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ORIGINAL PAPER

Cost-effectiveness analysis of new generation coronary CT scanners for difficult-to-image patients

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Abstract
Aims New generation dual-source coronary CT (NGCCT) scanners with more than 64 slices were evaluated for patients with (known) or suspected of coronary artery disease (CAD) who are difficult to image: obese, coronary calcium score > 400, arrhythmias, previous revascularization, heart rate > 65 beats per minute, and intolerance of betablocker. A cost-effectiveness analysis of NGCCT compared with invasive coronary angiography (ICA) was performed for these difficult-to-image patients for England and Wales.
Methods and results Five models (diagnostic decision model, four Markov models for CAD progression, stroke, radiation and general population) were integrated to estimate the cost-effectiveness of NGCCT for both suspected and known CAD populations. The lifetime costs and effects from the National Health Service perspective were estimated for three strategies: (1) patients diagnosed using ICA, (2) using NGCCT, and (3) patients diagnosed using a combination of NGCCT and, if positive, followed by ICA. In the suspected population, the strategy where patients only undergo a NGCCT is a cost-effective option at accepted cost-effectiveness thresholds. The strategy of using NGCCT in combination with ICA is the most favourable strategy for patients with known CAD. The most influential factors behind these results are the percentage of patients being misclassified (a function of both diagnostic accuracy and the prior likelihood), the complication rates of the procedures, and the cost price of a NGCCT scan.
Conclusion The use of NGCCT might be considered cost-effective in both populations since it is cost-saving compared to ICA and generates similar effects.

Keywords Cost-effectiveness · CT scanner · Coronary artery disease · Radiation · Imaging

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Introduction

In recent years imaging technologies have been developed rapidly, leading to the introduction of new generation coronary computed tomography (NGCCT) scanners. The latest generation of dual-source instruments may have a significant benefit over the current technologies, especially for difficult-to-image patients through improvements in image quality, and reductions in the scan duration and radiation exposure.

Currently, for patients suspected of coronary artery disease (CAD) the diagnosis is usually based on tests such as an invasive coronary angiography (ICA), functional imaging, computed tomography (CT) coronary angiography (CTCA), or a computed tomography calcium scoring. The appropriate diagnostic test depends on the likelihood of having CAD as described in the NICE clinical guideline [1]. If the likelihood of CAD is between 10 and 90 % then a patient will undergo further examination, i.e. 64-slice CT for the patients with a likelihood between 10 and 29 %. In addition, these diagnostic tests can also be used to decide whether a revascularization is necessary. The performance of 64-slice CT for diagnosing CAD has been well established. Recent systematic reviews have estimated that 64-slice CT, for the detection of $\geq$50 % coronary artery stenosis, is very accurate [2–4]. However, 64-slice CT cannot be (routinely) used for specific groups of patients who are difficult to image due to decreased image quality [5]. These include patients with: (1) arrhythmias, (2) heart rate > 65 beats per minute, (3) obesity, (4) coronary calcium level > 400, (5) a previous coronary revascularization with a stent, (6) β-blocker intolerance or (7) a previous coronary artery bypass graft (CABG). In these difficult-to-image patients, ICA, a more invasive diagnostic procedure, may therefore be indicated. Newer generation CT instruments may provide an alternative to an ICA for these patients, and have a lower procedure-related mortality and morbidity. One potential disadvantage may be a slightly lower sensitivity and specificity compared to ICA, which means a greater frequency of false positive (FP) and false negative (FN) results that may lead to incorrect treatment decisions, health loss and increased costs. We performed a cost-effectiveness study of the NGCCT compared with ICA for difficult-to-image patients for England and Wales.

Methods

The lifetime cost-effectiveness of NGCCT for difficult-to-image patient groups was estimated for two separate populations: patients with suspected CAD and patients with known CAD. The suspected CAD population includes patients with chest pain or other symptoms suggestive of CAD. Patients with known CAD were defined as patients with a diagnosis of CAD whose symptoms are no longer controlled with drug treatment and/or are being considered for revascularization. The characteristics (e.g. age, systolic blood pressure) of the difficult-to-image subgroups are based on the studies that are included in a systematic review [6]. The NGCCT has a different purpose in each population. For the suspected population the purpose of NGCCT is to diagnose CAD and, if present, a patient is treated with revascularization or medication. For the known population the purpose of NGCCT is to decide whether a revascularization is necessary.

Strategies

Three strategies were examined: (1) a strategy where patients only undergo an ICA (ICA–only strategy), (2) a strategy where patients only undergo the NGCCT (NGCCT–only strategy), and (3) a strategy where patients are first assessed with NGCCT and undergo an ICA if the NGCCT is positive (NGCCT–ICA strategy). NGCCTs are defined as dual-source cardiac CT scanners with >64 slices [Brilliance iCT (Phillips Healthcare), Somatom Definition Flash (Siemens Healthcare), Aquilion ONE (Toshiba Medical Systems), and Discovery CT750 HD (GE Healthcare)].

Models

The cost-effectiveness analyses were conducted by combining five models which were adjusted for this specific decision problem: (1) a decision model of the diagnostic pathway (diagnostic model) [7], (2) a Markov model reflecting the prognosis of CAD patients [disease progression model (DPM) [8]], (3) a Markov model to estimate the impact of radiation on cancer mortality and morbidity [York Radiation Model (YRM) [6] [9]], (4) a Markov model to account for mortality amongst persons without CAD [general population model (GPM) [7]] and (5) a Markov model was created by the authors to estimate the impact of stroke due to the initial test and treatment (stroke model). The diagnostic model (Figs. 1, 2), where the entire cohort of patients starts, splits the cohort into separate subcohorts of patients based on prior likelihood, treatment-dependent diagnostic performance and complication rates. It determines whether the long-term costs and effects are modelled through the DPM (Fig. 3), GPM (Fig. 4) or the stroke model (Fig. 4). For example, the prognosis of patients with a true positive (TP) test and no stroke was modelled with the DPM while

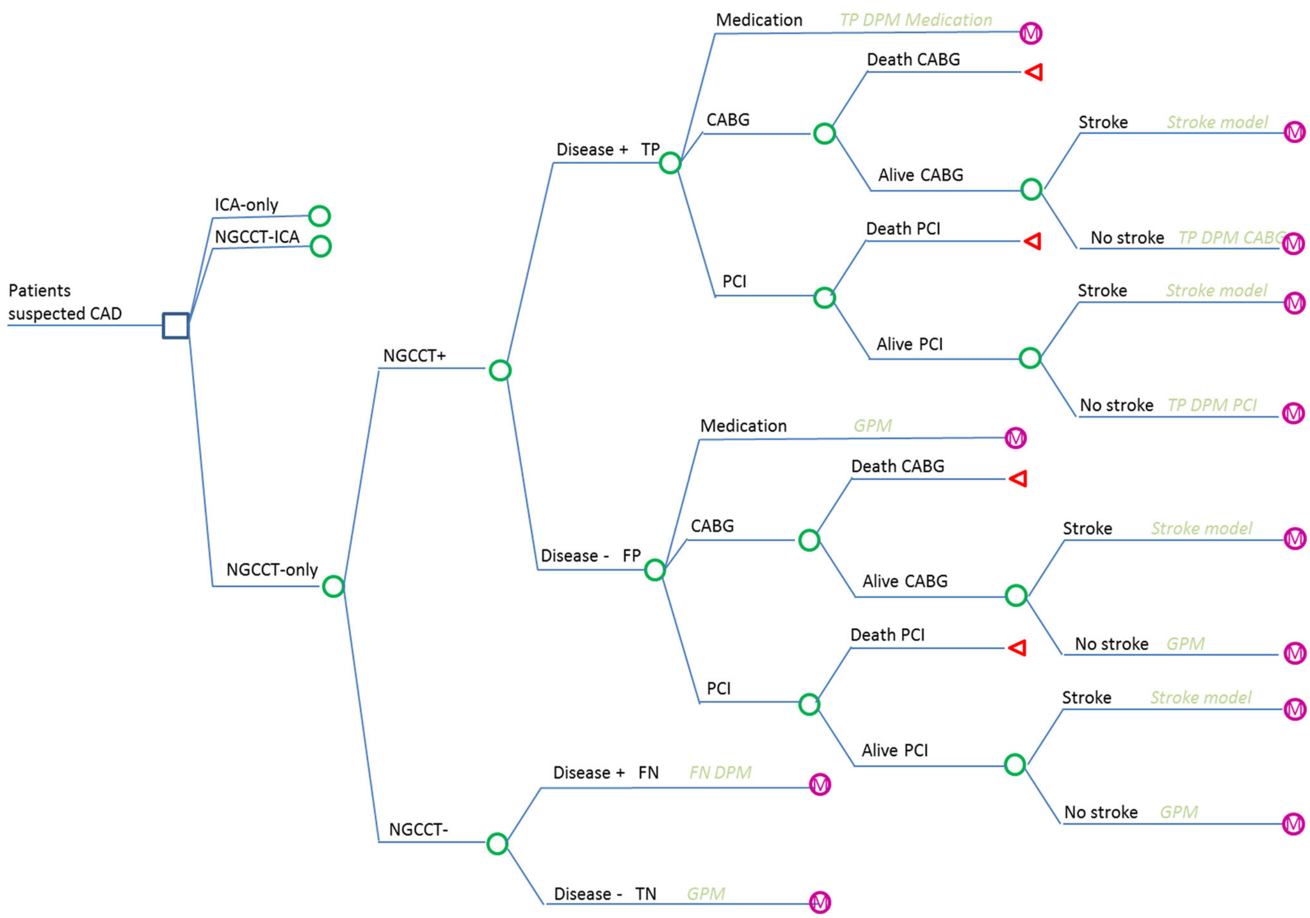

Fig. 1 Diagnostic model for suspected CAD population. *CAD* coronary artery disease, *ICA* invasive coronary angiography, *NGCCT* new generation coronary computed tomography, *TP* true positive, *FP* false positive, *FN* false negative, *TN* true negative, *CABG* coronary artery bypass graft, *PCI* percutaneous coronary intervention, *DPM* disease progression model

the prognosis of stroke patients was modelled using the stroke model. The YRM (Fig. 5) provided disutilities and costs due to radiation-induced cancer based on the radiation dose of the diagnostic tests and treatments; this model was applied to all patients undergoing the respective test or treatment. We then combined the results for all of the different models (i.e. diagnostic, GPM, stroke, YRM and DPM) to derive a complete cost-effectiveness estimate for each specific difficult-to-image subgroup. In conclusion, the diagnostic model and the YRM was used for the entire cohort and the DPM, stroke and GPM were used depending on the test result and complications (Table 28 [6]). The aim of the study was to compare the overall cost-effectiveness of the three strategies in each of the two populations (suspected and known CAD). Expert opinion ($N = 4$) from radiologists and cardiologists was used to gather information on the relative frequencies of patients (Tables 1, 2) in the difficult-to-image subgroups in the known or suspected CAD population (appendix 7 [6]). Multiplication of the relative proportions with the subgroup-specific costs and effects produced an overall incremental cost-effectiveness ratio (ICER) for both populations.

The analyses were based on cohort simulations. Costs and effects were discounted at 3.5 %, and the study was performed from a National Health Service perspective.

Model variables

Input parameters, based on published literature and expert opinion, are provided as supplementary data in Table S1 and in the full report [6].

Transition probabilities

Prior likelihood, accuracy estimates of the tests and complication rates of the procedures are important parameters in the diagnostic model. The prior likelihood (20 %) of having CAD in patients with suspected CAD was based on the clinical guideline “Chest pain of recent onset” [1]. Patients with a prior likelihood of 20 % are normally diagnosed with a 64-slice CT, the technology that the

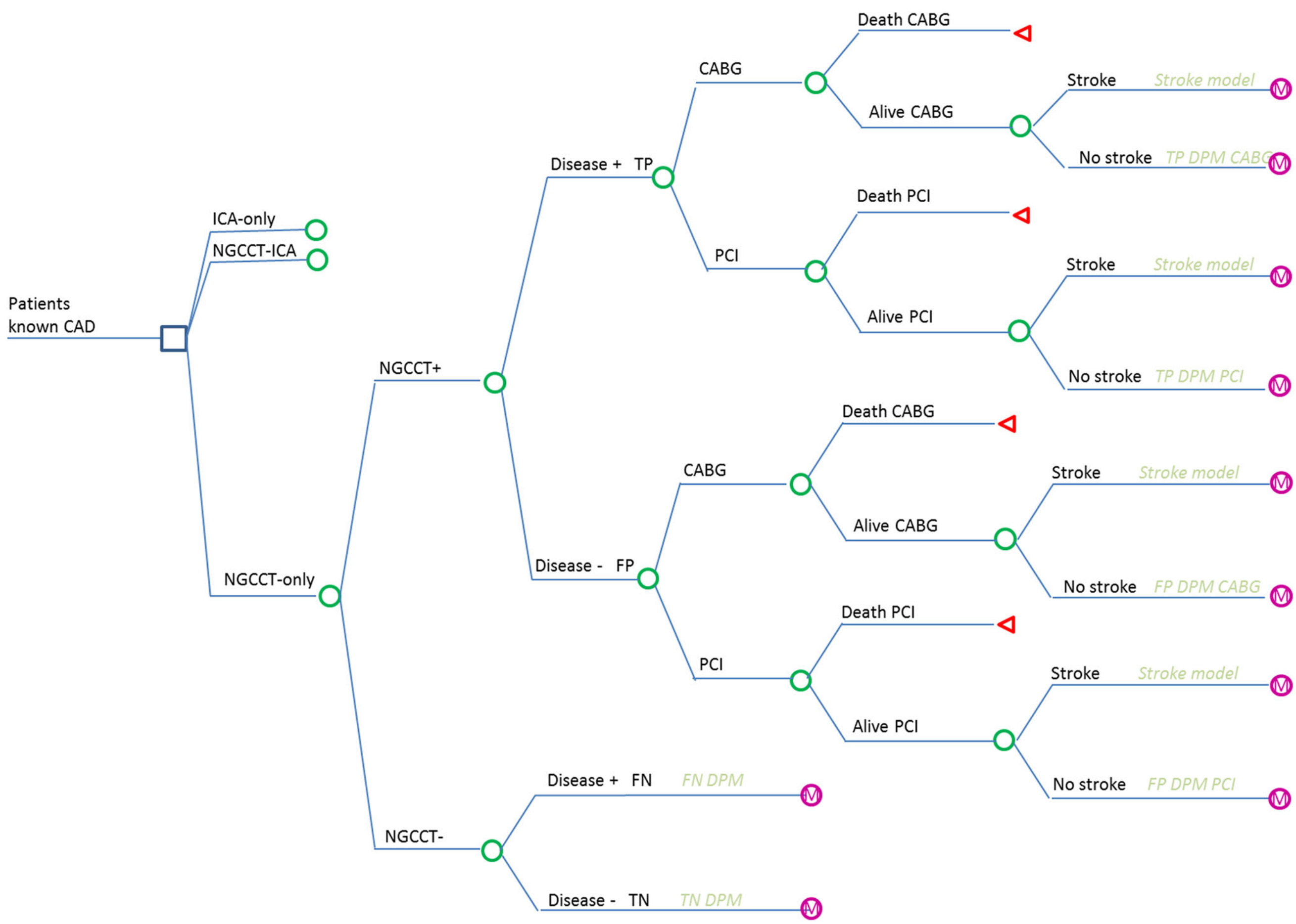

Fig. 2 Diagnostic model for known CAD population. *CAD* coronary artery disease, *ICA* invasive coronary angiography, *NGCCT* new generation coronary computed tomography, *TP* true positive, *FP* false positive, *FN* false negative, *TN* true negative, *CABG* coronary artery bypass graft, *PCI* percutaneous coronary intervention, *DPM* disease progression model

NGCCT will replace for patients who are difficult to image. The prior likelihood of performing a revascularization in patients with known CAD was based on the CE-MARC study [7] (Table S1). We used this estimate due to lack of data despite the possibility that the CE-MARC population may not perfectly match our population. The sensitivity and specificity of ICA were assumed to be 100 %, as in Mowatt et al. [2]. The estimates of the sensitivity and specificity for the NGCCT were based on a systematic review which aimed to identify accuracy estimates for all type of scanners [10]. This review found 21 studies evaluating the Somatom Definition Flash, one study evaluating the Aquilion ONE and one study evaluating the Discovery CT750 HD. In the remainder of the paper we will assume that these accuracy estimates are generalizable to other NGCCTs. Complication rates of ICA and the procedures were based on West et al. [11], Tarakji et al. [12], Serruys et al. [13], Rajani et al. [14], and Bridgewater et al. [15].

The risks of cardiovascular events for patients with CAD in the DPM were based on the results of the EUROPA trial [8]. We used four equations to calculate: (1) the probability of any event that will occur in one cycle of 3 months; (2) the probability that the event is fatal; (3) the probability of a subsequent event in the first year after a first non-fatal event and (4) the probability of a subsequent event after 1 year. Tables 21–26, 44 and 45 from Westwood et al. [6] present the input parameters and risk equations that were used in the DPM.

Life expectancy for patients without CAD was based on UK life tables [16]; the life expectancy for stroke patients was derived by adjusting the UK life tables for excess mortality risk based on an observational study of stroke patients [17] (Table 33 [6]).

The adjusted version of the YRM models the harmful consequences of radiation exposure. Based on age at exposure, gender, and radiation dose (mSv) we have estimated the probability of developing cancer. For patients developing radiation-induced cancer, the remaining quality-adjusted life-years (QALYs) given the average age of cancer incidence and the average treatment cost for cancer are calculated [9] (Tables 47 and 52 [6]).

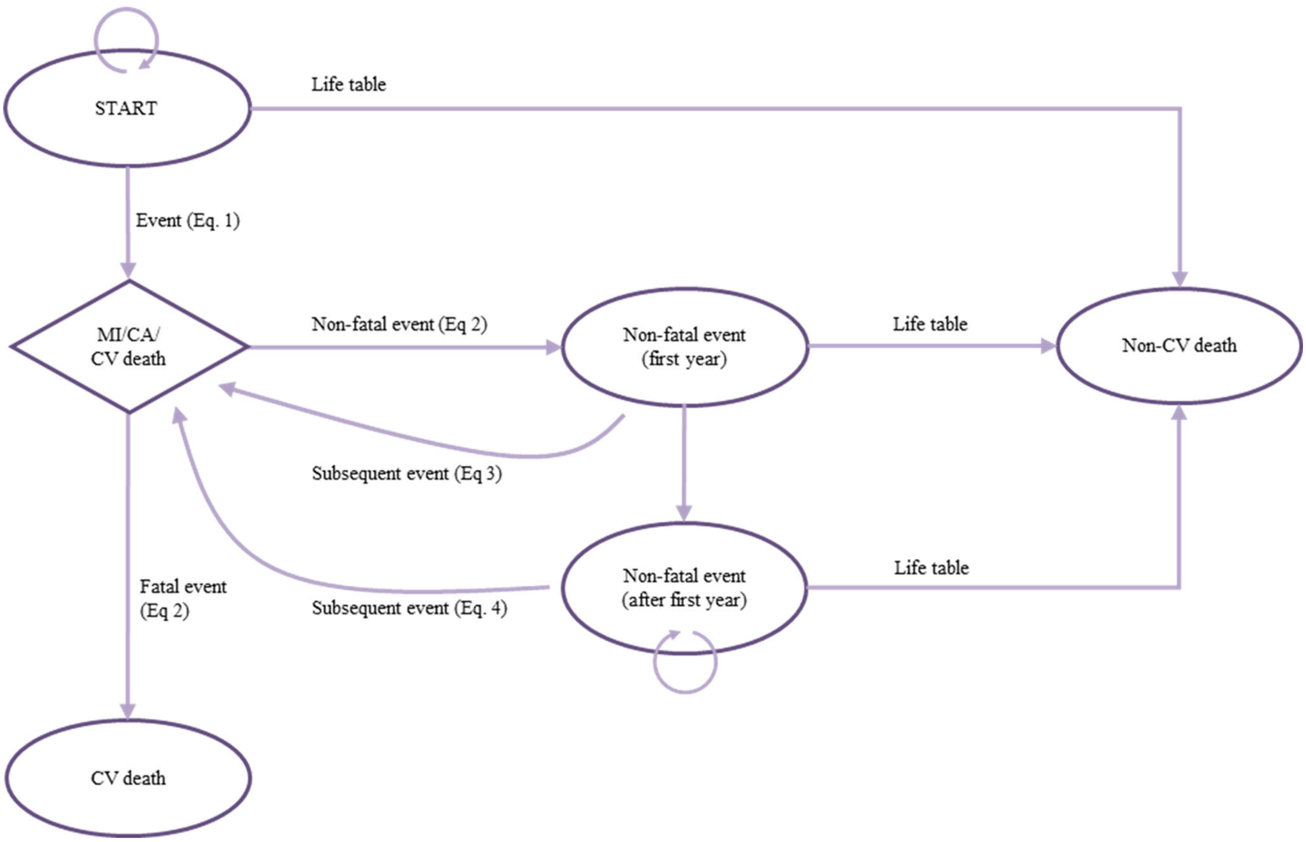

Fig. 3 Disease progression model. *MI* myocardial infarction, *CA* cardiac arrest, *CV* cardiovascular, *Eq* equation Adapted from Briggs et al. [8]

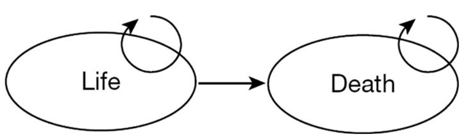

Fig. 4 Life-death model structure used for stroke model and GPM. *GPM* general population model

Costs

The costs of the three strategies included the cost of the diagnostic tests, non-fatal events [myocardial infarction (MI) and cardiac arrest], procedures (e.g. revascularization), CAD management costs (e.g. medication), stroke-related costs and costs due to radiation-induced cancer (Table S1). Original cost prices were inflated to reflect costs for 2010 using PSSRU Health Unit costs of Health and Social Care 2010 [18].

The price of the NGCCT procedure was calculated using a bottom-up costing since only data for CT in general (i.e. not specifically for CTCA) was available (Table 30 [6]). The costs occurring in the first year after a non-fatal cardiovascular event, a fatal cardiovascular event, and a non-cardiovascular fatal event were based on the EUROPA trial [19]. For subsequent years after the non-fatal event, the additional cost was estimated at £986 [8]. CAD

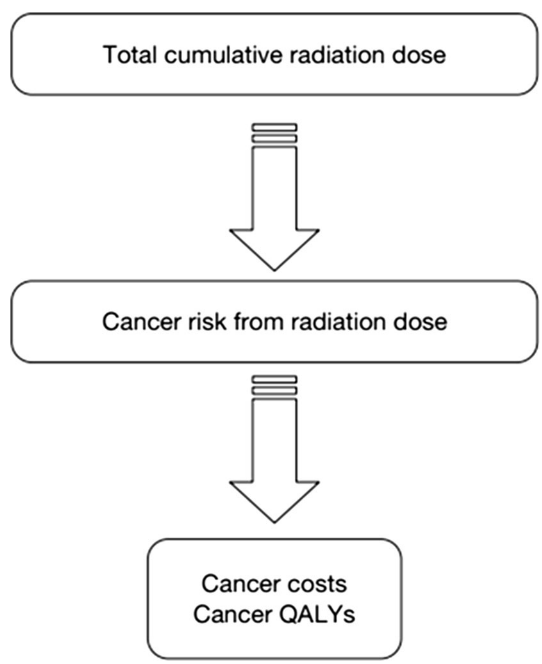

Fig. 5 York radiation model. *QALY* quality adjusted life years

management costs for each difficult-to-image patient group were calculated using a previously published regression model, which estimates costs using patient characteristics

Table 1 Cost-effectiveness of NGCCT for the suspected CAD population

Suspected CAD population	Relative proportions[a]	Costs			QALYs			ΔCosts	ΔQALYs	ICER (£/QALY)
		Mean (£)	SD	Range (2.5–97.5 %)	Mean	SD	Range (2.5–97.5 %)			
Overall										
NGCCT–only		5808	573	4683–6901	10.588	0.109	10.377–10.806			
NGCCT–ICA		5950	589	4825–7068	10.590	0.109	10.371–10.808	142	0.002	71,000
ICA–only		6534	572	5415–7642	10.597	0.107	10.385–10.797	584	0.007	83,429
Obese										
NGCCT–ICA	16.25 %	6297	1237	4055–8976	10.508	0.167	10.173–10.829			
NGCCT–only		6106	1202	3917–8695	10.508	0.167	10.159–10.824	−191	0.000	Dominates NGCCT–ICA
ICA–only		6968	1217	4743–9629	10.519	0.163	10.183–10.830	862	0.011	81,318
Arrhythmias										
NGCCT–ICA	11.75 %	6227	1190	4052–8706	9.419	0.171	9.073–9.748			
NGCCT–only		6077	1161	3943–8494	9.42	0.171	9.073–9.740	−150	0.000	Dominates NGCCT–ICA
ICA–only		6785	1205	4603–9367	9.448	0.166	9.112–9.761	708	0.029	24,645
Heart rate > 65 bpm										
NGCCT–only	29.25 %	6595	1256	4314–9287	10.967	0.156	10.642–11.258			
NGCCT–ICA		6758	1289	4419–9511	10.968	0.157	10.651–11.266	162	0.001	312,047
ICA–only		7342	1263	5027–10041	10.969	0.155	10.660–11.255	584	0.001	440,057
Coronary calcium level > 400										
NGCCT–only	27.50 %	5962	1168	3872–8456	10.201	0.169	9.855–10.520			
NGCCT–ICA		6142	1248	3973–8794	10.202	0.169	9.851–10.530	180	0.001	205,536
ICA–only		6801	1189	4711–9361	10.21	0.167	9.871–10.531	659	0.008	80,446
Intolerance β-blocker										
NGCCT–ICA	15.25 %	6430	1320	4082–9209	11.54	0.151	11.235–11.830			
ICA–only		7016	1242	4767–9576	11.541	0.148	11.242–11.824	586	0.001	972,803
NGCCT–only		6279	1240	4058–8850	11.542	0.151	11.234–11.828	−736	0.001	Dominant

[a] Expert opinion

such as age, diabetes mellitus, medication usage, and symptomatic disease [8]. Tables 35–38 from Westwood et al. [6] present the input parameters and risk equations that were used in the DPM. Costs due to radiation-induced cancer are based on a number of previous comprehensive assessments of the economic burden of treating several different types of cancer [9] (Table 46 [6]).

Health-related quality of life

The overall effectiveness of the three strategies was expressed in QALYs. QALYs represent a combination of life expectancy and health-related quality of life (HRQoL). The HRQoL estimates of CAD patients were based on three sources: UK population norms for the EQ5D [20] (Table 34 [6]), EQ5D scores per Canadian Cardiovascular Society class of angina pectoris [21] and treatment effect on HRQoL based on the RITA2 trial [22] (Tables 39–42 [6]). These sources were used to calculate HRQoL for each difficult-to-image group [7]. It was assumed that a non-fatal event was associated with a disutility of 0.0102 for the subsequent 3 months [23]. Loss in QALYs due to radiation-induced cancer were based on the UK population [9] (Tables 49 and 50 [6]). HRQoL of patients with stroke were estimated to be 0.37 using the results of the study of Sandercock et al. [17].

Assumptions

A number of assumptions were made in this study. First, the ICA ("gold standard") was assumed to have a sensitivity and specificity of 100 %. Second, we assumed that all diagnostic tests are performed immediately after each other without any relevant time delay. Third, we also assumed that the sensitivity and specificity of the tests for each difficult-to-image subgroup are the same for both populations. Lastly, the complication rates of revascularization and ICA were assumed to be the same in all

Table 2 Cost-effectiveness of NGCCT for the known CAD population

Known CAD population	Relative proportions[a]	Costs			QALYs			ΔCosts	ΔQALYs	ICER (£/QALY)
		Mean (£)	SD	Range (2.5–97.5 %)	Mean	SD	Range (2.5–97.5 %)			
Overall										
ICA–only		28,234	502	27,262–29,240	9.516	0.288	8.959–10.066			
NGCCT–ICA		27,785	531	26,785–28,786	9.537	0.283	8.986–10.081	−449	0.022	Dominates ICA–only
NGCCT–only		28,228	498	27,269–29,217	9.538	0.286	8.986–10.081	443	0.001	726,230
Obese										
ICA–only	10 %	29,694	928	27,973–31,562	8.857	0.464	7.823–9.674			
NGCCT–only		29,254	924	27,538–31,130	8.869	0.477	7.800–9.707	−439	0.012	Dominates ICA–only
NGCCT–ICA		29,177	920	27,465–31,024	8.872	0.46	7.891–9.700	−77	0.003	Dominant
Arrhythmias										
ICA–only	7.33 %	27,428	908	25,625–29,232	6.545	0.504	5.507–7.480			
NGCCT–ICA		27,084	916	25,316–28,912	6.588	0.503	5.552–7.523	−344	0.043	Dominates ICA–only
NGCCT–only		27,726	971	25,833–29,660	6.595	0.499	5.565–7.507	642	0.007	90,683
Heart rate > 65 bpm										
ICA–only	27.33 %	30,434	1169	28,219–32,764	11.223	0.381	10.400–11.894			
NGCCT–only		30,477	1190	28,226–32,927	11.233	0.377	10.424–11.906	43	0.011	4021
NGCCT–ICA		30,080	1184	27,853–32,486	11.242	0.378	10.429–11.903	−397	0.009	Dominant
Coronary calcium level > 400										
ICA–only	25.67 %	31,145	1079	29,054–33,300	9.271	0.538	8.155–10.216			
NGCCT–only		30,839	1103	28,753–33,092	9.301	0.533	8.201–10.288	−306	0.03	Dominates ICA–only
NGCCT–ICA		30,661	1075	28,643–32,861	9.306	0.539	8.138–10.259	−178	0.005	Dominant
Intolerance β-blockers										
ICA–only	9.33 %	29,339	986	27,478–31,345	10.016	0.392	9.188–10.720			
NGCCT–only		29,354	1004	27,446–31,377	10.039	0.392	9.206–10.746	14	0.024	610
NGCCT–ICA		28,972	988	27,121–30,976	10.042	0.394	9.185–10.740	−381	0.003	Dominant
Previous stent										
ICA–only	11 %	28,450	842	26,828–30,082	8.724	0.364	7.944–9.370			
NGCCT–ICA		28,056	855	26,413–29,690	8.737	0.358	7.960–9.371	−394	0.013	Dominates ICA–only
NGCCT–only		28,672	888	26,972–30,406	8.744	0.354	7.986–9.381	617	0.007	93,526
Previous CABG										
ICA–only	9.33 %	28,466	844	26,852–30,152	8.719	0.363	7.935–9.374			
NGCCT–ICA		28,088	859	26,458–29,797	8.725	0.36	7.963–9.389	−378	0.006	Dominates ICA–only
NGCCT–only		28,554	1028	26,682–30,723	8.725	0.359	7.956–9.382	466	0	2,943,850

[a] Expert opinion

subgroups. The full set of assumptions is provided in Westwood et al. [6].

Analyses

Base-case scenarios were based on a probabilistic sensitivity analysis (PSA) due to the non-linearity of the model. The PSA was performed by running a Monte Carlo simulation of 5000 simulations of the model. In the PSA, parameters were varied simultaneously using a priori defined distributions. Gamma distributions were used for costs, log-normal distributions for relative risks, and beta distributions were used for utility values and probabilities. In addition, a cost-effectiveness

Table 3 Intermediate outcomes

	Proportion correct classification	Misclassification		Test mortality	Test morbidity	Mortality revascularization	Morbidity revascularization[a]
		FPs	FNs				
Suspected CAD population							
ICA–only	1	–	–	0.00073	0.00064	0.00027	0.00047
NGCCT–ICA	0.9903	–	0.0097	0.00019	0.00018	0.00026	0.00044
NGCCT–only	0.8934	0.0969	0.0097	–	–	0.00039	0.00067
Known CAD population							
ICA–only	1	–	–	0.0007	0.0006	0.0030	0.0051
NGCCT–ICA	0.9818	–	0.0182	0.0001	0.0003	0.0028	0.0048
NGCCT–only	0.9042	0.0775	0.0182	–	–	0.0034	0.0058

[a] Stroke or MI due to the procedure

acceptability curve (CEAC) was created to present the probability of the diagnostic tests being cost-effective at varying willingness-to-pay thresholds. Scenario analyses were performed to determine the impact of different values for the input parameters on the ICERs. The cost price of the NGCCT, the prior likelihood of CAD in the suspected population, and the complication rates were varied. The cost price of NGCCT was fixed at £150 for the lower limit and at £207 for the upper limit; this range was based on the bottom-up costing method where we varied the number of procedures performed per year. The prior likelihood of the suspected population was increased to 0.3, which was the upper limit of the range when a 64-slice CT should be performed to diagnose patients suspected of CAD [1]. Worst-case and best-case scenarios for the NGCCT strategies were performed by varying the complication rates (lower and upper limits of 95 % confidence interval) of a revascularization and of the test. Moreover, cost-effectiveness acceptability curves were created to present the probability of a strategy being cost-effective given the willingness-to-pay threshold. Currently, NICE applies a threshold of £20,000–£30,000 per QALY gained [24]. More information concerning the modelling methods and input parameters can be found in Westwood et al. [6]. All analyses were performed using Microsoft Excel 2010.

Results

The base-case results, reflecting a frequency-weighted average of the results of the different subgroups, revealed that NGCCT was initially less expensive than ICA, but that the lower sensitivity and specificity of NGCCT leads to more incorrect diagnostic classifications (Table 3). Furthermore, the NGCCT reduces radiation-induced cancer, complications (stroke and MI) and mortality due to the diagnostic procedure compared with ICA. An overall QALY estimate and a separate QALY estimate per model for every strategy, subgroup and population are in Tables 57 and 58 in Westwood et al. [6].

Suspected CAD population

Table 1 presents the overall costs and effects for the suspected CAD population and the cost and effects per difficult-to-image subgroup. The strategies are arranged according to increasing effectiveness and ICERs are estimated for the two most effective strategies by comparing the strategies with the strategy that is ranked lower in effectiveness.

The three strategies differed very little in their effectiveness; the ICA–only strategy was only slightly more effective than the other strategies (i.e. 10.597 QALYs vs 10.590 QALYs for NGCCT–ICA and 10.588 for NGCCT–only). However, the ICA–only strategy was also the most expensive strategy (£6534), followed by NGCCT–ICA (£5950) and the NGCCT–only strategy (£5808). The NGCCT–only strategy might be considered as a cost-effective strategy, since its effectiveness is very similar to that of the ICA–only strategy and its overall costs are lower than that of the other strategies. The ICER of NGCCT–ICA versus NGCCT–only is considerably higher (£71,000) than the currently used threshold of £20,000–£30,000 per additional QALY. The ICA–only strategy generated the most effects but was also the most expensive strategy leading to an ICER that would exceed the threshold (£83,429). The subgroups analyses correspond with the overall results; however, ICA–only is the most cost-effective strategy for patients with arrhythmias (ICER: £24,645) if a threshold of £30,000 per additional QALY is used. Figure 6 shows a cost-effectiveness acceptability curve; the NGCCT–only strategy has the highest probability of being cost-

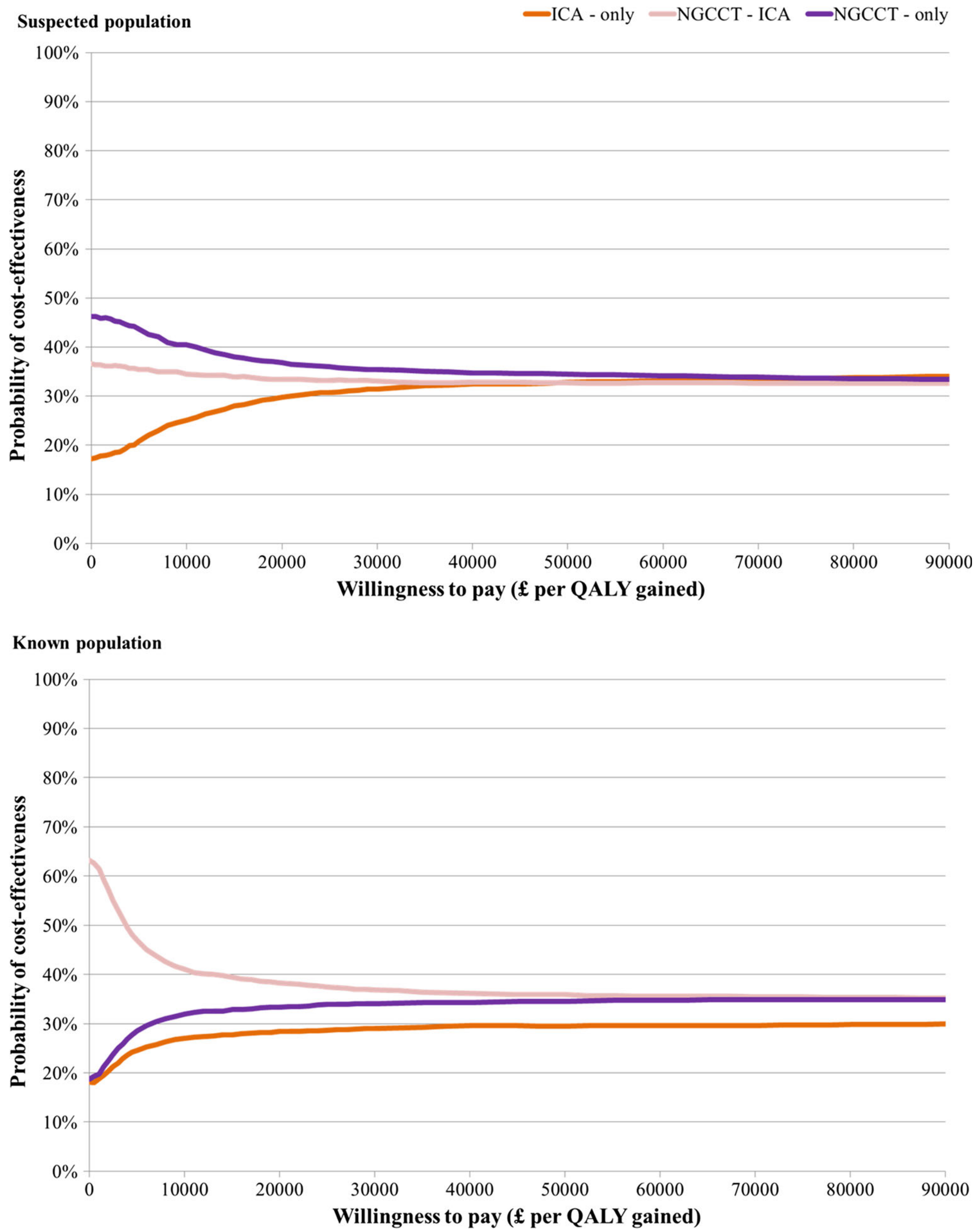

Fig. 6 Acceptability curves for suspected and known CAD populations. *CAD* coronary artery disease, *QALY* quality adjusted life years, *ICA* invasive coronary angiography, *NGCCT* new generation coronary computed tomography

effective if the cost-effectiveness threshold is less than £70,000. For thresholds above £70,000, the three different strategies are more or less equivalent. However, the probability of NGCCT–only being the cost-effective strategy is still less than 50 % compared with the other strategies, since the strategies have very similar total costs and effects.

Known CAD population

Table 2 shows the cost-effectiveness results for the known CAD population. The NGCCT strategies were more effective than ICA–only in all subgroups. Overall NGCCT–only was the most effective strategy (9.538 QALYs) compared to NGCCT–ICA (9.537 QALYs) and ICA–only (9.516 QALYs). However, NGCCT–only was also more expensive (£28,228) compared with NGCCT–ICA (£27,785) leading to an ICER of £726,230 per QALY gained. Consequently, NGCCT–ICA seems to be cost-effective for the known CAD population since the ICER of NGGCT–only (£726,230) is considerably higher than the threshold of £30,000 per QALY gained. When uncertainty is taken into account, the above results still hold. The acceptability curve graph (Fig. 6) shows that the NGCCT–ICA strategy has the highest probability of being cost-effective independent of the willingness-to-pay thresholds, while the ICA–only strategy has the smallest probability of being cost-effective.

Scenario analyses

The scenario analysis with a cost price of £150 for the NGCCT did not affect the overall results; the NGCCT–ICA strategy was still the most favourable strategy. However, when the price of the NGCCT was increased to £207, the ICA–only strategy became less expensive than the NGCCT–only strategy for the known CAD population. Varying the complication rates and the prior likelihood of having CAD for the suspected population did not change the overall results.

Discussion

64-slice CT has proven accuracy for the diagnosis of CAD in most patients [2–4]. However, these scanners are less useful for difficult-to-image patient groups, e.g. those with irregular or fast heartbeats, those who are obese, or in whom artefacts produced by high levels of coronary calcium or existing stents might reduce image quality. Newer generation CT scanners have the advantage of being capable of producing diagnostic quality images in these patient groups. This study has estimated the cost-effectiveness of new generation CT scanners in these difficult-to-image patients.

For patients with suspected CAD, the NGCCT–only strategy might be considered as cost-effective, since its effectiveness is very similar to that of the most effective strategy (difference: −0.009 QALYs) and since its overall costs are much lower than those of the other strategies. For patients with known CAD, a cost-effective strategy is probably NGCCT followed by ICA if the NGCCT is positive (NGCCT–ICA), since it yields the highest cost-saving, and dominates the ICA–only strategy.

Several other studies have also concluded that little differences in health outcomes across diagnostic strategies exist [25–27]. Furthermore, it was concluded that coronary CT angiography can be a cost-saving technique [26–28] that can help to avoid unnecessary invasive angiograms [27], although these results were found in studies evaluating the cost-effectiveness of 64-slice CT which has lower accuracy estimates than NGCCT.

Strengths and limitations

The strength of this cost-effectiveness analysis is that we were able to capture as well as possible the whole range of patient experience from diagnostics to clinical pathway to complications and radiation by combining economic model components. Of course, combining evidence with the use of economic models could be viewed as a limitation because it introduces uncertainty and it was necessary to make several assumptions. However, assumptions and evidence sources have been explicitly reported and uncertainty accounted for by probabilistic and scenario analyses.

The estimated accuracy of the NGCCT is based on the accuracy of ICA, which was assumed to be 100 %. The use of ICA as the gold standard is very common in this field [2], but this may have influenced our results since the estimated accuracy of the NGCCT is also based on the accuracy of the ICA. In addition, ICA in combination with fractional flow reserve is currently a frequently used procedure and can be considered to be a better alternative than ICA–only [29]. Moreover, accuracy estimates for NGCCT were only based on studies evaluating Somatom Definition Flash, Discovery CT750 HD and Aquilion ONE, since none of the studies evaluating the Brilliance iCT were eligible for inclusion. Extrapolation of the cost-effectiveness results to the other NGCCTs is therefore debatable. Furthermore, the accuracy estimates of the NGCCT are assumed to be the same for the known and suspected population and do not differ between the different types of NGCCT scanners. It is uncertain whether these assumptions may have led to an overestimate or an underestimate of the cost-effectiveness of NGCCT–only and NGCCT–ICA strategies.

The procedure costs of the NGCCT are estimated using a micro-costing approach. Unfortunately, no data were available on the consumables which are used during the procedure. However, the extra cost per person to make the NGCCT–only strategy not cost-effective vs the NGCCT–ICA strategy in the suspected CAD population would have to be about £80, given a willingness-to-pay threshold of £30,000/QALY. In the known CAD population, the extra cost would have to be over £1100 to make the NGCCT–ICA strategy not cost-effective vs the ICA–only strategy when a willingness-to-pay threshold of £30,000/QALY is used.

The prior likelihood of CAD in the suspected CAD population was based on the clinical guideline for chest pain of recent onset [1] and for the known population it was based on the prior likelihood estimated by the CE-MARC study [7]. According to the clinical guideline, CT scans are recommended for use in the diagnostic path of patients with a prior likelihood of CAD of 10–29 % and a non-zero calcium score [1]. This likelihood is based on presence of certain clinical symptoms (suggestive of angina), age, gender, diabetes, smoking and hyperlipidaemia. However, scenario analyses showed that the overall results did not change when the prior probability of patients suspected of CAD increased. For the prior likelihood estimate in the known CAD population, it is not entirely certain that the CE-MARC study [7] and our study consider exactly the same patient population. It is therefore possible that the actual prior likelihood in our populations differs from that currently assumed in our model.

Complication rates for the initial procedures are a compilation of various sources and are assumed to be the same for all subgroups. This assumption may have led to an inaccurate estimation of the MI and stroke rates for CABG, percutaneous coronary intervention (PCI) and ICA. Potential differences in any of these factors could lead to different conclusions for the various NGCCTs. However, we have performed scenario analyses changing the parameters, which did not alter our conclusions.

Implications

The NICE recommendations about the use of these scanners in the UK were based in part on the results of this study. They recommended the use of new generation cardiac CT scanners as an option for first line imaging of the coronary arteries in patients with suspected CAD and for first-line evaluation of disease progression to establish the need for revascularization in patients with known CAD in whom imaging with earlier generation CT scanners is difficult [30]. However, the use of the less cost-effective diagnostic strategy ICA shall remain a clinical option despite its less favourable cost-effectiveness ratio [31]. According to this guideline it was estimated that the number of people in England in whom imaging with earlier generation CT scanners is difficult can range from 10 to 18 million [30].

The results of this analysis may differ by setting due to differences in methodological, healthcare system or population characteristics [32]. Methodological characteristics including the perspective (e.g. societal) may not lead to a substantially different ICER since the mean age of the patients in most subgroups is above 60 and thus differences in productivity costs between strategies can be considered small. Most differences in costs and effects are incurred immediately and thus varying discount rates may not have a substantial impact. The intervention costs, prior likelihood, severity of the CAD, the availability of health care resources and clinical practice patterns are important aspects that need to be considered when the transferability of the results is assessed. However, the modelling methods and input parameters are presented in a transparent and reproducible way and therefore the developed model can be adapted to other jurisdictions.

Conclusions

The use of NGCCT in difficult-to-image CAD patients might be considered cost-effective based on the cost-effectiveness thresholds used in England and Wales. NGCCT is equal in effectiveness to ICA but is cost-saving in both the suspected CAD and the known CAD populations. NGCCT is therefore recommended in the assessment of patients who are difficult to image with earlier CT scanners.

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Compliance with ethical standards

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