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Understanding the relationship between surgical specialisation and outcomes following emergency surgery for colorectal cancer – a retrospective population-based study in the English NHS

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ABSTRACT

Introduction: Emergency colorectal cancer (CRC) surgery is associated with poor postoperative outcomes. In England, subspecialisation in general surgery has led to elective CRC surgery being provided by specialist CRC surgeons, while surgery for patients presenting as an emergency remains more variable. This study aimed to investigate the relationship between surgical specialisation and outcomes following emergency CRC surgery.
Materials and methods: Population-level study of all patients in England who underwent an emergency major surgical resection for CRC (2014–2019). CRC specialist surgeons were identified using their annual workload of elective and emergency resections and membership of a CRC multidisciplinary team. Multivariable logistic regression and Cox Proportional Hazards models were used to assess the relationship between specialisation and postoperative mortality and survival.
Results: During the study period, 14,065 patients underwent emergency major resections. Overall, 3962 surgeons were responsible for the operations, 931 were identified as specialist CRC surgeons. Following adjustment, patients whose major surgical resection was undertaken by a non-CRC specialist surgeon were significantly more likely to die within 30- (OR 1.25 95 %CI 1.08–1.45) and 90- (OR 1.29 95 %CI 1.17–1.44) days of surgery, and less likely to survive to two-years compared to those who were operated by a CRC specialist surgeon (HR 1.12 95 %CI 1.06–1.18).
Conclusion: Fewer than 3 in 5 patients needing an emergency operation for CRC benefit from being under the care of a CRC specialist surgeon. Better postoperative outcomes in patients presenting for emergency major bowel resection are associated with procedures that were undertaken by a CRC specialist.

1. Introduction

Emergency surgery for colorectal cancer (CRC) has been shown to be associated with poor postoperative outcomes, including higher postoperative mortality and in-hospital deaths, higher complication rates and lower disease free and overall survival rates [1–5]. These outcomes have been widely shown to be consistent even after adjustment for patient and tumour factors such as increasing comorbidity and advanced stage of disease. This has led others to hypothesise that factors such as the specialisation of the surgeon leading the operation, duration of time in theatre and speciality of the ward an individual is returned to may be significantly affecting the outcomes in question [6].

Since the Calman Hine report [7], reforms have introduced subspecialisation in general surgery, in the United Kingdom (UK), which

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has led to a subset of general surgeons with an interest in colorectal surgery or colorectal surgeons performing most elective colorectal cancer resections [8,9]. This change was reinforced by the development of multidisciplinary teams (MDTs) that were mandated by the NHS Cancer Plan [10] and regulated by a programme of National Cancer Peer Review.

Whilst care for individuals who present for surgery through an elective pathway has largely been standardised and protocolised [11] the question around who should operate on individuals with CRC who present as an emergency is ongoing. In the UK, there is variation in the speciality of those managing patients presenting with colorectal cancer as an emergency.

A study from Sweden found no significant reduction in short- or long-term survival associated with the specialisation of the surgeon undertaking the emergency resection for colon cancer and 30- or 90 day mortality, 5-year overall survival or 3-year recurrence free survival [12]. A study from the UK identified a reduction in 30-day post-operative mortality associated with CRC specialist surgeons however; this result was not significant following multivariable adjustment [13].

In contrast, others have shown a significant reduction in poor post-operative outcomes when comparing CRC-specialists to non-CRC specialist surgeons. The second report from the Emergency Laparotomy Network, with data from 35 NHS hospitals, indicated a significantly lower 30-day mortality for emergency colonic procedures performed by specialist colorectal surgeons compared with procedures performed by general surgeons without a colorectal specialism [14]. In a single institution observational study of emergency colorectal resections from 1993 to 2006 in Barcelona, the 30-day and in-hospital mortality was 18 % for patients operated by colorectal surgeons and 28 % when operated by general surgeons [15]. A study using the Swedish Colorectal Cancer Registry demonstrated a 5-year survival benefit with 35 % vs 31 % patients surviving emergency operations by colorectal and general surgeons, respectively [16].

Previous studies have differed in terms of whether there was a significant association between surgeon specialisation and outcomes, many studies have been restricted to include only colon cancers. The largest studies, to date, have come from Sweden, which has, at most, a fifth of the population of England with a lower density population and a better-resourced health economy [17,18]. This study aims to examine variation across the English NHS in the specialisation of surgeons undertaking colorectal cancer resections in an emergency setting and to understand the relationship between surgical specialisation and outcomes following emergency surgery for colorectal cancer.

2. Methods

2.1. Data and study cohort

Data for all patients who underwent a major surgical resection for CRC (ICD-10C18-C20) undertaken between January 1, 2014 and December 31, 2019 were obtained from the COloRECTal cancer data Repository (CORECT-R) [19]. This resource contains linked data from the National Cancer Registration and Analysis Service (NRCAS) dataset and Hospital Episode Statistics (HES) data [20,21]. Information extracted included age, sex, stage of CRC at diagnosis, site of tumour within the colon or rectum, socioeconomic status using the income domain of the Index of Multiple Deprivation (IMD) score and Charlson comorbidity score.

2.2. Specialisation

Individual surgeons were classified as CRC-specialist if they were included in the CRC Clinical Outcomes Publication (COP) 2020 [22] meaning they were a member of a colorectal multidisciplinary team (Type A), had a median annual workload of $\geq$20 elective or emergency CRC cases (Type B) or had a maximum annual workload of $\geq$20 elective or emergency CRC cases (Type C) (Fig. 1).

The median annual workload was calculated for each consultant responsible for care (using the General Medical Council (GMC) number) based on the number of major resections (elective and emergency) for colorectal cancer recorded in the HES data over the study period. Cases with incorrect GMC numbers, i.e. numbers that did not match any record held with the GMC (n = 393) were excluded from any further analysis. A median annual workload of $\geq$20 was used corresponding to previous national guidelines and recommendations [23–25]. To account for periods of training individual surgeons with a maximum annual workload of $\geq$20 major surgical resections for colorectal cancer (elective or emergency) were also classified as specialist. The three different methodologies used to identify CRC specialist surgeons (Fig. 1) were combined to produce a distinct group with surgeons being classified as specialist if they were flagged in any one of the three classifications.

2.3. Outcomes

Analyses were restricted to include only those patients whose major surgical resection was undertaken as an emergency at an NHS hospital, including all open, laparoscopic and robotic procedures. An emergency resection was defined as a resection that satisfied the following two criteria: 1) the method of admission for the resection procedure was recorded within the HES dataset as an emergency (e.g. through an accident and emergency department, or an emergency transfer, and 2) the number days between the admission and the resection was within two calendar days.

Thirty-day postoperative mortality was defined as a death occurring within 30-days of a major surgical resection, 90-day postoperative mortality as a death within 90-days. Death within the surgical episode was defined as a death occurring within the same admission to an NHS hospital as the emergency major surgical resection.

2.4. Statistical analysis

Descriptive analysis using Pearson's chi-squared statistic was used to compare the characteristics of patients who had their emergency major surgical resection performed by a CRC specialist surgeon and a non-CRC specialist. The proportion of resections undertaken by a CRC specialist was calculated for each MDT responsible for each operation. A funnel plot with the unadjusted proportion of resections undertaken by a CRC specialist and MDT workload was constructed to identify the number of outlying MDTs compared to the national average. As there was evidence of overdispersion, Laney's approach was used to correct the 95 % and 99.8 confidence limits of the funnel plot [26].

Multivariable logistic regression models were used to assess the relationship between surgeon specialisation and the risk of post-operative mortality. The adjustment variables included the following patient characteristics: age, sex, socioeconomic status, Charlson co-morbidity score, tumour site (right colon, left colon, colon unspecified, rectosigmoid and rectum), stage of disease at diagnosis (I, II, III, IV or unknown). These were included to adjust for patient prognosis and general health condition since variables directly measuring aspects such clinical performance status were not available. Additional adjustment variables included day of operation (weekday or weekend) and year of emergency major surgical resection (included as a continuous variable). Day of operation was included as some previous studies have shown an association of postoperative mortality with whether the patient's emergency colorectal surgery was performed during the week or weekend [27].

Sensitivity analyses were performed for the multivariable logistic regression models. Firstly, models were repeated while excluding those surgeons categorised as a CRC specialist based on workload alone (Type B and Type C). Secondly, models were repeated after Type B and Type C surgeons were reassigned to the non-CRC specialist group. Thirdly, to account for any influence of surgical team workload, 3 strata were

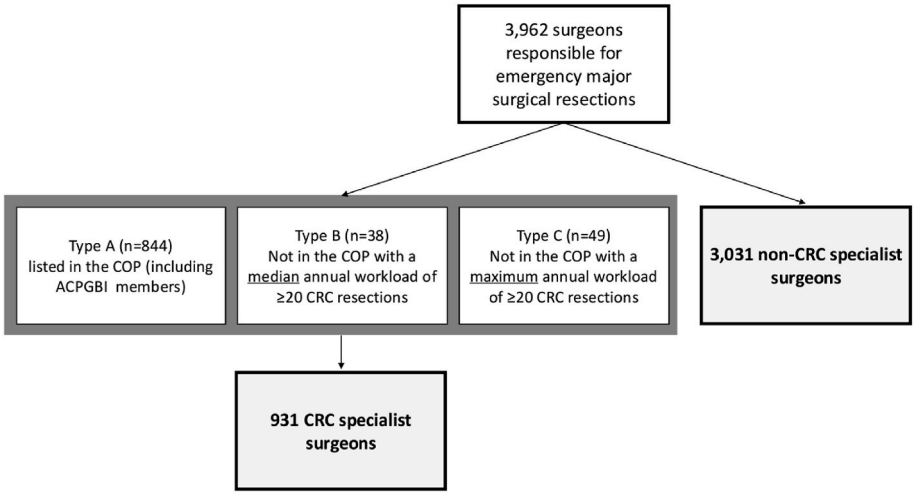

Fig. 1. Definition of CRC specialist surgeon.

created: low-, medium- and high-workload, based on the tertiles of MDT workload and the models were then repeated for each stratum.

Kaplan-Meier curves were used to describe overall survival following an emergency major surgical resection, stratified by speciality of the surgeon in charge of care. Multivariable Cox proportional hazards model were used to quantify the relationship between surgeon specialisation and survival (2-year and 5-year) after adjustment for other patient (age, sex, socioeconomic status, comorbidity) and tumour characteristics (stage and site).

Table 1
Characteristics of patients undergoing an emergency major surgical resection for colorectal cancer.

		Overall		CRC specialist		non-CRC specialist		
		n	%	n	%	n	%	P-value (χ^2-test)
Age (years)	<50	1265	9.0	720	8.5	545	8.9	0.231
	50–69	5382	38.3	3137	37.0	2245	36.6	
	70–84	6452	45.9	3778	44.6	2674	43.6	
	≥85	1506	10.7	842	9.9	664	10.8	
Sex	Male	7608	54.1	4412	52.0	3196	52.2	0.898
	Female	6997	49.7	4065	48.0	2932	47.8	
Socioeconomic status	1 – Least deprived	3140	22.3	1811	21.4	1329	21.7	0.002
	2	3353	23.8	2048	24.2	1305	21.3	
	3	2939	20.9	1662	19.6	1277	20.8	
	4	2761	19.6	1576	18.6	1185	19.3	
	5 – Most deprived	2412	17.1	1350	15.9	1032	16.8	
Charlson comorbidity score	0	9922	70.5	5834	68.8	4088	66.7	0.033
	1	2869	20.4	1613	19.0	1256	20.5	
	2	1103	7.8	638	7.5	465	7.6	
	≥3	711	5.1	392	4.6	319	5.2	
Tumour site	Right colon	7445	52.9	4388	51.8	3057	49.9	<0.001
	Left colon	5732	40.8	3232	38.1	2500	40.8	
	Colon, unspecified	276	2.0	133	1.6	143	2.3	
	Rectosigmoid	456	3.2	264	3.1	192	3.1	
	Rectum	696	4.9	460	5.4	236	3.9	
Stage of CRC	I	360	2.6	231	2.7	129	2.1	0.004
	II	4450	31.6	2650	31.3	1800	29.4	
	III	5718	40.7	3287	38.8	2431	39.7	
	IV	3587	25.5	2044	24.1	1543	25.2	
	Unknown	490	3.5	265	3.1	225	3.7	
Day of week	Weekday	10,979	78.1	6443	76.0	4536	74.0	0.006
	Weekend	3626	25.8	2034	24.0	1592	26.0	
Year of emergency major surgical resection	2014	2330	16.0	1321	15.6	1009	16.5	0.449
	2015	2521	17.3	1459	17.2	1062	17.3	
	2016	2527	17.3	1487	17.5	1040	17.0	
	2017	2370	16.2	1354	16.0	1016	16.6	
	2018	2476	17.0	1466	17.3	1010	16.5	
	2019	2381	16.3	1390	16.4	991	16.2	
Total		14,605		8477		6128		

3. Results

3.1. Patient characteristics

Of the 14,065 patients who underwent an emergency major surgical resection over the study period 58.0 % (n = 8477) had their procedure performed by a surgeon who was classified as a CRC specialist. Emergency major surgical resections performed by CRC surgical specialists involved fewer patients with higher levels of comorbidity (4.6 % had a Charlson score of ≥3 compared to 5.2 % amongst non-CRC specialists p = 0.033), less frequently had stage IV disease (24.1 % versus 25.2 % p = 0.004) and less often occurred at the weekend (24.0 % versus 26.0 % p = 0.006). A greater proportion of emergency major resections undertaken by surgeons identified as CRC specialists were for tumours in the right colon (51.8 % versus 49.9 %) and the rectum (5.4 % versus 3.9 %) (Table 1).

The type of major surgical resection varied by surgeon specialisation, the use of subtotal excision of the colon and rectum was higher amongst non-CRC specialist surgeons compared to CRC specialists (4.8 % versus 3.8 %), as was the use of Hartmann's procedure (19.5 % versus 17.5 %), whereas the reverse was true for anterior resection (4.4 % versus 6.3 %) (Supplementary Table S1).

3.2. MDT variation

The proportion of emergency CRC major surgical resections undertaken by CRC specialist surgeon at English MDTs, ranged from 8.1 % to 87.4 %. After adjustment for overdispersion, 3 MDTs were identified as having a significantly lower proportion than the national average at the 95 % level (Fig. 2).

3.3. Postoperative mortality

Overall, 5.3 % of patients who underwent an emergency major surgical resection died within the surgical episode, 7.7 % within 30-days of the operation, and 11.7 % within 90-days of the operation. Thirty-day postoperative mortality was lower amongst cases managed by a CRC specialist than those managed by a non-CRC specialist (6.5 % versus 9.4 %). After adjustment for age, sex, stage of disease, socioeconomic status, Charlson comorbidity score, site of tumour and weekday, odds of death within 30-days of a major surgical resection were significantly higher for those whose major resection was undertaken by a non-CRC specialist when compared to those operated on by a CRC specialist surgeon (OR 1.47 95 %CI 1.29–1.66, p < 0.001) (Table 2).

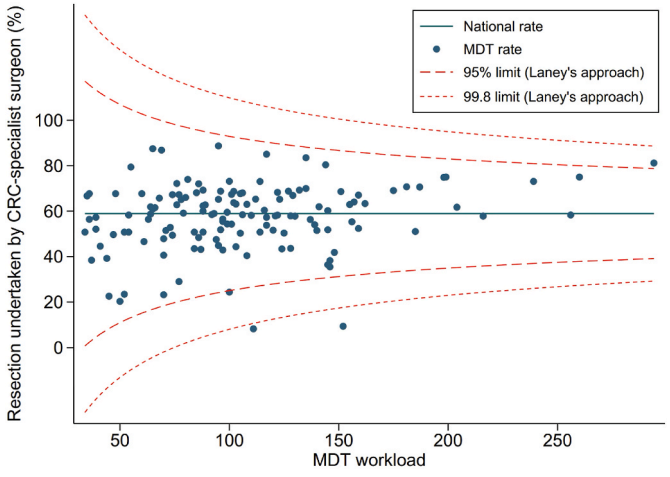

Fig. 2. Funnel plot for the observed percentage of major surgical resections undertaken by a CRC specialist surgeon at MDTs responsible for the operation. Each dot represents one MDT and is plotted against their MDT workload (volume). The horizontal line represents the national average. MDTs falling outside of the control limits are considered outliers at the 95 % level (2 standard deviations from the average) and 99.8 % level (3 standard deviations from the average).

The higher odds of death for those operated on by a CRC specialist surgeon remained at 90-days, where the crude rate for cases managed by a CRC specialist surgeon was 10.4 % compared to 13.4 % amongst those managed by a non-CRC specialist surgeon. Following adjustment for patient and tumour factors the odds of death within 90-days was significantly higher for those operated on by a non-CRC specialist surgeon (OR 1.29 95 %CI 1.17–1.44, p < 0.001). Similarly, the crude rate of death within the same surgical episode as the emergency major surgical resection was also higher for those whose resection was undertaken by a non-CRC specialist (6.1 % versus 4.8 %). Following adjustment for patient and tumour factors the odds of death within the surgical episode was significantly higher for those operated on by a non-CRC specialist surgeon (OR 1.29 95 %CI 1.17–1.44, p < 0.001) (OR 1.25 95 %CI 1.08–1.45). Full results of univariable and multivariable models for each outcome can be found in Supplementary Table S2–S4.

3.4. Sensitivity analyses

Excluding patients categorised through the workload criteria (Type B and Type C) had a negligible impact on the adjusted ORs for postoperative mortality when comparing odds of death for patients those resection was undertaken by CRC specialist compared to a non-CRC specialist. Similarly, reassigning Type B and Type C surgeons to the non-CRC specialist group had little impact on the adjusted ORs (Supplementary Table S5 and S6).

When stratifying by MDT volume, for the high volume stratum, there was not a significant difference in the odds of death within the surgical episode for those managed by a CRC specialist compared to a non-CRC specialist surgeon (OR 0.94 95 %CI 0.72–1.22, p = 0.622). However, there was a significant difference in the odds of death between those managed by a CRC specialist compared to a non-CRC specialist surgeon for 30-day postoperative mortality (OR 1.25 95 %CI 1.00–1.66, p = 0.049) and 90-day postoperative mortality (OR 1.23 95 %CI 1.02–1.48, p = 0.027). The adjusted ORs comparing odds of death between those managed by a CRC specialist compared to a non-CRC specialist surgeon in the low and medium stratum showed a small increase when compared to the unstratified models and were all significant (Supplementary Table S7).

3.5. Survival

Within 2-years of their resection, 39.3 % of patients who underwent an emergency major surgical resection for colorectal cancer had died. For those who were operated on by a CRC specialist surgeon this was 37.6 % compared to 41.8 % for those operated on by a non-CRC

Table 2
Results from multivariable logistic regression models in relation to CRC specialisation.

Outcome	Speciality	Died (N)	Died (%)	Adjusted OR (95 % CI)	P-value
Death in the surgical episode	CRC specialist	403	4.8	1.00 reference	
	Non-CRC specialist	373	6.1	1.25 (1.08–1.45)	0.003
30-day postoperative mortality	CRC specialist	547	6.5	1.00 reference	
	Non-CRC specialist	573	9.4	1.47 (1.29–1.66)	<0.001
90-day postoperative mortality	CRC specialist	884	10.4	1.00 reference	
	Non-CRC specialist	820	13.4	1.29 (1.17–1.44)	<0.001

specialist surgeon. Overall survival for those who were operated on by a non-CRC specialist was lower than that for those operated on by a CRC specialist surgeon (Fig. 3). Patients whose major surgical resection was undertaken by a non-CRC specialist surgeon were significantly less likely to survive to both two-years and five-years from the operation compared to those who were operated on by a CRC specialist surgeon (multivariable Cox proportional model: HR 1.12 95 %CI 1.06–1.18 and HR 1.10 95 % CI 1.05–1.15 respectively) (Supplementary Table S8 and S9).

4. Discussion

The data from this study indicate both short- and medium-term improvements in outcomes for patients who present as an emergency with bowel cancer if they are operated on by a surgeon identified as a CRC specialist. Fewer than 60 % of patients had the benefit of specialist surgical intervention by the end of the study period. It is surprising that decades after the NHS Cancer Plan [10] the delivery of emergency surgery to patients with CRC by a specialist surgeon ranges from 8.1 % to 87.4 % between surgical centres in England. This is an example of unwarranted variation that was formerly addressed by the National Cancer Peer Review process with inspection visits to all MDTs [28].

For surgeons in training in the UK, the indicative number of colorectal operations for completion of training in emergency general surgery is 20 (performed as elective or emergency procedures). This was published in the most recent General Surgery Curriculum [25]. This is a reduction in colorectal experience required from the previous Intercollegiate Surgical Curriculum Programme (ISCP) document from 2016, which required five Hartmann's procedures in addition to the minimum of 20 elective segmental colectomies [29]. Notwithstanding variability between units, the data indicate for the study period there were fewer that one operation performed annually per surgeon. Surgeons who do not perform colorectal resections in their elective practice after training are therefore unlikely to develop mastery of the techniques involved when compared with colleagues who regularly perform both elective and emergency colorectal resections. Participation in a formal surgical skills qualification such as the Endoscopic Surgical Skill Qualification System (EESQS) in Japan may improve patient outcomes [30]. While no such accreditation system for emergency surgery currently exists in the UK, an introduction of one may help reduce complication rates and postoperative mortality rates.

The proportion of Hartmann's procedures performed by non-CRC specialists was higher than for CRC-specialists in our study. Reversal of Hartmann's involves another major operation and is associated with a high complication rate [31]. Consequently, patients undergoing Hartmann's procedure are often left with a permanent stoma [32] which can significantly impact long-term quality of life [33]. Increasing the number of procedures performed by CRC-specialist may therefore also improve quality of life outcomes in addition to the mortality outcomes studied here and should be considered in subsequent studies.

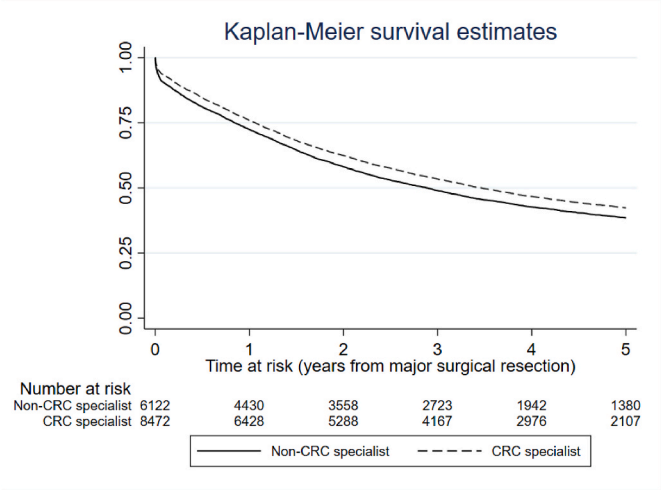

Fig. 3. Kaplan-Meier curves of overall survival following emergency major surgical resection, stratified by specialist status of surgeon in charge of care.

The large variation across surgical centres for the proportion of surgery performed by CRC-specialists may be due to several reasons. The latest organisational survey performed by the National Bowel Cancer Audit (NBOCA) in England and Wales, found that only 13 % of centres had a CRC-specialist always on call and thus ensuring patients requiring emergency surgery were always cared for by a specialist [34]. The availability of onsite bowel stenting may also have an impact on whether patients undergo emergency surgery immediately or they are stabilised and to then undergo an elective procedure (bridge to surgery). Stenting is a difficult technique that should be performed by those with the skill and experience. Bridge to surgery patients will be recorded as an elective patient by our definition and so excluded from our study. However, a centre having less CRC-specialists to perform stenting may result emergency surgery being more likely performed by a non-CRC specialist.

There are limited previous studies published, making international comparison difficult. A Swedish study of 656 patients found no difference in survival rates or postoperative mortality between surgeons classified in teams as colorectal, emergency surgical or general surgical [12]. A larger study in Denmark which included 4354 patients undergoing emergency surgery found a significant association between surgical specialisation and 90-day mortality, however, this was not significant after adjusting for hospital volume [35]. Denmark has undergone a period on centralisation for colorectal cancer surgery, which may help explain the impact of volume in the Danish study. In our study, the association between mortality and specialisation was attenuated in only the high volume stratum, however, a high volume hospital may have more CRC specialists which may confound the results. Denmark also has included emergency surgery performed by a specialist in their annual reporting of quality performance indicators, setting the desired rate at 90 % [36]. The observed rate of specialist led operations in Denmark increased from approximately 50 % in the mid-2000s to 80 % in the mid-2010s. This may have contributed to the improved mortality outcomes in patients undergoing emergency surgery.

While our study on surgical specialisation is the largest to date there are several limitations which should be considered. The most important limitation in our study may be the lack of confounding variables that were not possible to include. Clinical variables such as ASA grade and information on presentation such as obstruction and perforation would by highly relevant and enable better interpretation of the reasons behind the variation observed. Although we were able to include proxies for poorer health condition, such as Charlson comorbidity score and socioeconomic status, these variables are relatively blunt and insufficient to identify those patients with a poorer prognosis on presentation and reduce residual confounding. Unfortunately, the ideal level of clinical information required is not captured in the administrative, population-based datasets this study is based upon. Further studies, based upon richer data, are needed to confirm the mortality differences observed are due to levels of surgical specialisation rather than baseline case severity.

Not all GMC numbers could be matched with records held so were excluded from the analysis. These only constituted approximately 1 % of all cases and was most likely due to data input error at the source and this is therefore unlikely to impact the results. Additionally, only one consultant code can be recorded for the episode of care within the HES dataset, therefore if more than one surgeon/consultant is present, only one of these is attributed the case. In most cases the recorded surgeon will be the one with overall responsibility for the patient's care within that episode and therefore the most senior consultant, but it is not possible to verify this.

As the GMC specialist register does not record subspecialist interest for all registered general surgeons, we have made a pragmatic definition

of CRC specialist based on surgeon workload from HES data and presence in the COP. It is important to note that the definition of CRC specialist used in this study is likely to classify clinicians who are not classically defined as colorectal surgeons, such as emergency surgeons and other gastrointestinal surgeons who undertake a high number of CRC resections annually, as CRC specialists. This definition relies on practice over the study period and does not consider previous practice meaning it may also exclude some surgeons from the specialist category due to relinquished membership of an MDT or declining workload. Our sensitivity analyses showed that the workload classification had little impact on the results, but it was not possible to estimate the ascertainment level of surgical specialisation based on publication within the COP.

Early and mid-term outcomes following emergency major surgical resection for CRC were significantly better for those who were under the care of a CRC specialist surgeon. Further work to investigate the postoperative pathway for patients who undergo an emergency major surgical resection is needed to determine factors associated with this, such as intra operative decision making, postoperative complications and markers of quality of surgery such as nodal yield.

5. Conclusions

This study observed a 3 % lower 90-day postoperative mortality for patients who were operated on by a CRC specialist compared to a non-CRC specialist. A significant survival benefit was also demonstrated at 2 years for patients having emergency surgery under the care of a CRC surgeon. In addition, an unwarranted variation in the delivery of emergency surgery for patients with CRC has been described. These factors may be considered in the evaluation of CRC surgical services, as has been done for trauma and upper GI cancer surgery, with an aim to ensure the standard of surgical care is for emergency operations to be undertaken by specialist surgeons.

Ethics approval

23/SW/0069 - South West - Central Bristol Research Ethics Committee.

Availability of data and materials

The data used for this study are available from the National Cancer Registration and Analysis Service via the Data Access Request Service at NHS England, or via CORECT-R, subject to relevant approvals.

Authors contributions

Study conception and design (RB, PF, EM and MM), data acquisition (EM), quality control of data and algorithms (RB, EM), data analysis and data interpretation (RB, JT, AD, NB, PF, PQ, EM and MM), statistical analysis (RB, JT), manuscript preparation (RB, JT, PF, EM and MM), manuscript editing (RB, JT, AD, NB, PF, PQ, EM, and MM), manuscript review (RB, JT, AD, NB, PF, PQ, EM, and MM). All authors have approved the submitted manuscript.

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Role of the funding source

The funders had no role in the study design, collection, analysis or interpretation of the data, the writing of the manuscript or the decision to submit for publication.

Conflict of interest

None to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejso.2025.111181.

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