99 Aims & Objectives

We aimed to inform the cost-effective use of an automated system in the National Health Service (NHS)
in the United Kingdom (UK) by conducting a model-based economic evaluation, using evidence from
the VITAL II study.

103

104 Materials and methods

² Economic evaluation provides a framework in which to assess the costs and effects of alternative interventions, such as automated monitoring compared to standard care. For a comprehensive overview of concepts and methods, readers should refer to general texts, such as: Morris, Stephen, et al. Economic analysis in healthcare. John Wiley & Sons, 2012.

106 Economic Evaluation Overview

107 The study design was a model-based cost-effectiveness and cost-utility analysis using secondary data,
108 including retrospective analysis of the Vital II Research Database (RDB).

109 The short-term cost-effectiveness analysis (cost per event avoided) was restricted to the inpatient 110 episode, whilst the cost-utility analysis (cost per quality-adjusted life-year (QALY)) considered the 111 longer-term consequences of serious adverse events to extrapolate the findings to a lifetime horizon. 112 The QALY is a single index of both survival and health-related quality of life. The evaluation was 113 conducted from the perspective of the NHS.

114

115 A decision analytic model was developed to represent (1) use of an electronic automated advisory vital 116 signs monitoring and notification system to signal clinical deterioration; and (2) standard care use of 117 non-connected spot-check monitors, as is routine in the NHS (Fig 1). The model captures all events 118 during the inpatient stay based on data obtained from the Vital II study. Patients were admitted to the study wards following a short period of assessment and completion of admission documentation in the 119 120 Acute Medical Unit of the hospital in line with usual practice in the NHS. One of the wards specialised in Respiratory and one in Gastroenterological conditions but both wards took patients with other 121 conditions. Once on the ward, patients in the standard care pathway were monitored in line with hospital 122 policy, which stipulates the recording of vital signs in acutely unwell patients at least twice per day and 123 124 with increasing frequency in the presence of increasing severity of illness, usually four times per day. 125 Trained registered nurses and health care assistants obtained and recorded vital signs. Patients on the intervention pathway were monitored with an electronic automated advisory vital signs monitoring 126 system (IntelliVue Guardian Solution (IGS) including cableless sensors and MP5SC spot-check 127 128 monitors, Philips Healthcare, Boeblingen, Germany). Each spot-check monitor was used for a group of 6-8 co-located patients. During the inpatient episode 10 types of serious adverse events were collected 129 prospectively, and these were: acute myocardial infarction, pulmonary embolism, acute pulmonary 130 131 oedema, respiratory failure, stroke, severe sepsis, acute renal failure, emergency admission to the ICU,

cardiopulmonary arrest, death. At discharge the model estimates lifetime costs and quality adjusted lifeyears based on the principal serious event that occurred during the inpatient episode, or no event.

134

135 Fig 1. Diagram of economic model.

136

The model was parameterised using data from the VITAL II RDB (restricted to cases with complete NEWS score on admission n=3787/4402 (86%)), and purposive reviews of the literature to obtain longterm estimates of costs and outcomes, in line with standard methodology for populating economic models (16). Published economic evaluations were identified using UK National Institute for Health and Clinical Excellence (NICE) guidance and supplementary electronic searches of PubMed. Studies set in the UK, adopting a life-time horizon, reporting costs and QALYs for interventions/comparators that best reflected treating the condition/event in line with current practice, were selected.

144

145 The base-case model adopted a lifetime horizon to estimate the incremental cost per QALY gained, 146 which may be used to inform decisions concerning the cost effectiveness of the intervention compared 147 to standard care, in the UK. The analysis also reports costs per event avoided during the inpatient 148 episode.

149

150 Clinical parameters

151 Serious adverse events / Health utilities

Serious adverse events were obtained from the RDB. During the inpatient episode the model accounted for multiple events per patient. Health states at discharge were defined by the principal serious adverse event during inpatient episode. Where patients experienced multiple events the event with the worst health state was assumed at discharge. Each health state at discharge was assigned a Quality-AdjustedLife-Expectancy (QALE) that was obtained from a purposive search of the literature, adjusted for the age and sex of the model population (Table 1 and S1). The "no event" population were assigned a weighted average of chronic conditions reflecting admission to a gastroenterology ward (Crohn's Disease) or a respiratory ward (Chronic obstructive pulmonary disease (COPD) or Pneumonia).

160

161 **Resource Use**

During the inpatient episode resource use included length of stay on ward of admission (based on reason for admission and any subsequent serious adverse events), admission to ICU, use of monitoring equipment (the automated monitoring and notification system for the intervention arm, and nonconnected spot-check monitors in standard care). Post-discharge resource use was not available at a patient level and is captured within life-time costs (Table 1), calculated using secondary data [external to the VITAL II clinical study].

168

170 Table 1. Cost-utility model input parameters: principal event probabilities, lifetime costs and

171 quality-adjusted life years.

Parameter	Point Estimate	Distribution ¹	References
EVENT PROBABILITIES	Probability		
No Event_intervention	0.9451	Dirichlet-multinominal	
Event survive_intervention	0.0064	(3579, 24, 184)	[Footnote 2]
Inpatient mortality _intervention	0.0485		
No Event_control	0.9395	Dirichlet-multinominal	
Event survive_control	0.0106	(3558, 40, 189)	[Footnote 2]
Inpatient mortality_control	0.0499		
Non-fatal principal event intervention			•
Acute Myocardial Infarction	< 0.0000001		
Pulmonary Embolism	0.00006559	Dirichlet-multinominal	
Acute Pulmonary Oedema	0.00004368	(4.9231E-13, 0.0016,	
Respiratory Failure	0.00000000	0.0011,	[Footnote 2]
Severe Sepsis	0.00000001	3.6014E-13, 3.3553E-07,	
Emergency admission to ICU	0.99989071	24.3021, 1.9882E-07)	
Cardiopulmonary arrest	0.00000001		
Non-fatal principal event_ control			•
Acute Myocardial Infarction	0.0000007		
Pulmonary Embolism	0.00012726	Dirichlet-multinominal	
Acute Pulmonary Oedema	0.00002508		
Respiratory Failure	0.00000012	(2.9955E-06, 0.0051, 0.0010	[Footnote 2]
Severe Sepsis	0.19179070	4.9610E-06, 7.7047,	
Emergency admission to ICU	0.74615961	29.9749, 2.4865)	
Cardiopulmonary arrest	0.06189716		
INPATIENT COSTS	Inpatient Cost		
Inpatient episode cost	•	95% Central Range	
_control	2059.16	(1,957.03 to 2,174.21)	
Inpatient episode cost		95% Central Range	[Footnote 3]
_intervention	2046.99	(1,926.45 to 2,183.47)	
LIFETIME COSTS	Lifetime Cost		
Ward 1_Gastroenterology		Gamma	Bodger et al.
	£28,694	(25, 1147.75)	(2009)(20)
Ward 2_Respiratory		Gamma	NICE (2019),
	£10,555	(25, 422.19)	(2014)
		Gamma	NICE (2020a)
Acute Myocardial Infarction	£34,398	(25, 1375.91)	
		Gamma	Peek
Acute Pulmonary Oedema	£19,198	(25, 741.57)	(2010)(21)
		Gamma	Peek
Respiratory Failure	£19,198	(25, 767.92)	(2010)(21)
		Gamma	Soares
Severe Sepsis	£45,903	(25, 1836.14)	(2012)(22)
		Gamma	Peek
Emergency admission to ICU	£19,198	(25, 767.92)	(2010)(21)
		Gamma	Javanbakht
Cardiopulmonary arrest	£38,303	(25, 1532.14)	(2022)(23)
LIFETIME QALYS	QALE ⁴		
Healthy population (age, sex matched)	0.7722		McNamara
	9.7732	XT 1	(2023)(19)
ward I_Gastroenterology	7 40/25	Normal	Bodger et al.
Ward 2 Deering to a	/.4965	(7.50, 1.50)	(2009)(20)
ward 2_Kespiratory	7.00//		
	/.9806	(7.99, 1.00)	1

COPD			NICE
	4.8068		(2019)(24)
Pneumonia			NICE
	9.1604		(2014)(25)
		Normal	NICE
Acute Myocardial Infarction	6.0139	(6.01, 1.20)	(2020)(26)
		Normal	NICE
Pulmonary Embolism	6.9533	(6.95, 1.39)	(2020)(27)
		Normal	Peek
Acute Pulmonary Oedema	4.0633	(4.06, 0.81)	(2010)(21)
		Normal	Peek
Respiratory Failure	4.0633	(4.06, 0.81)	(2010)(21)
		Normal	Soares
Severe Sepsis	3.3345	(3.33, 0.67)	(2012)(22)
		Normal	Peek
Emergency admission to ICU	4.0663	(4.06, 0.81)	(2010)(21)
		Normal	Javanbakht
Cardiopulmonary arrest	3.0013	(3.00, 0.60)	(2022)(23)
RESOURCE USE	Resource Use		
Number of beds (n)	54	Fixed	
Mean length of stay (days)		Fixed	
_intervention	8.62		VIIAL II
Mean length of stay (days)		Fixed	PDP = 2787
_control	8.90		KDD II-3/8/
Cableless Sensor Use (rate)	0.123	Fixed	
Estimated product life (years)	5	Fixed	Assumption

172 Note. ¹Distribution used in probabilistic sensitivity analysis: Dirichlet-multinominal (n events of N=3787);

173 Gamma (alpha, beta), Normal (mean, standard deviation). ²Estimated using mlogit to adjust for baseline

174 differences in intervention group, age, sex, ward, base score on admission, on RDB (n=3787). ³Estimated using

175 GLM (with gamma family and log link) to adjust for baseline differences in intervention group, age sex, ward,

base score on admission, on RDB (n=3787) parameter uncertainty represented by 10,000 bootstrap replications.
 ⁴See S1 for worked example.

178 Unit costs

Unit costs associated with monitoring devices and inpatient stay were obtained from the manufacturer
and the NHS sources (Table 2). The cost of the intervention was calculated using information provided
by the manufacturer, and resource use observed in VITAL II. To calculate the mean cost of the
intervention per patient, the purchase price was annualised as follows:

183

184	Mean cost of technology per patient = $[(purchase price / product-life) + variable costs for 1-year]$
185	annual number of patients
186	Where: purchase price = fixed cost of IGS and MP5SC Monitors; variable costs = Health DOT wireless
187	sensors, mean length of stay is days from admission to discharge; and annual number of patients =

188 [(365/mean length of stay) * total number of beds with automated notification system enabled].

189 Assuming ward operates at 100% annual capacity and interest rate 0%.

190

191 Table 2. Unit costs of monitoring and inpatient stay.

Monitoring Device Costs (based on technology for two wards)		Cost
Intervention: IntelliVue Guardian Solution (IGS) with cableless sensors and MP5SC spot-check monitors (Philips Healthcare, Boeblingen, Germany)		(t)
Fixed costs: IGS + 12 MP5SC spot-check monitors		£77,448.61
Variable costs: Health DOT (cost per sensor)^		£107.50
Control: Cost of spot-check monitors used in routine care at district general hospital in UK		
Fixed cost: 12 Routine care spot-check monitors		£16,800
	Non-elective cost ^a	Cost per excess bed
Inpatient Costs		day ^b
Ward 1 (gastroenterology)*	£1,457	£259
Ward 2 (pulmonology)*	£1,641	£230
Acute Myocardial Infarction	£1,592	£264
Pulmonary Embolus	£1,525	£230
Acute Pulmonary Oedema	£1,543	£230
Respiratory Failure	£848	£230
Stroke	£3,609	£257
Severe Sepsis	£2,385	£239

Acute Renal Failure	£1,398	£239
ICU (bed day)	£1,620	n/a
Cardiopulmonary Arrest	£1,628	£264

^ The Vital II study (15) reported 12.3% of the intervention arm had at least one cableless sensor attached in the
intervention phase, these represent an additional variable cost to using IGS during this phase. In the current
analysis, Health DOT wireless sensors were substituted as an approximation of the costs for the cableless
sensors as the latter are no longer on the market. *Calculated as frequency weighted average of non-elective
activity (currency descriptions unavailable at district general hospital excluded prior to weighting); see S12-54
Tables for detailed activity codes / descriptions. a NHS Reference costs 2020/21. b NHS National Tariff
2020/21. See S56 Table for excess bed day trimpoints.

The unit cost of the non-connected spot-check monitors used in standard care are understood to be included within NHS activity costs (used to cost the inpatient stay), however, on the basis that IGS would displace the cost of the spot-check monitors, a unit cost for the monitors used in the control phase of the Vital II study, was included in the analysis.

204

NHS Reference Costs and the National Tariff (2020/21) were used to estimate the cost of hospital stay (NHS National Cost Collection database (2021)) (S12-45 Tables). A weighted average of total nonelective activity was calculated, for each episode. The NHS tariff was then used to obtain trim points and costs per excess bed day for non-elective activity (S56 Table). ICU and serious adverse event activity costs were added to ward costs to provide a cost from admission to discharge/death (Table 2).

210

Costs incurred during the inpatient stay were not discounted due to the time horizon of less than oneyear. Life-time costs and QALYs were discounted at a rate of 3.5% All costs were reported as UK

213 pounds, price year 2020/21 for NHS costs and most recent pricing for the intervention.

214

¹⁹⁹

216 Long-term costs

217 Life-time costs associated with each health state at discharge were obtained from a purposive review of published literature. As with QALE, the "no event" population were assigned a weighted average of 218 219 chronic conditions. Where the event health state was associated with a higher cost than "no event" the 220 cost of being in the event state was carried forward (all cases except pulmonary embolism). Lifetime 221 costs were inflated to 2020/21 using the NHS Cost Inflation Index (17,18) and scaled to reflect life-222 expectancy of the model population (17.74-years based on age 68-years, 48% male), using published 223 Life Expectancy Norms for the English Population accounting for age and sex (19). Costs incurred during the inpatient episode were added to life-time costs to determine total cost over the life-time 224 225 horizon.

226

227

228 Analysis

229 Number of events were summed for each patient in the observational study and probability of event 230 calculated using negative binomial regression to allow for baseline differences in age, gender, ward, and NEWS score on admission. Length of stay on the ward was calculated as the date of discharge, 231 minus day of admission, minus anytime in ICU. Total hospital costs for each patient were calculated as 232 the sum of device (automated or spot check), and inpatient stay costs (ward, ICU and serious adverse 233 event activity costs). Hospital costs were analysed using generalized linear regression models (GLM) 234 235 with gamma family and log link. Count data of events were analysed using negative binominal regression. The 95% central range for difference in events were calculated using non-parametric 236 237 bootstrap analysis with 10,000 replications.

239 Cost Effectiveness Analysis

240	The cost-effectiveness analysis considered the cost per event avoided and cost per life-years saved
241	(during the inpatient episode). The Incremental Cost Effectiveness Ratio (ICER) was calculated as the
242	incremental cost divided by the total number of events avoided or life-years gained.
243	
244	Cost Per QALY
245	Total Cost and QALE data were combined to calculate the ICER. The ICER of the lifetime cost-utility
246	analysis was calculated as follows:
247	
248	ICER = $\underline{\text{COST}_{\text{with IGS}} - \text{COST}_{\text{standard care no IGS}}}$
249	QALE with IGS – $QALE$ standard care no IGS
250	
251	Base-case Analysis
252	The base-case analysis assumed a monitoring device product life of 5-years and 12% cableless sensor
253	use in the intervention arm and extrapolated to a life-time horizon.
254	

255 Sensitivity Analyses

One-way sensitivity analysis was conducted on (1) product life from 5-year to 10-year or 15-years, (2)
cableless sensors use from rates of 0% to 100%. A threshold analysis was conducted to establish the
cost [and throughput] of testing at which the ICER is dominant (cost neutral/saving and more effective).
Calculation of equivalent annual cost calculation based on product life of 5-years and a 3.5% discount
rate / annuity factor 4.515 was also performed to assess impact on product price per patient.

262 **Probabilistic Sensitivity Analyses**

Probabilistic sensitivity analysis was performed on the cost-utility analysis, using Monte Carlo simulation with 10,000 replications sampled from the distributions presented in Table 1. Standard deviation was assumed to be 0.2 of the mean point estimate and parameters of distributions calculated accordingly, the assumption of this was tested using scenario analysis of 0.1 and 0.4. A costeffectiveness acceptability curve (CEAC) was constructed to illustrate the probability of testing being cost-effective at given thresholds of cost-effectiveness (28).

269

270

271 Subgroup analyses

272 Subgroup analyses was conducted on clinically meaningful subgroups of (1) Age (17-74-years, 75years +); (2) NEWS score on admission (3+, 6+); and (3) ICD 10 code of primary diagnosis (ICD 10 273 274 Diseases of respiratory system, ICD 11 Diseases of digestive system, "other" primary diagnosis i.e., 275 not ICD 10 or 11). Patient level data were stratified into groups and model parameters were re-276 calculated. Secondary parameters used in the cost-utility analysis were adjusted for subgroup 277 population age, sex, ward, and COPD/CFA status (S67 Table). To allow for comparative cost-278 effectiveness within and between groups the net monetary benefit (at the £20,000 per QALY 279 threshold) and net health benefit of each strategy was calculated and plotted on the cost-effectiveness plane. 280

281

All data were analysed in Microsoft® Excel® for Microsoft 365 MSO (16.0.13801.20442) or STATA
17 and the study is reported according to the Consolidated Health Economic Evaluation Reporting
Standards(29).

286 **Research Governance**

287 The VITAL II before-and-after study was approved by the hospital human research ethics committee

288 (Reference 12/WA/0050, Protocol number SD-05163-BBN-IGS A.2). This study recruited patients

- from the 5th of October 2012 to the 17th of April 2015.
- 290 The VITAL II Study Data Base (VSDB) was de-identified according to the Health Insurance Portability
- 291 Act HIPAA (full de-identification). This new fully de-identified RDB was approved by IRAS (REC
- reference: 21/WA/0172; IRAS project ID: 298601) and the economic evaluation was approved by
- Bangor University Healthcare & Medical Sciences Academic Ethics Committee (16/07/2021) and
- Health Care Research Wales (HCRW)(21/09/2021). Patient consent was not required. Data was
 accessed for research purposes on the 11th of October 2021. Authors of this manuscript had no access
- to information that could identify individual participants during or after data collection.

297

298 **Results**

299

Base Case Analyses

The study population (n=3787) had a median age of 71 years (Inter Quartile Range (IQR): 59-81), 52%
were female, just over half were admitted to the pulmonology ward (56%), and the mean NEWS value
on hospital admission was 3.15 (sd=2.82) (S<u>7</u>8 Table). Based on (unadjusted) observed data the
frequency of adverse events per patient was lower with IGS (1.15 intervention versus 1.37 control).
(S<u>8</u>9 Table).

306

307 Short-term Cost-effectiveness Analysis

The device cost for using the automated intervention was estimated to be £846 per bed per year, which
equates to £19.98 per patient episode (based on 2,287 patients per year); compared to £1.52 per patient

- 310 for spot-check monitors in standard care (Table 3). The total NHS cost for the hospital episode,
- however, was lower with the intervention (£2047 IGS, compared to £2059 control), driven by higher
- 312 cost of treating events. IGS was also associated with improved health outcome (-2.7% reduction in
- 313 serious adverse events). (Table 4).
- 314

315 Table 3. Cost of intervention automated monitoring and notification and control spot-check

316 monitoring.

	Intervention	Control
	IntelliVue Guardian Solution (IGS)	Cost of spot-check monitors
	with cableless sensors and MP5SC	used in routine care at district
	spot-check monitors (Philips	general hospital in UK
	Healthcare, Boeblingen, Germany)	
Total Cost (for 1-year)	£45,691.66	£3,360.00
Total cost per bed per year ^{\$}	£846.14	£62.22
Cost per patient episode ^{\$}	£19.98	£1.52

317 Note. ^{\$}Base case: 5-yrs, 54 beds, 0.12 cableless; [#]Base case: 5-yrs, 54 beds, 0.00 cableless using straight line

depreciation. Economic equivalent annual cost calculation based on product life of 5-years and a 3.5% discount
 rate / annuity factor 4.515: £20.71 intervention; £1.68 control.

320

321 Table 4. Cost effectiveness of an automated notification system for deteriorating ward patients in

322 a district general hospital.

	Intervention (95% CR)	Control (95% CR)	Incremental (95% CR)
Costs			
Hospital Costs (£, short-term)	2,046.99	2,059.16	-12.17
	(1,926.45 to 2,183.47)	(1,957.03 to 2,174.21)	(-182.07 to 154.80)
Lifetime Costs (£)	17,644.52	17,687.70	-43.18
	(12,913.48 to 22,958.80)	(12,985.16 to 22,961.88)	(-225.16 to 163.09)
Total Cost	19691.52	19746.86	-55.35
	(14930.96 to 24977.91)	(15021.67 to 25048.15)	(-309.26 to 209.39)
Effectiveness (short-term)			
Predicted count of Events	0.0666	0.0933	-0.0267
(mean n events per patient)	(0.0543 to 0.0786)	(0.0743 to 0.1114)	(-0.0475 to -0.0064)
Quality-adjusted-life-	7.3702	7.3415	0.0287
expectancy (lifetime)	(5.2892 to 9.4685)	(5.2678 to 9.4200)	(-0.0485 to 0.1097)

323 Note. CR: Central Range

325 Life-time Cost-utility Analysis

326 Extrapolating the results from discharge to a lifetime horizon, by modelling differences in lifetime costs

and QALYs, showed IGS was associated with a mean QALE of 7.37 (95% CI: 5.29 to 9.47) compared

to a QALE of 7.34 (95% CI: 5.27 to 9.42) for standard care. Mean total costs over a lifetime were

329 £19,692 (95% CI: £14,931 to £24,978) for the intervention and £19,747 (95% CI: £15,022 to £25,048)

for standard care. Mean incremental QALYs was estimated to be 0.029, which is equivalent to ~10 days

of perfect health; whilst mean incremental cost was estimated to be -£55.35. (Table 4).

332

Results of the subgroup and sensitivity analyses

Results of the sensitivity analyses

The cost-effectiveness of IGS was robust to changes in product life and dominant to a cableless senor rate of 0.23. The threshold at which IGS becomes more costly is £32.06 i.e., a 60% increase in cost per patient inpatient stay (S<u>910</u> Table). Economic equivalent annual cost calculation based on product life of 5-years and a 3.5% discount rate / annuity factor 4.515 made a minor adjustment to incremental cost (£0.56).

340

341 **Probabilistic Sensitivity Analysis**

The cost-effectiveness plane for the cost effectiveness analysis (£/events) is illustrated in Fig 2. This shows the distribution of simulations for the cost per event avoided analysis in the short term (to discharge) – the majority of simulations show a reduction in events (to the left of the y axis), with wider variation in incremental cost (above and below the x axis).

346

347 Fig 2. Cost-effectiveness plane: cost-effectiveness analysis £/event avoided during inpatient stay.

349 The cost-effectiveness plane for the base-case cost-utility analysis is illustrated in the Fig 3. The distribution of the simulations indicates that IGS results in high utility (health gain) but at a lower cost 350 351 in 50% of simulations (south-east quadrant). The cost-effectiveness acceptability curve (CEAC) (Fig 4) 352 indicates the probability of IGS being cost-effective is 81% at the £20,000 threshold; and, 80% at the 353 £30,000 per QALY thresholds (upper and lower end of the UK healthcare decision making threshold 354 for cost-effectiveness); this was robust to changes in parameter uncertainty (at the $\pounds 20,000$ threshold: 355 from 79% with standard deviation 0.4 of the mean to 82% with standard deviation of 0.1 of the mean). 356 Fig 3. Cost-effectiveness plane: cost-utility analysis with life-time horizon. 357 358

359 Fig 4. Cost-effectiveness acceptability plane: cost-utility analysis with life-time horizon.

360

Results of the subgroup analyses

Stratified cost-effectiveness analysis indicated the automated notification system was cost-effective 362 for all strategies, except for NEWS on admission 6+, where the ICER was in the south-west quadrant 363 364 of the cost-effectiveness plane (cost saving but less effective) and did not reach the threshold for cost-365 effectiveness on the UK NHS (S10 4 Table). Whilst automated monitoring of patients under 75-years 366 provided the greatest net benefit and was relatively more cost-effective compared to the older subgroup; the adoption of automated monitoring remains the dominant strategy - associated with 367 368 increased health gain and cost savings, over a lifetime horizon – in subgroups defined as older age, 369 NEWS on admission less than 6, and primary ICD codes of 10 or 11 ($S_{12}-S_{415}$ Figs). The base-case 370 (all patients) resulted in the greatest cost-saving.

371

372 **Discussion**

Use of an automated notification system for deteriorating ward patients was cost-effective and
associated with small costing saving in the analysis of data from a previous interventional study from
the UK. Increased use of cableless sensors is associated with higher costs, however, the intervention
remains cost-effective even when the rate is 100% (ICER: £3,107/QALY). Stratified costeffectiveness analyses indicated that IGS, compared to spot-check monitors used in standard care,
remains cost effective (dominant or below the ICER threshold for decision making) in all subgroups
except NEWS on admission 6+.

381 Mohr at al.(30) conducted a retrospective analysis of implementing an early deterioration detection solution for general care in patients at a US hospital. The study used Medicare inpatient claims for a 382 regional hospital, that reported on 445 patient admissions, majority over age 65-years and over half 383 384 female. Average hospital costs per discharge were reduced by 18%, average LOS was significantly reduced – driven by a reduction in general care LOS. Complications, in-hospital mortality, and 30-day 385 386 all cause readmissions were similar. We report a significant reduction in serious adverse events, and 387 when extrapolated to a lifetime, a small improvement in QALYs. Our UK study also reports cost 388 reductions, but of much smaller magnitude than this US study, which may in part be explained by 389 differences in costing processes - furthermore, we do not have data on re-admission.

Vroman (31) also reported on the economics of continuous vital sign monitoring in patients after elective abdominal surgery –their retrospective analysis of clinical outcomes and in-hospital costs reported less frequent ICU admissions, shorter length of stay and lower costs, in the intervention phase. The analysis was based on 855 patients in a Dutch hospital, of similar age and gender to the current UK evaluation. In this study interest was more focused on continuous monitoring with the wearable biosensor, but the findings appear comparable for the inpatient episode.

396

397 Strengths

To our knowledge, this is the first study from the UK to model the cost-effectiveness of an electronicautomated advisory vital signs monitoring and notification system. The present study used data from

the VITAL II study, and therefore the probabilities in the model were based on individual patientlevel data, collected, that reflected real-world situations. Furthermore, the study extrapolated beyond
hospital discharge to model a lifetime horizon, to capture the full costs and outcomes potentially
associated with a change in monitoring technology.

404

405 Limitations

406 The analysis did not account for maintenance costs of the electronic automated advisory vital signs 407 monitoring and notification system, or routine spot-check monitoring. It was assumed the intervention 408 would displace existing requirements; however, it may be reasonable to estimate a 10% increase to 409 cover training and maintenance, in which case the intervention would remain dominant. The time 410 horizon of the cost-effectiveness model was limited to duration of inpatient stay, however, we 411 extrapolated to a lifetime horizon to minimise time horizon bias. Whilst utility data were not 412 collected at a patient level, we used published estimates from UK studies, that were adjusted for age 413 and sex to match the patient population observed in the VITAL II clinical study. The analysis did not 414 account for the opportunity cost of automated versus human monitoring, whist this replicates policy 415 (staffing levels are required to remain constant), time spent on monitoring represents resource that 416 could be redistributed to other elements of care. It is also noted that the economic evaluation used a reduced sample of the before-and-after study (n=3787/4402) and whilst adjusted probabilities used in 417 the model are a robust reflection of available data, difference in point estimates of mortality between 418 419 intervention and control of complete cases are more conservative than those reported in the 420 effectiveness study (15), which may underestimate the cost-effectiveness of the intervention. Finally, the assumption of 100% ward capacity, may be judged to be an optimistic bound, however, it is usual 421 422 practice in NHS hospitals to fill ward to capacity to create space at 'the front door' for assessment of 423 new patients.

424

425 **Implications**

426 This analysis highlights the cost-effectiveness of using an electronic automated advisory vital sign

427 monitoring and notification system for patients on general wards. Based on our previous publication

428 investment in the intervention is likely to have a significant effect on patient outcomes, while having

429 potential cost-savings – suggests good use of scarce resources.

430

431 **Future Research Directions**

432 Further research, collecting health utilities and long-term health and social care resource use is

433 required for a more robust estimate of costs and outcomes.

434 The impact of automated monitoring solutions on staffing also warrants further exploration.

435

436 Conclusion

Pragmatic use of automated monitoring in routine clinical practice for acute emergency admissions on
general wards is an economically dominant strategy, where the joint distribution of costs and QALYs
is associated with a positive net benefit. Adopting this technology is likely to result in both reduced
costs and improved outcomes.

441

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443

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538 Supporting Information

- 539
- 540 S1. Worked example of QALE Calculation.
- 541 S12 Table. NHS Reference Costs Ward 1 (gastroenterology) inclusion and exclusion.
- 542 S23 Table. NHS Reference Costs Ward 2 (pulmonology) inclusion and exclusion.
- 543 S<u>3</u>4 Table. NHS Reference Costs Critical Care.
- 544 S45 Table. NHS Reference Costs Serious Events.
- 545 S⁵⁶ Table. Trimpoints used to calculate excess bed days.
- 546 S₆₇ Table. Baseline characteristics of subgroup model populations.
- 547 S<u>7</u>8 Table. Patient Characteristics.
- 548 S⁸⁹ Table. Unadjusted frequency of serious adverse events and associated model probabilities.
- 549 S<u>910</u> Table. Results of Sensitivity and Scenario Analyses.
- 550 S101 Table. Net health benefit and net monetary benefit of alternative strategies [subgroups].
- 551 S12 Fig. Cost-effectiveness plane for base-case and all subgroup analyses.
- 552 S213 Fig. Cost-effectiveness plane for base-case and all subgroups by age.
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- 554 S415 Fig. Cost-effectiveness plane for base-case and all subgroups by Primary ICD code.
- 555