CENTRE VARIATION IN MORTALITY FOLLOWING POST-HOSPITALISATION ACUTE KIDNEY INJURY: Analysis of a large national cohort

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Abbreviations

AIC	Akaike Information Criterion
AKI	Acute Kidney Injury
AKI1	Acute Kidney Injury Stage 1
AKI2	Acute Kidney Injury Stage 2
AKI3	Acute Kidney Injury Stage 3
CCI	Charlson Comorbidity Index
H-AKI	Post-Hospitalisation Acute Kidney Injury
HES	Hospital Episodes Statistics
IMD	Index of Multiple Deprivation
KDIGO	Kidney Disease: Improving Global Outcomes
MPI	Master Patient Index
NCEPOD	National Confidential Enquiry into Patient Outcomes and Death
NHS	National Health Service
ONS	Office for National Statistics
RRT	Renal Replacement Therapy
SCr	Serum Creatinine
SHMI	Summary Hospital Mortality Indicator
SMR	Standardised Mortality Ratio
UKRR	UK Renal Registry
VPC	Variance Partition Co-efficient

ABSTRACT

Background: Routine monitoring of outcomes for patients with Acute Kidney Injury (AKI) is important to drive ongoing quality improvement in patient care. In this study, we describe development of a case-mix adjusted 30-day mortality indicator for patients with post-hospitalisation AKI (H-AKI) across England, to facilitate identification of any unwarranted centre-variation in outcomes.

Methods: We utilised a routinely collected national dataset of biochemically detected AKI cases, linked with national hospitals administrative and mortality data. 250,504 H-AKI episodes were studied in total, across 103 NHS hospital trusts, between January 2017 - December 2018. Standardised mortality ratios (SMRs) were calculated for each trust using logistic regression; adjusting for age, sex, primary diagnosis, comorbidity score, AKI severity, month of AKI, and admission method.

Results: Mean 30-day mortality rate was high at 28.6%. SMRs for 23/103 trusts were classed as outliers, 12 above and 11 below the 95% control limits. Patients with H-AKI had mortality rates over 5 times higher than the overall hospitalised population in 90/136 diagnosis groups and over 10 times higher in 60/136 groups. Presentation at trusts with a co-located specialist nephrology service was associated with a lower mortality risk, as was South Asian or Black ethnicity. Deprivation, however, was associated with higher mortality.

Conclusions: This is the largest multi-centre analysis of mortality for patients with biochemically ascertained H-AKI to date, demonstrating once again the considerable risk

associated with developing even mild elevations in serum creatinine. Mortality rates varied considerably across centres and those identified as outliers will now need to carefully interrogate local care pathways to understand and address reasons for this, with national policy required to tackle the identified health disparities.

KEY LEARNING POINTS

What is already known about this subject?

- Historically, significant concerns were raised regarding the quality of care provided to patients with AKI in England, thought to contribute to instances of avoidable patient harm and death.

- We have now established a national database of laboratory detected biochemical AKI cases across England, linked to hospitals administrative data and mortality records - providing a valuable resource for routine monitoring and study of AKI patient outcomes.

- Standardised mortality ratios are routinely used to compare case-mix adjusted patient outcomes across acute hospitals in the English National Health Service and are also routinely reported for dialysis units in the USA.

What this study adds?

- We have utilised linked national AKI datasets to calculate ‘case-mix’ adjusted 30-day standardised mortality ratios for patients with post-hospitalisation AKI across

England. This will facilitate identification of any unwarranted centre variation in patient outcomes.

- 250,504 AKI episodes were studied in total across 103 NHS hospital trusts, making this the largest reported cohort of patients with biochemically ascertained, post-hospitalisation AKI to date. Overall 30-day mortality rate was high at 28.6% with significant centre variation observed.

- Potential health inequalities for patients with AKI in England were also identified; patients at centres with a co-located specialist nephrology service had lower mortality rates and patient deprivation was associated with a higher risk of death.

What impact this may have on practice or policy?

- Centres identified as outliers will need to carefully examine their local care pathways for patients with AKI, to try and better understand and address potential reasons for this.

- National policy will also be required to try and improve our understanding of how we can address health inequalities for patients with AKI across England.

INTRODUCTION

Acute Kidney Injury (AKI) is a common syndrome affecting up to 1 in 5 hospitalised patients worldwide.[1-4] Patients with AKI are vulnerable to serious complications, including renal failure requiring dialysis, prolonged hospitalisation, chronic kidney disease and death.[1, 5, 6] Previously reported 30-day mortality rates for patients with AKI range between 15-30%; dependent on methods used to define AKI and patient population studied. [4, 7]

Concerns regarding shortcomings in the care of patients with AKI across England first came to light in 2009, following publication of the 'National Confidential Enquiry into Patient Outcomes and Death (NCEPOD)' report. Care was deemed 'good' in only 30% of 'post-admission AKI' cases, contributing to many instances of avoidable patient harm and death.[8] Quality improvement in AKI care has since been highlighted as a national patient safety priority, leading to commissioning of an innovative National Health Service (NHS) campaign termed "Think Kidneys".[8] As part of this campaign, an algorithm was developed to facilitate automated detection of AKI cases, based on elevations in serum creatinine, in keeping with KDIGO AKI staging criteria.[9, 10] In 2014 it became mandatory for all NHS laboratories in England to implement this algorithm and to report AKI alert data to the UK Renal Registry (UKRR), where it is centrally collated in a database called the 'Master Patient Index (MPI)'. The MPI is enriched through data linkage with NHS hospitals administrative data (Hospital Episodes Statistics, HES), UKRR datasets and national mortality data, providing a valuable resource for population wide study and monitoring of AKI patient outcomes, essential to drive ongoing quality improvement in AKI care.

In this paper we describe, in a transparent and reproducible fashion, how we have utilised the linked MPI dataset to develop a standardised, case-mix adjusted 30-day mortality indicator for patients with "post-hospitalisation AKI" (H-AKI) across England, to facilitate identification of any unwarranted centre-variation in patient outcomes.

METHODS

Study Design

This was a retrospective observational study of adult patients (>18 years) with biochemically ascertained H-AKI, between 01/01/2017 - 31/12/2018, at acute healthcare organisations (termed 'trusts' in the NHS) across England. Each NHS Trust may consist of between one and five acute hospitals, with some shared infrastructure e.g. laboratory information management systems.

Dataset

The MPI includes data from laboratories in England on patients who have triggered AKI alerts. All providers were mandated to implement the 'NHS AKI Algorithm'.[10] To support a standardised national implementation, "Think Kidneys" worked collaboratively with laboratories, clinicians and commercial suppliers of Laboratory Information Management Systems. The specified NHS mandated algorithm detects a rise in serum creatinine (SCr) from baseline values in the same laboratory. The index SCr is defined as C1. Two Reference Values (RV) are defined: RV1, the lowest SCr Day -1 to Day -7 and RV2, the median of all measurements Day -8 to Day -365. The RV which gives the higher C1/RV ratio is used to generate the AKI alert, graduated into three levels of severity 1, 2 and 3, corresponding to a ratio of 1.5-2.0, 2.0-3.0 and >3.0 times baseline values respectively.[11] In addition, a SCr rise of

≥26µmol/l in the preceding 48 hours generates an AKI1 alert when the ratio is <1.5. If the ratio is >1.5 and C1 is >354µmol/l or 3 x upper limit of normal, an AKI3 alert is generated. Patient identifiers facilitate linkage of MPI with HES, UKRR datasets and mortality data feeds from the UK Office for National Statistics (ONS). [12, 13, 14] Patients in the MPI known to be on dialysis at time of AKI alert are removed by UKRR during data cleaning. Patients without a baseline creatinine do not generate an alert, no matter how high C1 is, but our study design and NHS structure reduce the likelihood of no baseline being available. The majority of the population are served by a single, local NHS laboratory and so community baseline tests are available as a baseline, and even where absent, the baseline is established by the admission creatinine and only alerts 48 hours or more into admission were analysed.

Study Cohort

Our cohort comprised patients with H-AKI only, defined as AKI episodes first detected 2 or more days after date of hospital admission in HES.[15, 16] Moreover, H-AKI episodes were only included from hospital trusts that had submitted 12 months complete AKI alert data to the UKRR (calendar year 2017 and/or 2018), to account for the potential impact of seasonality on AKI incidence and outcomes.[17, 18] Pregnant patients identified through diagnostic codes in HES were specifically excluded from our cohort, as the NHS AKI algorithm is not yet validated for this population. All patients from included trusts had follow-up until death or 30 days after discharge. *Supplementary File A outlines further details on cohort selection.*

Outcome

The main outcome of interest was mortality in hospital or within 30 days of discharge, referred to in this paper as '30-day mortality'.[12]

Covariates

Our AKI mortality indicator has been adapted from the 'Summary Hospital Mortality Indicator (SHMI)' methodology, which is the official mortality metric reported for NHS hospitals in England.[19] Risk factors considered in the analysis included; age, sex, month of admission, elective or emergency admission, diagnosis group (categorised using a validated revision of the 'Clinical Classification System')[20], comorbidity score (AKI specific re-weighting of Charlson Comorbidity Index as detailed in *Supplementary File B*) and first AKI alert warning level (1, 2 or 3). [21] The 'Akaike Information Criterion (AIC)' was used for variable selection and for assessing the inclusion of interactions between clinically relevant covariates.[22] These were diagnosis group and age, AKI warning level and age, comorbidity score and age, and diagnosis group and comorbidity score. *Supplementary File C details how each covariate was extracted from our dataset.*

Statistical Modelling

All analyses were conducted using SAS 9.4 and Stata/MP12. 30-day mortality was modelled using logistic regression, including selected covariates. Age was kept as a continuous variable, but as it was found to have a non-linear relationship with mortality, it was entered into the model as a restricted cubic spline with 3 knots at 67.0, 78.0 and 85.9 years. Funnel plots were created using outputs from the logistic regression model. Each patient was given an expected probability of dying, based on coefficients from the logistic regression model that corresponded to individual patient risk factors.[23] These probabilities were then summed for patients at each trust to calculate the overall expected number of deaths. Trust specific

'Standardised Mortality Ratios (SMR)' were then generated by dividing their observed number of deaths by the expected number of deaths.

Additional analyses

Hospital trusts which offer 'specialised nephrology services' i.e. acute start haemodialysis were identified using UKRR records and this was added as a co-variate to the logistic regression model used to generate trust SMRs, to explore the impact on 30-day mortality.

The impact of ethnicity and deprivation on mortality following H-AKI was also explored by their addition as co-variates to the logistic regression model used to generate trust SMRs. Self-reported ethnicity and Index of Multiple Deprivation (IMD)[24] data were extracted from HES. IMD is the official measure of deprivation in England, calculated at neighbourhood level it comprises 7 domains; income, employment, health deprivation/disability, education/ skills, crime, barriers to housing/services and living environment. IMD scores have been categorised into quintiles for our analysis.

For the main analysis, any patients with an inter-hospital transfer (IHT) (survivors and non-survivors) were allocated to the trust at which the first AKI alert was generated. Any alerts occurring within the first 48 hours of an IHT were attributed to the referring trust. Supplementary analysis was also performed however, excluding any patients who underwent an IHT.

Model Fit

To evaluate the impact of 'case-mix adjustment', using each selected covariate, on trust SMRs, figures similar to Bland-Altman plots were created.[25] Obtaining the expected deaths for each trust from two nested models and plotting the difference between the two values against the mean of the two values allows a visualisation of the effect of additional covariates upon trust SMRs. Trusts displayed outside of the guidelines of y=±0.05x have more than 5% difference in their SMR between the two models. To determine how much trust variation was explained by the full model compared to the null model, variance partition coefficients (VPCs) were also calculated, based on the latent response formulation after fitting multilevel models with a random effect term for the level 2 variable *Trust*.[26]

RESULTS

Study Cohort

250,504 H-AKI episodes were studied in the final cohort (Figure 1), captured from 103 hospital trusts (74 for calendar years 2017 and 2018, 12 for 2017 only, 17 for 2018 only and 21 acute/ non-specialist English NHS trusts excluded from both years due to incomplete data).

Patient Demographics

Overall cohort median age was 78.0 years (IQR: 67.0 – 85.9), with median age across individual hospital trusts ranging between 66.0 - 82.9 years (IQR: 76.9 – 80.5). 49.6% of the overall cohort were male (Trust range, 43.4% - 57.2%). Complete patient numbers and demography by anonymised Trust are displayed in *Supplementary Table S1*.

Mortality rates

71,742 (28.6%) patients with H-AKI died in hospital or within 30 days of discharge. The unadjusted mortality rate varied between 22.3%-35.5% across hospital trusts.

217,182 (86.7%) first detected AKI alerts in the cohort were AKI1, with a range across trusts of 68.9% - 91.1%. 24,654 (9.8%) first-detected AKI alerts were AKI2 and 8668 (3.5%) were AKI3.

Mortality increased with increasing AKI level, 26.7%, 40.6% and 43.2% for AKI1, AKI2 and AKI3 respectively.

Figure 2 shows unadjusted 30-day mortality rates for our cohort within 136 different diagnosis groups that have been compared to figures obtained from NHS digital for the overall hospitalised population in England during 2018.[27] Summary HES data for this plot is supplied in *Supplementary Table S2.* Patients with H-AKI in 90/136 diagnosis groups had mortality rates >5 times higher than the overall hospitalised population and >10 times higher in 60/136 diagnosis groups. Only one group ('cardiac arrest and ventricular fibrillation') had a lower mortality in the H-AKI cohort.

Risk Factors

Increasing age, higher AKI warning level at first alert, higher comorbidity score, male sex, emergency admission and admission during winter months were all associated with a higher risk of death (Table 1). Where interactions between covariates were included in our model the effects vary across the range of values of those covariates and *Supplementary Table 3*

displays coefficients at a range of values for these interactions, with pneumonia displayed as the largest diagnosis group.[28]

Table 1: Adjusted odds ratios and confidence intervals from the logistic regression model used to generate Hospital Trust Standardised Mortality Ratios (SMRs)

Variable	Levels of covariates	Adjusted Odds Ratio*		
		Estimate	95% LL	95% UL
Sex	Male vs Female	1.27	1.25	1.30
Age	1 year increase	1.04	1.04	1.05
Admission Method	Emergency vs Elective	3.48	3.31	3.66
AKI alert warning level	AKI 2 vs AKI 1	1.96	1.88	2.05
	AKI 3 vs AKI 1	2.12	1.98	2.28
	AKI 3 vs AKI 2	1.08	1.00	1.17
Comorbidity Score	(1 unit increase)	1.23	1.21	1.26

** Model adjusted for sex, age, admission method, AKI alert warning level, comorbidity score, month of alert and diagnosis group. Detailed Odds Ratios for each month of the year, diagnosis group and across interaction terms displayed in Supplementary Table S3.*

Centre Variation

Figure 3 demonstrates the funnel plot of Trust SMRs for our cohort, calculated using outputs from our logistic regression model. Owing to the large amount of variation between trusts, the funnel plot is presented with 95% and 99.8% control limits, inflated using an additive random-effects model with a 10% trim for over-dispersion.[29] Despite this, more trusts fall outside of the control limits than would be expected through chance variation alone (23/103 and 8/103 outside of 95% and 99.8% control limits respectively).

Diagnosis groups with the largest numbers of patients were pneumonia, septicemia, congestive cardiac failure and hip fracture. Within these diagnosis groups fewer trusts (8, 11, 8, and 7 respectively) were outside of the 95% control limits (Figure 4).

On-site specialist nephrology services

43/103 included trusts had a co-located specialist nephrology service, found to be associated with significantly reduced 30-day mortality when added to our logistic regression model (odds ratio 0.97, 95% confidence limits 0.95-0.99). When restricting to patients presenting with more severe AKI2 and AKI3, the odds ratio reduced further (odds ratio 0.91, 95% confidence limits 0.87-0.96, Figure 5).

Patient ethnicity and deprivation

Table 2 demonstrates odds ratios associated with ethnicity and deprivation groups (when added as covariates to the logistic regression model we used to generate trust SMRs). South Asian and Black ethnicity were associated with lower mortality compared to White ethnicity and patients from the most deprived areas were found to have the highest mortality risk.

Table 2: Odds ratios from logistic regression model - with ethnicity and deprivation included as covariates

Variable	Levels of covariates		Adjusted Odds Ratio*		
		Proportion of cohort	Estimate	95% LL	95% UL
Ethnicity	White	90.7%	1		
	South Asian	3.3%	0.78	0.74	0.83
	Black	1.6%	0.76	0.70	0.83
	Other	1.5%	1.32	1.23	1.41
	Unknown	0.8%	0.84	0.77	0.92
	Missing	2%	1.58	1.42	1.75
Deprivation quintile	Least deprived	17.8%	0.90	0.88	0.93
	2	19.6%	0.93	0.90	0.96
	3	20.9%	0.91	0.89	0.94
	4	20.3%	0.96	0.93	0.99
	Most deprived	20.8%	1		
	Missing	0.5%	0.94	0.81	1.08

** Model adjusted for age, sex, ethnicity, deprivation, admission method, AKI alert warning level, comorbidity score and month of alert.* Complete model output displayed in *Supplementary Table S4. LL = Lower Limit. UL = Upper Limit*

Inter-Hospital Transfers

24,147 patients (9.6% of cohort) underwent an IHT. 60% of these patients generated their first AKI alert prior to/ within 48 hours of transfer and these AKI episodes were attributed to the referral centres. All patients with their first AKI alert occurring > 48 hours after an IHT were attributed to the receiving centre.

When excluding patients with IHTs from our analysis, parameter estimates from the logistic regression model remained similar. These estimates and the distribution of centres by funnel plot in the 'all patient analysis' and the 'sensitivity analysis excluding IHT patients' are compared in Supplementary File E.

Model Fit

Using "AKI reweighted Charlson comorbidity scores" (Table 3) as a covariate in the logistic regression model instead of the original Charlson comorbidity index (CCI)[30] or the 'Dr. Foster reweighting of CCI' used in SHMI[21], decreased the AIC, indicating a better model fit.

Figure 6 displays funnel plots for hospital SMRs generated using unadjusted (Model 1), age-sex adjusted (Model 2) and age-sex-AKI level adjusted (Model 3) logistic regression models, alongside the final fully adjusted model that we have used for our analysis (Model 4). *Figure 7* displays 'Bland-Altman' plots comparing these models, and also the model with ethnicity and deprivation included (Model 5). The Variance Partition Coefficients(VPC) derived from the multi-level models suggest that 45% of between trust variation in mortality present in the unadjusted model was explained by the patient-level risk factors in the fully adjusted model (a reduction in VPC from 1.2% to 0.7%).

Table 3: Re-weighting of Charlson Comorbidity Score for patients with AKI

Comorbidity	Original Charlson Comorbidity Score	Dr. Foster reweighting used in SHMI	Mean of Log Odds* from 200 bootstrapped samples	SD of Log Odds* from 200 bootstrapped samples	**AKI reweighted score**
MI	1	5	0.21	0.007	**0**
Cerebrovascular disease	1	11	0.25	0.009	**1**
Heart Failure	1	13	0.51	0.006	**2**
Rheumatic disease	1	4	0.07	0.012	**0**
Dementia	1	14	0.44	0.008	**1**
Diabetes	1	3	0.02	0.006	**0**
Mild liver disease	1	8	0.98	0.017	**2**
Peptic ulcer disease	1	9	0.34	0.019	**1**
Peripheral vascular disease	1	6	0.27	0.009	**1**
Chronic pulmonary disease	1	4	0.32	0.006	**1**
Malignancy	2	8	0.78	0.008	**2**

Diabetes complications	2	-1	-0.15	0.018	**0**
Paraplegia	2	1	0.35	0.016	**1**
Renal disease	2	10	0.17	0.006	**0**
Malignancy metastatic solid tumour	6	14	1.43	0.009	**3**
Medium or severe Liver disease	3	18	1.38	0.017	**3**

* *Adjusted for age, sex, level of AKI alert, month of AKI alert, and each comorbidity group individually.*

SD = Standard deviation, AKI = Acute kidney injury, SHMI = Summary Hospital Mortality indicator[19]

DISCUSSION

Key Findings

Mean 30-day mortality rate for patients with H-AKI in England was high at 28.6%, rising with AKI stage. A large proportion (86.7%) of AKI episodes were AKI1 (mild) at first alert, but associated with high mortality nonetheless. SMRs varied considerably across acute hospital trusts, with 23/103 classed as outliers (12 above and 11 below the 95% control limits).

Comparison with previous studies

To our knowledge this is the largest study to date reporting 30-day mortality rates and associated risk factors for a national, multi-centre cohort of patients with biochemically defined H-AKI. Additionally, the development of a standardised mortality indicator to facilitate national benchmarking and centre comparison of AKI patient outcomes, has not been described previously.

There is considerable heterogeneity in published literature with regards to AKI case ascertainment and reporting of mortality rates (in-hospital/30-day/90-day), making direct

comparison of our findings difficult. The hitherto largest cohort included 205,765 AKI episodes in US veterans (AKI also determined biochemically).[31] In-hospital mortality rate was lower than for our cohort (19.6%), possibly due to assessment of in-hospital mortality only, inclusion of 'all hospitalised' AKI cases and/or differences in patient demographics and co-morbidity burden. A previous England-wide analysis of HES coded AKI cases (2008-2013) quoted an in-hospital mortality rate of 27.1%.[38] Analysis of AKI episodes captured using the MPI, as in our study, is much more likely to give a reliable estimate of patient mortality however, as HES coding underestimates true AKI incidence; UKRR analysis has shown that only 48.2% of patients with AKI1 and 83% of patients with AKI3 in the MPI were coded as having AKI in corresponding HES episodes during 2018.[3]

Many of the risk factors for mortality identified in this study have been described previously, including increased mortality for patients presenting in winter months.[17, 18, 5, 32, 33] Reasons behind this association are not fully understood at present. Seasonal variations in the severity of underlying/acute illnesses and/or the impact of increased emergency admissions to acute hospitals in winter months might play a role but needs to be investigated further.

Health Inequalities

Abraham et al. previously reported lower mortality rates for patients with AKI at hospitals in England that have on-site specialist nephrology services, examined using HES data only.[34] Here, we have attempted more robust case-mix adjustment (adaptation of SHMI methodology), alongside capture of a wider group of patients using the MPI, with similar findings. In our study, 'specialist nephrology services' refers specifically to 'renal centres' with acute haemodialysis capacity outside of intensive care settings. Unfortunately, we were

unable to further stratify non-renal centres i.e. by presence of on-site nephrologists or AKI nurse specialists. Existing regional renal networks, AKI outreach services and inter-hospital transfer pathways will need to be examined in more detail to gain better understanding of factors governing this disparity. Importantly, a previous analysis of data from a single UK centre noted that only 7% of AKI cases were directly managed by nephrologists.[35] It is therefore imperative that a "hospital-wide" approach is followed when investigating these findings rather than one focussed solely on renal services.

Ethnicity and deprivation were excluded as covariates from the logistic regression model used to calculate trust SMRs, as we were anxious not to obscure variation that exists between hospitals on the basis of these factors. Additional analyses however revealed that patients from areas of greatest deprivation in England had the highest mortality rates, consistent with findings from previous UK studies.[36, 37] Again, further work is needed to fully understand the contributing factors. It is possible that differences in health related behaviour explain some of the variation e.g. delayed presentation to hospital, smoking, alcohol excess or illicit drug use.

Patients of White ethnicity were found to be at higher risk of mortality than those of Black or South Asian ethnicity. Two previous HES based analyses of patients with AKI in England noted similar findings, as did a US analysis of 'National Inpatient Sample' data.[33, 38, 39] Interestingly, improved survival has also been noted amongst non-white ethnicity patients on maintenance dialysis across North America and Europe[40, 41]. It is difficult to postulate the reasons behind these observations; further work is still required to better our understanding, including exploration of possible genetic associations.

Study Limitations

The NHS AKI algorithm relies on identifying a rise in serum creatinine from laboratory held 'baseline' values, taken within the preceding 12 months[10]. The "one healthcare system" design of the NHS, encompassing both community and hospital healthcare, is such that when a patient is admitted to hospital there is a historical laboratory record of serum creatinine available for most patients. Nevertheless, we acknowledge that there are some patients with no community baseline, or where the community baseline is in a different laboratory, for example patients admitted to regional tertiary centres or in the largest English cities with multiple labs. Younger patients are also less likely to have a community baseline, but the vast majority of AKI is in older patients. Because of these concerns about completeness we have added the 48-hour rule and not analysed alerts prior to this. For emergency admissions there will be a baseline 'admission day' SCr and patients being admitted for major elective surgery routinely have a 'pre-admission' creatinine check in the same laboratory. With the majority of patients having a pre-admission or admission baseline, and the additional safety net of the 48-hour rule, we have a high degree of confidence that we are describing H-AKI. We acknowledge the slim possibility that patients who experience an AKI provoking insult in the community may not trigger an alert until more than 48 hours into the admission, but the fact that a very modest SCr rise of 26μmol/l in that first 48 hours will trigger an alert further reduces this risk.

We have not analysed the incidence of H-AKI across English hospitals, as it was not the focus of this study and such data is already published as an unadjusted analysis. For reference, unadjusted incidence of H-AKI using the MPI varies from 1.3-4.7% by centre.[3] We could not

improve on this because we do not have access to complete data on clinical coding from hospital admissions in England that were not complicated by an AKI alert, which would be needed for calculating casemix adjusted AKI rates. Large tertiary centres managing more complex patients may have a higher volume and incidence of AKI and we have taken this into consideration by calculating standardised mortality ratios (SMRs), examining the observed/ expected mortality rates for patients with AKI, where expected mortality rates taken into account the total number of patients with AKI at each trust alongside detailed casemix adjustment. Of note however, the four headline diagnoses associated with AKI (pneumonia, septicemia, congestive cardiac failure and hip fracture) are common to all acute hospitals, not just specialist centres.

We were unable to explore further whether the difference in overall mortality rates and mortality for patients with H-AKI, within specific diagnosis groups e.g. cardiac arrest, arose from the competing risk between developing H-AKI and death within the first 48 hours of admission. This would require data on all admitted patients, not just those who triggered an AKI alert, which we do not have access to. We have however undertaken further supplementary analysis, comparing mortality rates for patients who generated a first AKI alert within 48 hours of admission to the SMRs we calculated for patients with H-AKI after 48 hours (Supplementary File F). This demonstrates a broad correlation between centres with high unadjusted AKI mortality in the first 48 hours of an admission and those with a high SMR for AKI after 48hours. This argues against a competing interest between death in the first 48 hours and H-AKI deaths, although does not disprove it.

Of note, we used the first detected AKI alert level in our logistic regression model. Although patients with multiple alerts in an AKI episode might progress to have an alert with a higher warning level, this has happened during the admission, and therefore could be an indicator of difference in care which would be unnecessarily "adjusted out" if we used peak creatinine values in our model instead.

We were unable to address some potential confounding and bias issues due to limitations of hospital administrative data e.g. severity of acute/ comorbid conditions (recorded just as YES/NO), whether patients were on a palliative care pathway and reverse causality (i.e. patients who were already dying generating an AKI alert), but we believe that these issues are likely to be similar across all trusts. Creatinine values were not available for all patients in the MPI and HES coding of chronic kidney disease is known to be poor; we were therefore also unable to reliably identify a sub-group of patients with 'acute on chronic' kidney impairment for additional analyses.[42]

Future Work

Infrastructure is now in place to allow longitudinal monitoring of H-AKI patient 30-day mortality rates using our indicator, which may be particularly useful when assessing response to any future quality improvement interventions. Additional patient outcomes can also be explored using the linked MPI dataset e.g. length of hospital stay, readmission rates and progression/duration of AKI, which can eventually be incorporated into a composite "AKI patient outcomes dashboard", that will facilitate more comprehensive monitoring of AKI patient outcomes nationally.

CONCLUSION

AKI remains an important patient safety concern across hospital settings in England, with even mild elevations in serum creatinine associated with a high mortality risk. There was considerable variation observed in NHS hospital trust SMRs and centres identified as outliers will now need to carefully investigate and address possible reasons for this. National strategy will also be required to understand and address the observed health disparities in AKI patient outcomes in association with access to specialist renal services, ethnicity and deprivation.

STATEMENTS

Disclosure Statements:

The results presented in this paper have not been published previously in whole or part.

The authors of this paper have no conflict of interests to declare

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Ethics statement:

AKI alert data for patients in England are collated by the UK Renal Registry under section 251 permissions of the NHS Act (2006), as detailed in the Renal Association patient privacy notice.[43] HES linkage occurs under a 'Data Sharing Agreement' between NHS digital and UKRR. This work met UKRR criteria for quality improvement activities and was therefore exempt from full ethics review. Patient data was pseudonymised and all analysis was undertaken in accordance with the 'Data Protection Act (2018)', the 'General Data Protection Regulations (2016)' and Caldicott principles.

Data Sharing Statement:

The AKI-MPI dataset is available from the UK Renal Registry and can be applied for at the following link: 'https://renal.org/audit-research/how-access-data/ukrr-data/apply-access-

ukrr-data'. HES data is available via application to NHS Digital. Section 2.5.1. permissions will be necessary to link the two datasets however.

STROBE Checklist:

All findings have been reported in accordance with the STROBE checklist for observational studies[44].

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REFERENCES:

1. Ronco C, Bellomo R, Kellum JA. Acute kidney injury. *Lancet*. Nov 23 2019;394(10212):1949-1964. doi:10.1016/s0140-6736(19)32563-2

2. Selby NM, Casula A, Lamming L, et al. An Organizational-Level Program of Intervention for AKI: A Pragmatic Stepped Wedge Cluster Randomized Trial. *Journal of the American Society of Nephrology*. 2019;30(3):505-515. doi:10.1681/asn.2018090886

3. UK Renal Registry (2020):Acute kidney injury (AKI) in England – a report on the nationwide collection of AKI warning test scores from 2018: https://renal.org/wpcontent/uploads/2020/07/AKI_report_FINAL.pdf

4. Susantitaphong P, Cruz DN, Cerda J, et al. World incidence of AKI: a meta-analysis. *Clin J Am Soc Nephrol*. Sep 2013;8(9):1482-93. doi:10.2215/cjn.00710113

5. Chertow GM, Burdick E, Honour M, Bonventre JV, Bates DW. Acute kidney injury, mortality, length of stay, and costs in hospitalized patients. *J Am Soc Nephrol*. Nov 2005;16(11):3365-70. doi:10.1681/asn.2004090740

6. Horne KL, Packington R, Monaghan J, Reilly T, Selby NM. Three-year outcomes after acute kidney injury: results of a prospective parallel group cohort study. *BMJ Open*. 2017;7(3):e015316. doi:10.1136/bmjopen-2016-015316

7. Jurawan N, Pankhurst T, Ferro C, et al. Hospital acquired Acute Kidney Injury is associated with increased mortality but not increased readmission rates in a UK acute hospital. *BMC Nephrology*. 2017/10/20 2017;18(1):317. doi:10.1186/s12882-017-0729-9

8. Stewart J FG, Smith N, Kelly K, Mason M. *Acute Kidney Injury: Adding Insult to Injury. NCEPOD*. 2009.

9. KDIGO. Kidney Disease: Improving Global Outcomes (KDIGO) Clinical Practice Guideline for Acute Kidney Injury (AKI). 2012;

10. Selby NM, Hill R, Fluck RJ. Standardizing the Early Identification of Acute Kidney Injury: The NHS England National Patient Safety Alert. *Nephron*. 2015;131(2):113-7. doi:10.1159/000439146

11. NHS England: NHS AKI Algorithm. https://www.england.nhs.uk/wp-content/uploads/2014/06/psa-aki-alg.pdf Accessed February 2021

12. Herbert A, Wijlaars L, Zylbersztejn A, Cromwell D, Hardelid P. Data resource profile: hospital episode statistics admitted patient care (HES APC). *International journal of epidemiology*. 2017;46(4):1093-1093i.

13. NHS Digital. Methodology to create provider and CIP spells from HES APC data. http://www. hscic.gov.uk/media/11859/Provider-Spells-Methodology/pdf/Spells_ Methodology.pdf. Accessed February 2021

14. Office for National Statistics. Personal Demographics service data. https://www.ons.gov.uk/census/censustransformationprogramme/administrativedatacensusproject/datasourceoverviews/personaldemographicsservicedata. Accessed February 2021

15. *Renal Assocation: Clinical Practice Guidelines - Acute Kidney Injury*. 2019. https://renal.org/wp-content/uploads/2017/07/FINAL-AKI-Guideline.pdf Accessed February 2021

16. Wonnacott A, Meran S, Amphlett B, Talabani B, Phillips A. Epidemiology and outcomes in community-acquired versus hospital-acquired AKI. *Clin J Am Soc Nephrol*. Jun 6 2014;9(6):1007-14. doi:10.2215/cjn.07920713

17. Iwagami M, Moriya H, Doi K, et al. Seasonality of acute kidney injury incidence and mortality among hospitalized patients. *Nephrol Dial Transplant*. Aug 1 2018;33(8):1354-1362. doi:10.1093/ndt/gfy011

18. Phillips D, Young O, Holmes J, et al. Seasonal pattern of incidence and outcome of Acute Kidney Injury: A national study of Welsh AKI electronic alerts. *International Journal of Clinical Practice*. 2017;71(9):e13000. doi:https://doi.org/10.1111/ijcp.13000

19. NHS Digital. About the Summary Hospital-level Mortality Indicator (SHMI). Accessed July 2020, https://digital.nhs.uk/data-and-information/publications/ci-hub/summary-hospital-level-mortality-indicator-shmi Accessed February 2021

20. HCUP - Clinical Classification Software. https://www.hcup-us.ahrq.gov/toolssoftware/ccs10/ccs10.jsp Accessed February 2021

21. Campbell MJ, Jacques RM, Fotheringham J, Maheswaran R, Nicholl J. Developing a summary hospital mortality index: retrospective analysis in English hospitals over five years. *Bmj*. Mar 1 2012;344:e1001. doi:10.1136/bmj.e1001

22. Judith D. Singer JBW. *Applied Longitudinal Data Analysis: Modeling Change and Event Occurrence*. Oxford University Press; 2003.

23. Spiegelhalter DJ. Funnel plots for comparing institutional performance. *Stat Med*. Apr 30 2005;24(8):1185-202. doi:10.1002/sim.1970

24. UK Government. *The English Index of Multiple Deprivation (IMD) 2015 – Guidance*. 2015. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/464430/English_Index_of_Multiple_Deprivation_2015_-_Guidance.pdf Accessed February 2021

25. Campbell M, Jacques R, Fotheringham J, Pearson T, Maheswaran R, Nicholl J. An evaluation of the summary hospital mortality index. *Sheffield: The University of Sheffield*. 2011;

26. Austin PC, Merlo J. Intermediate and advanced topics in multilevel logistic regression analysis. *Statistics in Medicine*. 2017;36(20):3257-3277. doi:10.1002/sim.7336

27. NHS digital. SHMI diagnosis Group Crude Mortality Jan 2018 Dec 2018 Accessed July 2020, 2020. https://digital.nhs.uk/data-and-information/supplementary-information/2020/shmi-diagnosis-groups-crude-mortality-jan18-dec18 Accessed February 2021

28. Jain A, McDonald HI, Nitsch D, Tomlinson L, Thomas SL. Risk factors for developing acute kidney injury in older people with diabetes and community-acquired pneumonia: a population-based UK cohort study. *BMC Nephrology*. 2017/05/01 2017;18(1):142. doi:10.1186/s12882-017-0566-x

29. Spiegelhalter DJ. Handling over-dispersion of performance indicators. *Quality & safety in health care*. 2005;14(5):347-351. doi:10.1136/qshc.2005.013755

30. Quan H, Li B, Couris CM, et al. Updating and validating the Charlson comorbidity index and score for risk adjustment in hospital discharge abstracts using data from 6 countries. *Am J Epidemiol*. Mar 15 2011;173(6):676-82. doi:10.1093/aje/kwq433

31. Lafrance J-P, Miller DR. Defining acute kidney injury in database studies: the effects of varying the baseline kidney function assessment period and considering CKD status. *American journal of kidney diseases*. 2010;56(4):651-660.

32. Wang HE, Muntner P, Chertow GM, Warnock DG. Acute kidney injury and mortality in hospitalized patients. *Am J Nephrol*. 2012;35(4):349-55. doi:10.1159/000337487

33. Kolhe NV, Muirhead AW, Wilkes SR, Fluck RJ, Taal MW. National trends in acute kidney injury requiring dialysis in England between 1998 and 2013. *Kidney International*. 2015/11/01/ 2015;88(5):1161-1169. doi:https://doi.org/10.1038/ki.2015.234

34. Abraham KA, Thompson EB, Bodger K, Pearson M. Inequalities in outcomes of acute kidney injury in England. *QJM: An International Journal of Medicine*. 2012;105(8):729-740.

35. Selby NM, Crowley L, Fluck RJ, et al. Use of Electronic Results Reporting to Diagnose and Monitor AKI in Hospitalized Patients. *Clinical Journal of the American Society of Nephrology*. 2012;7(4):533. doi:10.2215/CJN.08970911

36. UK KR. *Kidney health inequalities in the United Kingdom: reflecting on the past, reducing in the future*. 2018.

37. Hounkpatin HO, Fraser SDS, Johnson MJ, Harris S, Uniacke M, Roderick PJ. The association of socioeconomic status with incidence and outcomes of acute kidney injury. *Clinical Kidney Journal*. 2019;13(2):245-252. doi:10.1093/ckj/sfz113

38. Kolhe N, Muirhead A, Wilkes S, Fluck R, Taal M. The epidemiology of hospitalised acute kidney injury not requiring dialysis in England from 1998 to 2013: retrospective analysis of hospital episode statistics. *International journal of clinical practice*. 2016;70(4):330-339.

39. Waikar SS, Curhan GC, Ayanian JZ, Chertow GM. Race and Mortality after Acute Renal Failure. *Journal of the American Society of Nephrology*. 2007;18(10):2740-2748. doi:10.1681/asn.2006091060

40. Roderick P, Byrne C, Casula A, et al. Survival of patients from South Asian and Black populations starting renal replacement therapy in England and Wales. *Nephrol Dial Transplant*. Dec 2009;24(12):3774-82. doi:10.1093/ndt/gfp348

41. Kucirka LM, Grams ME, Lessler J, et al. Association of race and age with survival among patients undergoing dialysis. *Jama*. Aug 10 2011;306(6):620-6. doi:10.1001/jama.2011.1127

42. Hapca S, Siddiqui MK, Kwan RSY, et al. The Relationship between AKI and CKD in Patients with Type 2 Diabetes: An Observational Cohort Study. *Journal of the American Society of Nephrology*. 2020:ASN.2020030323. doi:10.1681/asn.2020030323

43. Renal Association. Data Privacy Notice. https://qualitysafety.bmj.com/pages/wp-content/uploads/sites/44/2018/08/Policy-on-Ethic-Reviews2018.pdf Accessed February 2021

44. STROBE statement—checklist of items that should be included in reports of observational studies. *International Journal of Public Health*. 2008;53:3-4.

SUPPLEMENTARY FILES

Supplementary File A:

a) Details of inclusion and exclusion criteria for NHS acute hospital trusts
b) Defining AKI 'episodes'
c) Defining post-hospitalisation AKI and attributing AKI episodes to a hospital spell and provider

Supplementary File B:

Reweighting of Charlson Comorbidity Index for Patients with AKI

Supplementary File C:

Extracting Covariates from dataset

Supplementary File D:

Missing Data

Supplementary File E:

Comparing parameter estimates from the logistic regression model and funnel plots after patients with an inter-hospital transfer had been removed.

Supplementary File F:

Relationship between deaths for patients who generated their first AKI alert within 48 hours of admission and SMRs for patients with H-AKI across included NHS Trusts

References

SUPPLEMENTARY TABLES

- Supplementary Table S1: Detailed demography and patient outcomes by hospital trust
- Supplementary Table S2: Detailed list of 136 diagnosis groups: Unadjusted mortality rates for post-hospitalisation AKI patient cohort vs overall hospitalized population in England during 2018
- Supplementary Table S3: Adjusted odds ratios and confidence intervals from the logistic regression model used to calculate NHS Hospital Trust Standardised Mortality Ratios (SMRs) – presented for each individual variable.
- Supplementary Table S4: Complete odds ratio from logistic regression model with ethnicity and deprivation included as covariates

DETAILED TABLE AND FIGURE LEGENDS

Figure 1: Consort Flow Diagram

Final cohort of patients with post-hospitalisation AKI episodes analysed in this study, outlining all relevant exclusions.

Supplementary Table S1: Detailed demography and patient outcomes by hospital trust (anonymised)

In this table we display details regarding mean patient age, sex, number of AKI level 1, 2 and 3 alerts, overall patient deaths and deaths stratified by AKI level at the 103 NHS hospital trusts in our study (anonymised).

Figure 2: Mortality of patients with H-AKI alerts compared to overall hospital population, across 136 diagnosis groups

Unadjusted mortality rates within 136 diagnosis groups were plotted for patients with H-AKI alerts in our cohort against figures for all hospitalised patients in England, obtained from NHS digital.[27] In 90 of the diagnosis groups mortality was at least five times higher in the H-AKI population, and 60 diagnosis groups had mortality more than ten times higher. Only one group (cardiac arrest and ventricular fibrillation) had a lower mortality in the H-AKI cohort. Further detail on the diagnosis groups can be found in *Supplementary Table S2.*

Supplementary Table S2: Detailed list of 136 diagnosis groups: Unadjusted mortality rates for H-AKI patient cohort vs overall hospitalized population in England during 2018

In this table we present further detail on the SHMI diagnosis groups we have used for case-mix adjustment in our model. The proportion of patients and unadjusted mortality rates for patients in each group during calendar year 2018 are displayed for our H-AKI cohort and the overall hospitalised population in England (Supplied by NHS digital).[27]

Table 1: Adjusted odds ratios and confidence intervals from the logistic regression model used to calculate NHS Hospital Trust Standardised Mortality Ratios (SMRs)

The odds ratios for each covariate in our final logistic regression model are shown in this table. Increasing age, higher AKI warning level at first alert, higher comorbidity score, male sex, emergency admission and admission during winter months were all found to be associated with a higher risk of death.

Supplementary Table S3: Adjusted odds ratios and confidence intervals from the logistic regression model used to calculate NHS Hospital Trust Standardised Mortality Ratios (SMRs) – data presented for each individual variable. In this version of Table 1, the odds ratios are presented for each individual variable. *Due to interactions in the model, ORs must be presented at a certain level of other variables. Age OR presented for Age = 77, AKI level 2, Pneumonia diagnosis group and comorbidity score = 0. Comorbidity score OR presented for Age = 77 and Pneumonia Diagnosis group. AKI alert warning level OR presented for Age = 77. Diagnosis Group OR presented for Age = 77 and Comorbidity score = 0. This table is accompanied by "predictibilty plots"* for the four largest diagnosis groups, displaying the predicted probability of mortality across the age ranges, at various levels of selected risk factors. Each small plot contains a separate line for each AKI alert level, and the four plots for each diagnosis group are for four different values of Comorbidity Score. The probabilities are

all calculated for Female patients with an Emergency Admission in July. The table also displays odds ratios for mortality across each month of the year and individual diagnosis groups.

Figure 3: Funnel Plot of Standardised Mortality Ratios (SMRs) by Hospital Trust

Each patient in our cohort was given an individual expected probability of dying, based on the coefficients from the logistic regression model (Table 1) that corresponded to their individual risk factors. The expected probability for each patient was summed across all patients at each trust, to calculate the overall expected number of deaths at that trust. Standardised Mortality Ratios (SMRs) were then calculated as the observed number of deaths divided by the expected number of deaths. Owing to the large amount of variation between trusts, the funnel plot is presented with 95% and 99.8% control limits, inflated using an additive random-effects model with a 10% trim for over-dispersion. Significant national variation was observed in trust SMRs, with 23 of 103 trusts shown to be outliers (95% control limits), 12 with higher SMRs and 11 with lower SMRs.

Figure 4: Standardised Mortality Ratios (SMRs) for trusts in the four largest diagnosis groups in H-AKI cohort

Logistic regression models were run to explore centre variation in 30 day mortality, specifically for patients within the 4 largest diagnosis groups. These were pneumonia, septicaemia, congestive cardiac failure and hip fracture. The included terms in the model for this analysis were age, sex, comorbidity score, AKI severity, month of AKI, and admission method. Funnel plots were created using outputs from this model. We found that within these diagnosis groups, fewer trusts were outside of the 95% control limits than when mortality for all patients with H-AKI was compared across trusts.

Figure 5: Funnel plot of Standardized Mortality Ratios (SMRs) by Hospital Trust for patients with AKI2 & AKI3: Presentation at nephrology centre added as a covariate

Presentation at a trust with a co-located nephrology centre was added to the logistic regression model previously used to calculate trust SMRs. The model was limited to patients first presenting with AKI2 or AKI3 and funnel plots were generated from the outputs. 95% and 99.8% control limits included on the plot. There was a small but statistically significant reduction in risk of mortality for patients presenting at centres with specialist nephrology services (Odds Ratio 0.91, 95% confidence limits 0.87-0.96)

Table 2: Odds ratio from logistic regression model with ethnicity and deprivation included

In this table we have added patient ethnicity and deprivation data to the logistic regression model used to generate trust SMRs (Table 1). South Asian and Black ethnicity were associated with a lower risk of mortality compared to White patients. The most deprived quintile had higher mortality than other quintiles. Only ethnicity and deprivation data are presented in this table, with the complete model output presented in Supplementary Table S4.

Supplementary Table S4: Odds ratio from logistic regression model with ethnicity and deprivation included

The full output from logistic regression model displayed in Table 2.

Table 3: Re-weighting of Charlson Comorbidity Score for patients with AKI

The Summary Hospital-Level Mortality Indicator (SHMI) methodology uses a reweighting of the Charlson Comorbidity Index (CCI) by Dr Foster Intelligence from their 'Hospital Standardised Mortality Ratio (HSMR)' methodology.[19] In order to more accurately reflect comorbidities amongst patients with AKI, a reweighting of the score given to each comorbidity group, calculated using the Master Patient Index (MPI).

Figure 6: Funnel Plots demonstrating impact of case-mix adjustment on variation in Trust Standardised Mortality Ratios (SMRs)

4 funnel plots are displayed, demonstrating variation in SMRs for patients with H-AKI across included hospital trusts. The plots demonstrate sequential reduction in the number of outlying trusts as our model was built from unadjusted to age-sex adjusted, age-sex-AKI level adjusted and age-sex-primary diagnosis-comorbidity score-AKI severity-month of AKI-admission method adjusted (final model). The impact of case-mix adjustment in explaining some of the variation observed in trust SMRs is clear from these plots

Figure 7: Modified Bland-Altman plots displaying changes in trusts' expected deaths calculated during model development

To assess what impact on trusts' standardised mortality ratios inclusion of additional covariates into the logistic regression model had, figures similar to Bland-Altman plots were created.[25] Obtaining the expected deaths for each trust from two nested models and plotting the difference between the two values against the mean of the two values allows a visualisation of the effect of the additional covariates upon the SMRs. Trusts displayed outside of the guidelines of $y=\pm 0.05x$ have more than 5% difference in their SMR between the two models. Here we can visualise that the greatest difference in number of expected deaths was

when an age and sex adjusted model was compared to an unadjusted model and when the age and sex adjusted model was compared to our final model.