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Research paper

National cost savings, operational and safety benefits from use of magnetocardiography in the assessment of emergency department chest pain patients

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ABSTRACT

Study objectives: Patients frequently present to the emergency department (ED) with chest pain requiring further risk stratification. Traditional cardiac diagnostics such as stress testing may expose patients to ionizing radiation, may not be readily available, may take significant time for testing and interpretation, and adds cost to the workup. Magnetocardiography (MCG) is an alternative approach to assess candidates more quickly and efficiently than routine downstream testing.
Design: We created and ran 1000 trials of a Monte Carlo simulation. Using this simulation, we modeled the national annual impact by averting further cardiac diagnostics.
Setting: All EDs in the United States.
Participants: All ED adult patients with chest pain.
Interventions: Simulated use of MCG to reduce avoidable downstream cardiac diagnostics.
Main outcome measures: Our primary outcome was to estimate the impact of an MCG-first strategy on the annual national cost savings among eligible patients in the ED. Our secondary outcomes were the estimated reduction in short-stay hospitalizations, cancer cases, and cancer deaths due to radiation exposure.
Results: An MCG-first strategy was estimated to save a mean (±SD) of $574 million (±$175 million) by avoiding 555,000 (±93,000) downstream cardiac diagnostic tests. This resulted in a national annual cumulative decrease of 500,000 (±84,000) hospitalizations, 7,600,000 (±1,500,000) bed hours, 409 (±110) new cancer diagnoses, and 210 (±56) new cancer deaths due to radiation exposure from avoidable cardiac diagnostics.
Conclusions: If adopted widely and used consistently, an MCG-first strategy among eligible patients could yield substantial benefits by averting avoidable cardiac diagnostic testing.

1. Introduction

Chest pain is the second leading cause of emergency department (ED) visits in adults in the United States, representing almost 7.8 million encounters and approximately 5.5 % of all ED visits [1]. Current tools (e.g., high sensitivity troponin [hsTn], electrocardiogram [EKG]) have limited ability to diagnose ischemia, including unstable/crescendo angina, unstable plaque, and other conditions that may merit early interventions such as Cardiology consultation, medication and risk factor optimization, and even cardiac catheterization with revascularization. As a result, a substantial portion of ED patients are further observed in the ED, observation unit, or inpatient setting for downstream cardiac testing (e.g., coronary computed tomography angiography [CCTA] or stress testing [ST]) or referred for outpatient testing within days following the ED visit. These tests add substantial time, cost and often ionizing radiation exposure to the patient's encounter.

Magnetocardiography (MCG) is a rapid, non-invasive, radiation and contrast-free method that records the magnetic fields generated by the

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heart's electrical activity and can be performed while the patient rests. Various studies have demonstrated comparable sensitivities when comparing MCG to ST in detecting ischemic myocardium. Most recently, the MAGNETO trial revealed a comparable sensitivity of 66.7 % in MCG vs. non-invasive ST in detecting myocardial ischemia [2]. This same study revealed that the median time to test for patients undergoing MCG was 2.9 h versus 22.9 h for all STs.

Incorporation of MCG into the ED workflow of chest pain evaluation after EKG and troponin testing may offer numerous advantages in today's healthcare landscape, which is marked by limited resources and overcrowded facilities. Rather than an extended, often overnight stay due to limited availability of CCTA or ST, MCG would be completed within minutes and could potentially be performed 24 h per day, thus substantially reducing hospital length of stay (LOS). This approach minimizes risks associated with standard downstream cardiac testing modalities, such as radiation exposure and adverse reactions to pharmacologic and contrast agents, and mitigates the inherent risks of hospitalization. Moreover, implementing MCG presents a promising avenue for significant cost savings for patients and healthcare institutions. This paper explores the potential of a widely adopted MCG-first approach to reduce downstream cardiac testing and radiation exposure as a time-saving and cost-efficient alternative in the evaluation of ED chest pain patients.

2. Materials and methods

2.1. Study population and design

We developed a Monte Carlo simulation model to estimate the annual cumulative number of cardiac diagnostic tests averted, national healthcare cost savings, short-stay hospitalization reductions, and preventable radiation exposure from using an MCG-first approach among ED patients with chest pain who require additional cardiac testing at the end of their initial ED evaluation. A Monte Carlo simulation runs many model iterations using random values selected from the data distributions for each input. The results of all iterations are then averaged so that each outcome variable is represented with a distribution, mean, and standard deviation of the final estimate, accounting for the uncertainty native to the model inputs.

Monte Carlo simulations have previously been utilized in medical research, including a study evaluating the national cost savings from increased use of dedicated observation units [3]. We ran a standard 1000 model iterations using input parameters derived from the most recent data distributions available in the literature. This study analyzed publicly available data and was exempt from institutional board review at our institution.

We display our model and inputs in Fig. 1 and Table 1. We used Medicare payments as a proxy for costs, consistent with previous cost savings analyses [4]. We assumed a 10 % relative standard deviation for input estimates when not otherwise specified, with a lower and upper bound of 0 % and 100 % for percentages. Further, due to the lack of a reliable and available estimate of the proportion of ED chest pain patients undergoing further cardiac diagnostics for whom a negative MCG result would permit an immediate discharge, we assumed a value of 90 % in our base case and performed a sensitivity analysis around this value.

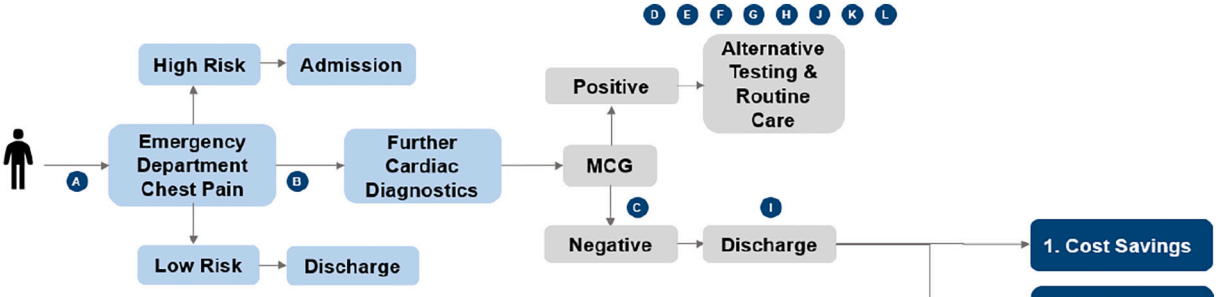
2.2. Statistical analysis

We used Crystal Ball (Release 11.1.2.4, Oracle Corporation, Austin, TX) for our analysis. We assumed a normal distribution for all inputs with reported standard deviations (SD). However, we assumed a Beta-PERT (Beta Program and Evaluation Review Technique) distribution for inputs associated with an interquartile range or 95 % confidence interval. BetaPERT distributions are smooth distributions characterized by minimum, most likely, and maximum values [5,6]. Accordingly, they are most appropriate for describing variables with a reported range of values.

3. Results

3.1. Main model outputs

We found that an MCG-first strategy resulted in a mean national annual savings of (±SD) of $574 million (±$175 million) by avoiding 555,000 (±93,000) downstream cardiac diagnostic tests (See Fig. 2). Further, our model produced a cost estimate of $3.4 billion in the base case, indicating that an MCG-first approach would yield about 14.4 % in



Model Inputs:
(A) Annual number of adult ED visits for chest pain
(B) Percentage of ED chest pain visits with subsequent cardiac diagnostics
(C) Percentage of MCG tests that are negative
(D) Distribution of cardiac diagnostic types (e.g., SPECT, PET, ETT, stress echo, CCTA)
(E) Medicare reimbursement for routine cardiac diagnostics
(F) Medicare reimbursement for MCG
(G) Medicare reimbursement for observation hospitalization (APC 8011) vs ED facility visit charge (99825)
(H) Length of stay in hospital for patients waiting for cardiac diagnostics to be performed and read
(I) Percent of patients with cardiac diagnostics being rate-limiting step for discharge
(J) Radiation exposure by study type (mSv)
(K) New cancer cases and deaths, by gender, per 100 mSv radiation exposure

Model Outputs:
1. Annual Cost Savings from Averted Routine Cardiac Diagnostics = (A * B * C * D * E) + (A * B * C * G) - (A * B * F)
2. Annual Cumulative Reduction in Bed Hours = A * B * C * D * H * I
3. Annual Avoided Hospitalizations = A * B * C * I
4. New Cancer Cases and Deaths Avoided = A * B * C * D * J * K

Fig. 1. Model Inputs.

Table 1
Model inputs.

Input	Description	Estimate	SD or Interval	Distribution Type	Source & Reference
A	Annual Number of ED chest pain visits in the US	7,811,000	649,000	Normal	2021 NHAMCS [1]
B	Percentage of patients in "A" who receive further cardiac diagnostics within a week of the ED visit	18.5 %	1.9 %	Normal	2011 MarketScan Commercial Claims and Encounters data [24]
C	Percent of patients with negative MCG results in population "B"	38.6 %	3.9 %	Normal	Multicenter prospective study [2]
Patients ineligible for MCG plus those with a positive or indeterminant MCG result are the population who go on to further cardiac diagnostics distributed as D.1-D.4					
D.1	Percent of conventional stress tests that are myocardial perfusion tests	64.8 %	0.65 %	Normal	2011 MarketScan Commercial Claims and Encounters data [24]
d.1	Percent of perfusion tests that are SPECT	97.0 %	9.7 %	Normal	Medicare 2010–2019 Physician/Supplier Procedure Summary files [25]
d.2	Percent of perfusion tests that are PET	3.0 %	0.3 %	Normal	Medicare 2010–2019 Physician/Supplier Procedure Summary files [25]
D.2	Percent of conventional stress tests that are Stress Echo	12.0 %	1.2 %	Normal	2010–2017 National Emergency Database [26]
D.3	Percent of conventional stress tests that are ETTs	14.2 %	1.4 %	Normal	2011 MarketScan Commercial Claims and Encounters data [24]
D.4	Percent of cardiac diagnostic tests that are CCTA	7.4 %	0.7 %	Point estimate	2010–2017 National Emergency Database (26)
1. Medicare reimbursement for cardiac testing by type, including MCG					
E.1	Medicare payment for perfusion stress/SPECT (facility)	Bundled in APC 8011	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.2	Medicare payment for perfusion stress/SPECT (interpretation) CPT 78454 (−26)	$62.25	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.3	Medicare payment for PET (facility)	Bundled in APC 8011	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.4	Medicare payment for PET (interpretation) CPT 78942 (−26)	$82.55	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.5	Medicare payment for CCTA (facility)	Bundled in APC 8011	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.6	Medicare payment for CCTA (interpretation) CPT 75574 (−26)	$111.18	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.7	Medicare payment for ETT (facility)	Bundled in APC 8011	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.8	Medicare payment for ETT (interpretation + supervision) CPT 93015 + 93,018	$71.90 + $13.65	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.9	Medicare payment for Stress Echo (facility)	Bundled in APC 8011	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
E.10	Medicare payment for Stress Echo (interpretation) CPT 93351 (−26)	$80.56	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 (27)
F	Medicare payment for MCG	$510.68	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 [27]
G.1	Observation facility cost (APC 8011)	$2610.71	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 [27]
G.2	Medicare facility cost for ED visit CPT 99285	$170.30	NA	Point estimate	CMS Medicare Physician Fee Schedule 2024 [27]
2. Bed hours saved					
H	ED length of stay for patients with chest pain undergoing a traditional cardiac testing approach (bed-hours)	15.3	1.5	Normal	Retrospective data from 6 large US EDs from 2013 to 2015 [28]
3. Avoided hospitalizations					
I	Percent of ED observation chest pain visits where cardiac diagnostics are rate-limiting step to discharge	90 %	NA	NA	Author assumption; see sensitivity analysis
4. Average effective radiation dose from SPECT, PET, and CCTA (mSv)					
J.1	Radiation associated with SPECT perfusion stress testing (mSv)	10	NA	NA	Dose Imaging Registry [29–31]
J.2	Radiation associated with PET perfusion stress testing (mSv)	3	NA	NA	Dose Imaging Registry [29–31]
J.3	Percent of SPECT and PET that is male	57 %	5.7 %	Normal	Large international data registry in 2013 [32]
J.4	Radiation associated with CCTA (mSv)	3	1	Normal	Dose Imaging Registry [29–31]
J.5	Percent of CCTA that is male	47.3 %	4.7 %	Normal	Prospective study at 193 sites in North America between 2010 and 2013 [18]
K.1	Excess solid cancer cases per 100,000 persons from exposure to 100 mSv, males	800	400–1600	BetaPERT	BEIR VII model [33]
K.2	Excess solid cancer cases per 100,000 persons from exposure to 100 mSv, females	1300	690–2500	BetaPERT	BEIR VII model [33]
K.3	Excess leukemia cases per 100,000 persons from exposure to 100 mSv, males	100	30–300	BetaPERT	BEIR VII model [33]
K.4	Excess leukemia cases per 100,000 persons from exposure to 100 mSv, females	70	20–250	BetaPERT	BEIR VII model [33]
K.5	Excess solid cancer deaths per 100,000 persons from exposure to 100 mSv, males	410	200–830	BetaPERT	BEIR VII model [33]
K.6	Excess solid cancer deaths per 100,000 persons from exposure to 100 mSv, females	610	300–1200	BetaPERT	BEIR VII model [33]

(*continued on next page*)

Table 1 (*continued*)

Input	Description	Estimate	SD or Interval	Distribution Type	Source & Reference
K.7	Excess leukemia deaths per 100,000 persons from exposure to 100 mSv, males	70	20–220	BetaPERT	BEIR VII model [33]
K.8	Excess leukemia deaths per 100,000 persons from exposure to 100 mSv, females	50	10–190	BetaPERT	BEIR VII model [33]

SD = standard deviation, ED = emergency department, US = United States, MCG = Magnetocardiography, SPECT = single photon emission computed tomography, PET = positron emission tomography, ETT = exercise tolerance test, CCTA = coronary computed tomography angiogram, APC = ambulatory payment classification, CPT = current procedural terminology, mSv = MilliSievert.

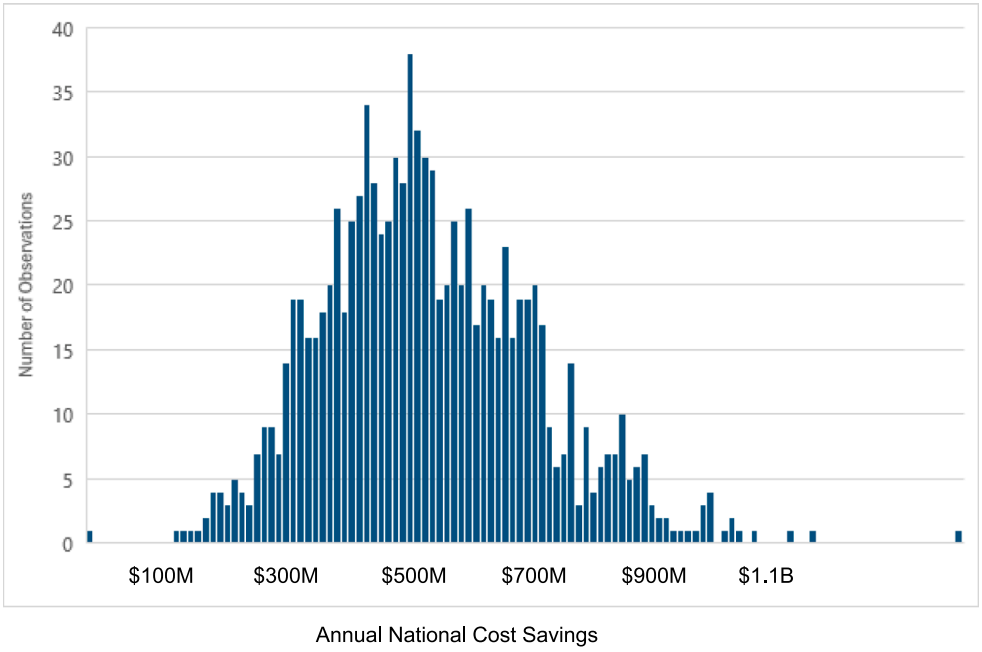


Fig. 2. Annual National Cost Savings.

cost savings. In Figs. 3, 4, 5a, and b, we show the resulting national annual cumulative decrease of 500,000 (±84,000) hospitalizations, 7,600,000 (±1,500,000) bed hours, 409 (±110) new cancer diagnoses, and 210 (±56) new cancer deaths due to radiation exposure from avoidable cardiac diagnostics.

To examine the facility-level impact of an MCG-first approach in this patient population, we also estimated the annual cost savings for an ED with various common annual visit volumes using the other base-case model assumptions. At 30,000 annual adult visits, the cost savings would be $124,000 (±$36,000) with 1650 (±310) fewer bed hours and 107 (±18) avoided hospitalizations. At 60,000 annual adult visits, the cost savings would be $243,000 (±$72,000) with 3300 (±600) fewer bed hours and 214 (±35) avoided hospitalizations. Finally, at 90,000 annual adult visits, the cost savings would be $366,000 (±$106,000) with 4900 (±950) fewer bed hours and 320 (±52) avoided hospitalizations.

3.2. Sensitivity analysis

We varied the assumption of a 90 % rate of immediate discharge following a negative MCG result to examine the impact on our main outcome of cost savings. Reducing this value to 70 % reduces the cost savings to $451 million (±$130 million). Further reducing it to 50 % results in a cost savings of $320 million (±$100 million).

4. Discussion

This study investigated the potential advantages of an MCG-first approach among eligible patients requiring further cardiac diagnostics to evaluate for occlusive coronary artery disease (CAD). Our main finding was over $500 million in annual cost savings, driven by avoidable typical cardiac diagnostic testing and the hospitalizations typically required to obtain them. Additionally, we found a longer-term benefit of avoidable cancer cases and subsequent deaths due to reduced radiation exposure. Our findings support further investigation of how MCG can be more routinely integrated into the care of ED patients requiring additional cardiac testing.

These results contribute to the expanding literature demonstrating the value of MCG in the diagnosis of CAD [7]. Numerous studies have been conducted over the past several decades, during which MCG technology and diagnostic criteria have continued to evolve. These studies consistently demonstrate increased sensitivity and accuracy of MCG, particularly in ED chest pain patients. Park et al. found MCG's sensitivity and negative predictive value to be twice as high as ECG, troponin, and echocardiography in discriminating CAD in acute chest pain patients [8]. While ECG and MCG capture heart electrical activities, MCG's non-contact nature renders it unaffected by tissue or fluid conductivity variations, with no attenuation or distortion as occurs in other testing modalities such as single-photon emission computed tomography (SPECT) [9]. In another study, MCG was shown to have higher specificity and comparable sensitivity, PPV, and NPV compared to SPECT [10]. The MAGNETO study, a multicenter study by Mace et al., showed MCG had a sensitivity of 66.7 % and specificity of 57.1 % in detecting coronary ischemia comparable to non-invasive ST, which had a similar sensitivity of 66.7 % and specificity of 89.9 %. Moreover, MCG had a shorter mean time to test (3.2 h vs 22.8 h, $p < 0.0001$) along with

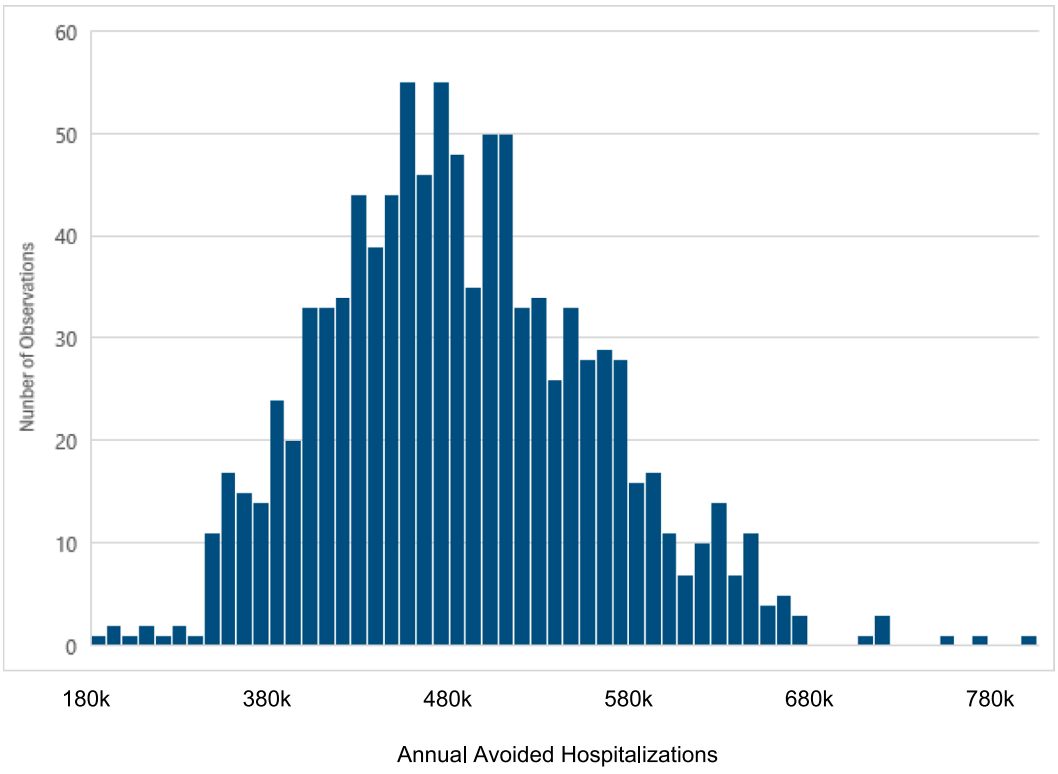


Fig. 3. Annual National Avoided Hospitalizations.

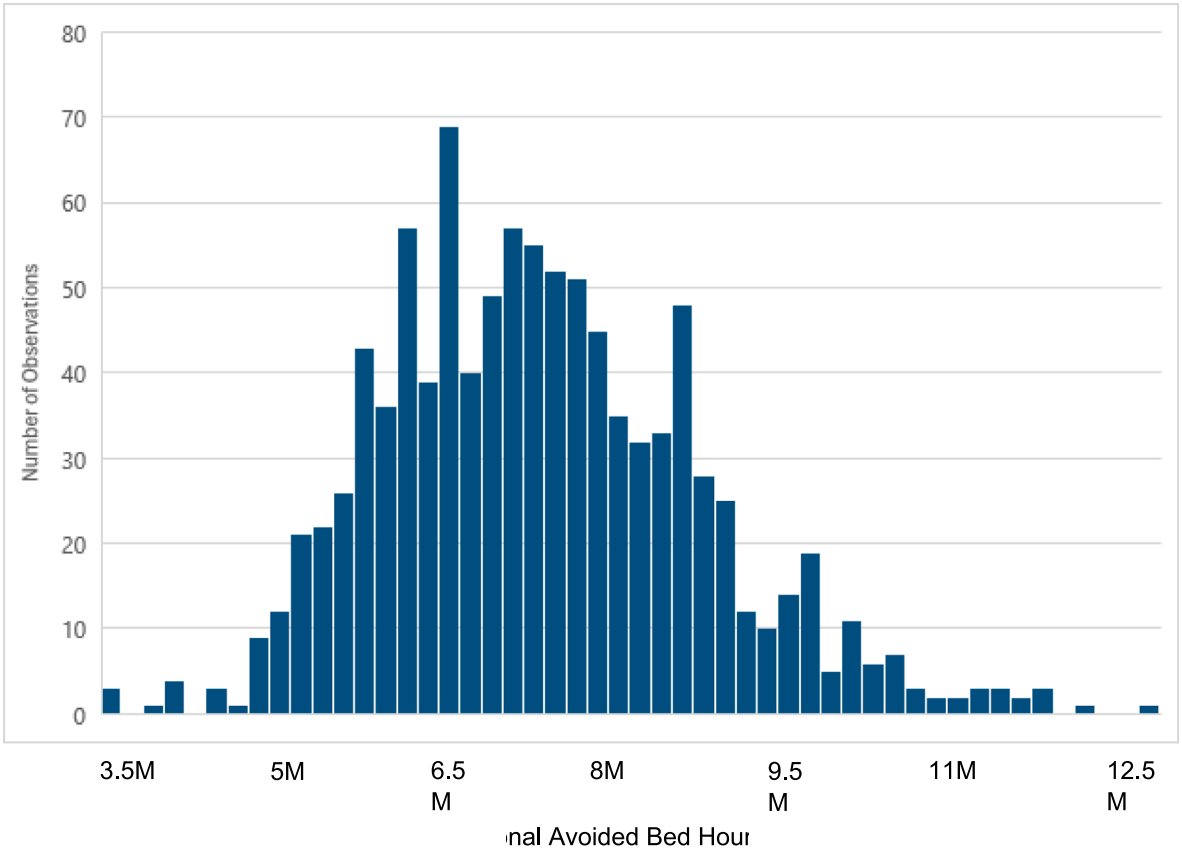


Fig. 4. Annual National Avoided Bed Hours.

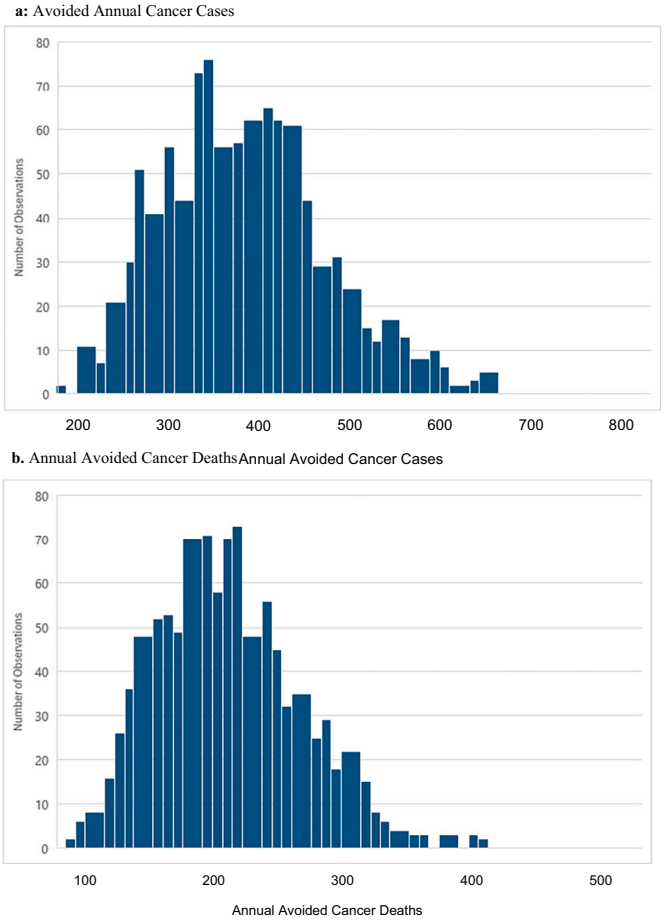


Fig. 5. Annual Reduction in Radiation-Exposure-Related National Cancer Cases and Deaths
a: Avoided Annual Cancer Cases
b. Annual Avoided Cancer Deaths.

higher patient satisfaction scores using a five-point Likert scale for four categories, including total time, comfort, recovery, and overall experience. (4.7 vs. 3.0, $p < 0.0001$) [2]. However, despite its potential benefits, barriers exist to the widespread adoption of MCG in the ED. These barriers include cost considerations, limited equipment and trained personnel availability, and the need for further validation through large-scale clinical trials.

The evolution of hsTn assays has brought significant advancements in the clinical decision-making and management of patients presenting with chest pain in the ED. The 2022 AHA/ACC guidelines reflect this shift by recommending against further testing among low-risk patients who effectively rule out acute coronary syndrome (ACS) with hsTn results [11]. Various studies, such as Yore et al., have shown significantly lower admission rates, ST, and coronary revascularization after implementing an hsTn pathway [12]. In addition, there has been a notable reduction in the proportion of chest pain patients placed in an observation unit for evaluation of chest pain as a larger number of patients can now be more confidently ruled out for ACS earlier in their ED course [13]. Despite these advantages, hsTn adoption has been slow since the 2017 FDA approval in the United States, with about two out of every three hospitals currently using older-generation assays [14]. Diagnostic uncertainty persists in a notable proportion of patients who may fall into the intermediate range where ACS is not confirmed yet cannot be confidently ruled out. This uncertainty arises in cases where elevated hsTn levels may signal alternative pathologies besides CAD, rendering further diagnostic modalities essential, especially in cases where hsTn can be elevated due to secondary causes, such as in critically ill patients or those with chronic kidney disease [15]. Furthermore, while hsTn levels indicate ongoing myocardial ischemic injury, MCG enables earlier detection of patients with potentially reversible myocardial ischemia before injury, instances where hsTn elevation is not significantly detectable, necessitating serial testing [9]. Additionally, studies have highlighted age-related variations in the diagnostic accuracy of cardiac troponin, with older patients exhibiting reduced specificity and positive predictive value [16]. This uncertainty underscores the need for additional diagnostic modalities, such as MCG, to supplement hsTn.

Conventionally, ST has been a cornerstone as a non-invasive method in evaluating patients with suspected cardiac ischemia. Some evidence suggests that incorporating hsTn into a chest pain decision pathway decreases the need for ST. In the study above by Yore et al. using a HEART pathway, patients with an indeterminate hsTn change were considered intermediate risk and were placed in observation and/or underwent ST [12]. Such additional testing is consistent with the 2022 American College of Cardiology expert consensus in the evaluation of acute chest pain in the ED [11]. Although the number of STs performed within seven days of ED arrival decreased from pre- to post-implementation of hsTn, 10.2 % of patients (compared with 12.8 %, $p < 0.001$) were still evaluated with ST post-implementation of hsTn. Therefore, although hsTn may decrease the need for ST in low-risk patients, it does not obviate its use in evaluating ED chest pain patients with intermediate risk.

CCTA has emerged as a common modality for chest pain evaluation of ED patients that promises quicker dispositions. Multiple studies have shown a decreased length of stay and increased percentage of direct discharges from the ED without adverse clinical consequences with a CCTA-based strategy [17,18]. However, there are many limitations associated with CCTA, including renal function consideration, the need for beta-blockade and nitroglycerin administration, and reduced sensitivity in patients with known CAD/stents and in those of increased age with increased calcification [19]. Furthermore, both CCTA and ST utilizing SPECT also include risks associated with radiation exposure and financial burden [19,20,28]. A study by Hoffman et al. showed an increase in downstream testing with higher radiation exposure with an early-CCTA strategy and the cumulative mean cost of care compared to the standard evaluation [22]. In summary, both ST and CCTA have limitations and risks and add to the cost of care. These constraints underscore the valuable role that MCG can play as an alternative to additional downstream testing conducted in the ED as a more sustainable, affordable, radiation-free modality.

Our analysis was a simulation model, and thus, it was limited by the model inputs and structure accuracy. We employed Monte Carlo methods to better account for uncertainty in our inputs and informed our model variables using the most recent and widely accepted sources. However, we also had to make assumptions and adjustments regarding model inputs when data were unavailable. Importantly, we did not account for MCG equipment acquisition and maintenance costs and staff training expenses related to MCG testing and result interpretation. We also did not account for the fixed costs associated with CCTA and ST since these cardiac tests would still be required with an MCG-first strategy. Finally, we represent cost savings as avoidable healthcare expenses, which may be best realized in an accountable care organization or global budget framework; in a fee-for-service environment, hospitals may less directly capture cost savings. However, the value of safely reducing avoidable admissions and saving bed hours is still highly valuable in capacity constrained systems.

Future research could focus on several key areas to further encourage and optimize the utilization of MCG. First, efforts can be directed towards further refining the sensitivity and specificity of MCG in detecting myocardial ischemia, potentially through advanced machine learning algorithms and signal processing techniques. Additionally, research is needed to assess the efficacy and potential impact of using MCG as an alternative to ST and to explore the integration of MCG with existing diagnostic modalities, such as EKG and hsTn, in creating accelerated

diagnostic protocols. Finally, larger studies assessing the clinical outcomes and cost-effectiveness of MCG implementation in a diverse patient population could provide valuable insights into its potential role as a standard of care in the ED. Overall, MCG's future development will depend on ongoing advancements in sensor technology, poised to produce compact, affordable, and even portable devices [23].

5. Conclusions

Our simulation model suggests an MCG-first clinical algorithm for ED patients with chest pain requiring further cardiac diagnostic testing could yield substantial national cost savings in averted testing, decreased short-stay hospitalizations, and reduced radiation exposure, preventing consequent cancer morbidity and mortality. Further research is needed to explore the drivers of this clinical workflow's lack of widespread adoption.

Ethics declaration

This study analyzed publicly available data and was exempt from institutional board review at our institution. We had no direct patient interactions and obtained no PHI to complete this work.

CRediT authorship contribution statement

Christopher W. Baugh: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Margarita E. Pena:** Writing – review & editing, Methodology, Conceptualization. **Robert B. Takla:** Writing – review & editing, Methodology, Conceptualization. **Ahmad O. Hadri:** Writing – review & editing, Writing – original draft. **Sharon E. Mace:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

C.W.B. is a paid speaker for Roche Diagnostics and has previously participated in Roche, Salix Pharmaceuticals, Pfizer, and AstraZeneca advisory boards, consults for Abbott Laboratories, and is an advisor to Lucia Health Guidelines.

M.E.P. participates in the Genetesis scientific advisory board.

R.B.T. is a paid speaker for Janssen and AstraZeneca Pharmaceuticals and is employed by Genetesis as the chief medical officer.

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Prior presentation

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