Social Science & Medicine 352 (2024) 117014

Contents lists available at ScienceDirect

Social Science & Medicine

journal homepage: www.elsevier.com/locate/socscimed

# What happens when the tasks dry up? Exploring the impact of medical technology on workforce planning

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ARTICLE INFO

Handling Editor: Prof. Richard Smith

*Keywords:*
Technological diffusion
Complementarity
High-skilled workforce
Workforce elasticity
Task reallocation

ABSTRACT

Increasing evidence suggests that new technologies tend to substitute for low skilled labour and complement highly skilled labour. This paper considers the manner in which new technology impacts on two distinct groups of highly skilled health care labour, cardiologists and cardiac surgeons. We consider the diffusion impact of PCI as it replaces CABG in the treatment of cardiovascular disease in the English NHS, and explicitly estimate the degree to which the cardiac surgical workforce reacts to this newer technology. Using administrative data we trace the complementarity between CABG and PCI during the mature phase of technology adoption, mapped against an increasing employment of cardiologists as they replace cardiothoracic surgeons. Our findings show evidence of growing employment of cardiologists, as PCI is increasingly expanded to older and sicker patients. While in cardiothoracic surgery, surgeons compensate falling CABG rates in a manner consistent with undertaking replacement activity and redeployment. While for cardiologists this reflects the general findings in the literature, that new technology enhances rather than substitutes for skilled labour, for the surgeons the new technology leads to redeployment rather than a downsizing of their labour.

## 1. Introduction

There is a growing literature examining the impact of technological change on the composition of labour inputs, suggesting that new technology adoption is largely skill-biased (Bekman et al., 1998; Morrison Paul and Siegel, 2001; Acemoglu, 2002; Mokyr et al., 2015), acting as a substitute for non-skilled labour and as a complement to skilled labour (Autor et al., 2003). Despite the general conclusion of technological progress inducing a bias towards a complementary highly skilled labour force, there are of course sectoral and technology-specific differences in the degree of skill upgrading across industries (Autor et al., 1998; Ho, 2008). The health care sector is a particularly interesting case, given that it is a highly labour-intensive sector and displays the extensive use of ever-changing technology by highly skilled labour.

Technology uptake within the health care sector, driven by potential improvements in health outcomes, has been established as a major driver of health care expenditure for most developed countries (Newhouse, 1992; Okunade and Murthy, 2002; Smith et al., 2009; Skinner and Staiger, 2015; Lamiraud and Lhuillery, 2016). The analysis of health care technology continues to be largely considered in terms of the description of the adoption and diffusion aspects of new technologies through examining quality (health) improvement with different lines of re-search focused on different technology types (McClellan et al., 1994; Cutler and McClellan, 2001; Chandra and Skinner, 2012). There has been very little analysis of the impact of technology adoption on labour substitutability or changes in labour force composition more generally as newly adopted health care technologies mature. While some studies, such as Skinner and Staiger (2015) and Chandra and Staiger (2007), discuss productivity gains as correlated with differential technology adoption, there is little specific examination of workforce changes as a consequence of technology adoption and diffusion in this sector. Given that the workforce ac-counts for approximately 60% of expenditure in most health care systems (Imison and Bohmer, 2013), it is important to understand the impact that medical innovations have on staffing.

There is evidence suggesting that technological change in this sector might promote the demand for skilled labour, but it is not entirely clear

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https://doi.org/10.1016/j.socscimed.2024.117014
Received 23 November 2023; Received in revised form 8 May 2024; Accepted 20 May 2024
Available online 27 May 2024

what specific impact new technology, as it replaces old technology, has on health care production. Empirical evidence shows that the diffusion of some new high-cost technology, as well as new technology with lower unit costs tends to enlarge the treated volume of the patient population (McClellan et al., 1994; Cutler and Huckman, 2003; Skinner and Staiger, 2015). In other words, new health care technology may promote output expansion as it diffuses and is applied to a wider patient population. Such mechanisms are consistent with an increased demand for skilled labour. However, there is surprisingly little empirical evidence of the overall impact that new health care technology has generally on the health care production process, and in particular how new technology directly impacts on the medical workforce.

David et al. (2009) do examine the impact on hospital specialists of technology uptake in three diagnostic and treatment technologies and find some evidence of new technology reducing the use of highly specialised labour, with the precise impact differing across different employment arrangements. They consider the type of capital-embodied technologies used in Acemoglu and Finkelstein (2008), who find that moving to the fixed-price Medicare Prospective Payment System (PPS) induced an increase in the capital-labour ratio through a push for the adoption of new technologies and a subsequent decline in labour. There is limited analysis of capital-labour substitution outside of the US health care system. Within the UK National Health Service rather dated research undertaken at the aggregate level finds a strong substitutability between various categories of labour and capital generally (Gray and McGuire, 1989). Of course any predicted impacts of technology on workforce will depend on both the specific technology under consideration and the institutional context. The TECH Investigators (Bech et al., 2009) for example, although not considering labour impact, show that new technologies are associated with a slower rate of up-take and diffusion in centrally funded jurisdictions than in those that have less central control.

The contribution of this paper is to provide specific empirical evidence on the diffusion of a medical technology and its impact on the incumbent technology in the context of the English NHS, as it affects the skilled health care labour composition arising from a specific diffusion of this technology. The analysis is framed in a context of a health technology maturing over the diffusion process to become increasingly common and replacing the older incumbent technology. We focus on Percutaneous coronary intervention (PCI), also known as Percutaneous Transluminal Coronary Angioplasty (PTCA). We use PCI throughout to include angioplasty as first introduced without stents, as well as the upgraded technology that includes stents and drug-eluting stents sometimes referred to as PCI. We follow the diffusion of PCI as it matures as a technology and continues to displace an incumbent technology Coronary Artery Bypass Graft (CABG), also used to treat cardiovascular patients, to assess any changes to the associated medical and surgical workforce. PCI and CABG are particularly interesting cases as there is a very clear labour division in the service provision of each technology type. Whereas only cardiothoracic surgeons perform CABG, a separate skilled labour set, cardiologists, only perform PCI.[1] This labour specialisation holds across many health care systems, including the USA (Cutler and Huckman, 2003). At a system level, PCI was introduced as a less invasive and cheaper procedure to treat cardiovascular disease than the existing technology CABG, therefore embedding changes in the required labour composition. This is a very distinct feature of this paper. Whereas most of the empirical evidence focuses on one type of physician replacing an incumbent technology by the new one (Barrenho et al., 2021; Maynou et al., 2022; Escarce, 1996), this paper concerns two separate.

To motivate our analysis of the workforce impacts, we first establish the relationship between PCI and CABG procedures at the aggregate hospital level by estimating the degree of substitution or complementarity of PCI, the less invasive and less expensive technology, as it impacts on CABG. Complementarity here is not defined as traditional price complementarity, but the allocation of treatments to patient populations. Both CABG and PCI are procedures to increase blood flow in diseased coronary arteries. CABG surgery involves the replacement of the diseased heart vessel(s), while PCI is a procedure used to unblock the occlusion within the vessel(s). Generally, the more severely diseased the vessel the greater the justification for the use of CABG rather than PCI. Therefore more severely ill or complex patients tend to receive CABG (Spadaccio and Benedetto, 2018; Doenst et al., 2019; Stone et al., 2019). We detail below that, in line with this, as the PCI technology matures the initial weak complementarity with CABG is coupled with increasing substitutability between these technologies over time. However, we also note that PCI sees a treatment (output) expansion effect which we refer to as indication creep. That is, we note that PCI is progressively rolled out to riskier and older patient groups, with CABG being retained as a treatment for a diminishing group of patients with the highest levels of complication.

We next turn to our primary focus on any resultant workforce impacts. Due to the distinct allocation of personnel skill-mix involved in undertaking PCI and CABG, we are particularly interested in what happens to one group of skilled labour, cardiothoracic surgeons, as the newer technology, PCI, replaces CABG. An obvious impact would be an associated fall in the demand for such surgeons as PCI, which is undertaken by cardiologists, is considered to be as effective for a large number of cases, is less invasive and is less costly as a treatment. If there were a one-to-one substitution of PCI for CABG we would witness a mechanistic substitution of cardiologists for cardio-thoracic surgeons. The empirical evidence, calculated through our elasticity of labour response, shows that this does not occur and that the labour impact is more nuanced.

During the maturing phase of the new PCI technology, which is our focus of attention, it seems some cases, presumably the most complex, are retained by cardiothoracic surgeons using the older CABG technology. Yet even here the proportion of complex cases seen by cardiothoracic surgeons falls as PCI sees output expansion through our notion of indication creep. We detail that rather than leading to a fall in the number of cardiothoracic surgeons in the NHS, this work group responds to the decline in their volume of CABG procedures (as a consequence of the large increases in PCI volume) by increasing other types of cardiovascular surgery. In particular, we document increasing volumes of heart value surgery as CABG rates decline. It is difficult to establish whether this is a result of the increase in available capacity of existing cardiothoracic surgeons to respond to pent up demand in this area or whether it is the creation of new (supplier induced) demand. In this respect it is worth noting that in the.

NHS all surgeons are salaried so there is no financial incentive at play. Overall, we conclude that the diffusion of the new technology has a direct, increasing impact on the workforce through replacement and treatment expansion, and an indirect effect as the composition of the workload for cardiothoracic surgeons changes as PCI displaces CABG.

The paper details our analysis as follows. We begin by describing the institutional back-ground. Section 3 describes our data and presents some stylised facts on the evolution of PCI/CABG use and workforce groups within the English NHS. In section 4, we outline the empirical strategies used to investigate the various impacts of adopting PCI over CABG, specifically the workforce impact and the cardiothoracic surgeon displacement effect within the UK NHS. The empirical results are presented in section 5 followed by concluding remarks.

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[1] Cardiothoracic surgeons perform surgery, whether open or laparoscopic, on a range of conditions centred around the chest, including heart disease. While cardiologists are not surgeons, but medically trained to administer treatments, including laparoscopic interventions such as PCI, solely for heart disease. The two groups work in tandem when considering cardiac patients in terms of the diagnosis and treatment physician types each responsible for either the old or new surgical technology.

## 2. Institutional background

Health care is a heavily labour intensive sector and the UK NHS is no exception, with approximately 70% of recurrent costs devoted to labour. The workforce employed in the UK health and care sector accounts for approximately 12.5% of the total UK workforce, with the English NHS being the dominant employer directly employing approximately 1.3 million staff, of which approximately 240,000 are hospital-based physicians, and contracting with other staff groups, including approximately 45,000 General Practitioners (GPs) in England alone. Medical school entrance and physician workforce planning is centralised through a government body, Health Education England, that sets the total number of publicly funded employment positions available to the NHS within any year. A centralised, national pay and remuneration committee sets the wage structure for the entire English NHS, which is constrained to be affordable under the tax-funded NHS budget. Mediation of physician employment occurs through the use of defined within employment training programmes organised by professional bodies such as the Royal College of Physicians and the Royal College of Surgeons. Specialty choice is managed through the medical schools and the Royal Colleges. While individual providers directly employ staff, aggregate physician supply is consequently heavily regulated.

Within the hospital sector the mix of employment across specialties (for example across cardiology and cardio-thoracic surgery) is decided through each specialty within an individual hospital making a business case for new appointments to its hospital management, as determined by current staffing levels and the anticipated need for greater volumes of particular staff. This anticipated need reflects the demand for specific treatments, defined by the pattern of GP patient referral to specific hospitals, patient selection and the underlying technology use. Treatment demand itself is managed by the individual hospital specialties through waiting lists, admission and discharge decisions, although these decisions are them-selves susceptible to centrally defined NHS performance target levels. Employment demand across the different specialties is therefore ultimately determined by choices made by individual hospital providers. This demand draws on the aggregate supply of the existing workforce and new specialist trainees. New staff, regardless of their specialty, are offered NHS con-tracts, covering pay grade and conditions of employment that are governed nationally.

NHS patients presenting with symptoms of coronary heart disease are referred by their GP to a cardiologist for PCI or a cardiothoracic surgeon for CABG. Almost all NHS hospitals employ cardiologists, but CABG is only performed at a more limited number of NHS hospitals that employ cardiothoracic surgeons. Individual patient selection for a particular procedure, PCI or CABG, is based on the GP referral decision and subsequent clinical decisions as informed through risk scoring. Low risk patients tend to be referred for PCI (Spadaccio and Benedetto, 2018; Stone et al., 2019). However, given high levels of patient heterogeneity, (in terms of disease severity, comorbidities, age and other patient characteristics), and some ongoing discussion over appropriate use in the medical literature, there is considerable overlap in the application of the two therapies as patient risk levels change (Spadaccio and Benedetto, 2018; Doenst et al., 2019; Stone et al., 2019). Cardiologists may themselves refer patients to cardiothoracic surgeons, especially when PCI has been undertaken but has been unsuccessful.

Treatment of coronary heart disease by PCI is less invasive and only requires the use of catheterisation (cath) labs, rather than the higher cost surgical theatre and recovery time required by the invasive surgical treatment associated with CABG. Such cath labs can be readily converted from existing capital and do not require the extensive build associated with new surgical theatre once capacity has been reached. In the UK the less invasive technology PCI is approximately one-third of the cost of CABG, and, given a shorter treatment and recovery time, higher volume of patients can be seen. As we show below, around 59 NHS England hospitals undertake PCI only, while 30 hospitals offer both PCI and CABG procedures. The new PCI technology therefore has a direct impact on the staffing mix of individual hospitals that decide to employ both technologies (PCI and CABG), and also on the sec-tor wide deployment across the NHS of cardiologists, who perform PCI, and cardiothoracic surgeons, who only perform CABG, across the NHS.

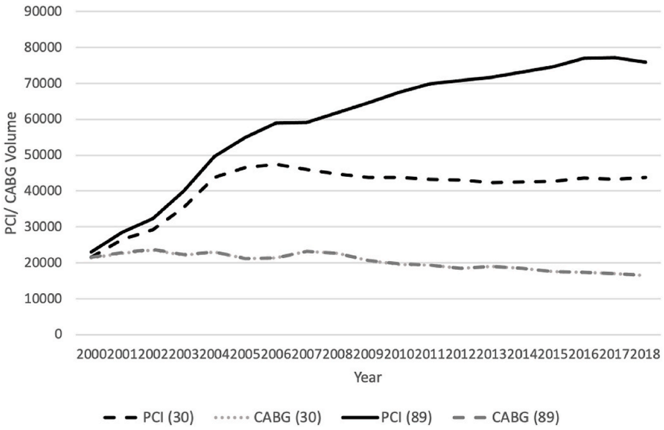


**Fig. 1.** PCI and CABG volumes
*Notes*: CABG is only performed in a sub-group of 30 hospitals, hence the trend in CABG volumes for the sample of all 89 hospitals and the subset of 30 hospitals performing both technologies is the same and overlaps in Fig. 1.
Source: HES data.

## 3. Data and descriptive statistics

To analyse PCI diffusion and its impact on labour composition we primarily use a rich ad-ministrative dataset, the Hospital Episode Statistics (HES), which records information on all patient admissions in the English NHS. It includes identification of the senior physician who undertook a given procedure, allowing identification of the senior cardiologist for PCI procedures and cardiothoracic surgeon for CABG surgeries. These data allow assessment of the impact of procedure changes in the volume on the senior staff directly associated with performing PCI increasingly and CABG. Our sample includes all patients admitted for CABG or PCI as main surgery, based on OPCS-4 procedure codes. See Table A1 for a detailed list of codes for each procedure. We consider all elective and emergency admissions from financial year 2000/2001 to financial year 2018/19, as thereafter surgery was badly disrupted by the COVID19 pandemic. Hereafter, we refer to each financial year by the year when it starts, e.g. 2000 refers to financial year 2000/2001. Each patient record contains clinical information on the admission date, diagnosis, main operation, date of operation, all other surgical interventions the patient might have had and discharge date. The dataset also includes organisational and geographical information, and importantly we are able to link each episode to the anonymised identifier of the physician actually performing the intervention. As noted below, we augment this HES data set with NHS workforce data provided through the NHS Electronic Staffing Record (ESR).

### *3.1. PCI and CABG volumes*

We first aggregate HES data at the hospital level to construct a longitudinal dataset that includes total volumes for PCI and CABG per hospital and year. This allows tracking the trends over time of these procedures. This dataset produces an unbalanced panel of 178 hospitals from 2000 to 2018. PCI and CABG volumes are adjusted by population at risk, therefore volumes are for the population of individuals aged 45 and above in the Primary Care Trust (PCT) where the hospital is located. PCTs were administrative organisations in place during the first half of our study period and were responsible for the commissioning of primary and secondary health care services. After the Health and Social care Act of 2012, these were replaced by Clinical Commissioning Groups (CCGs).

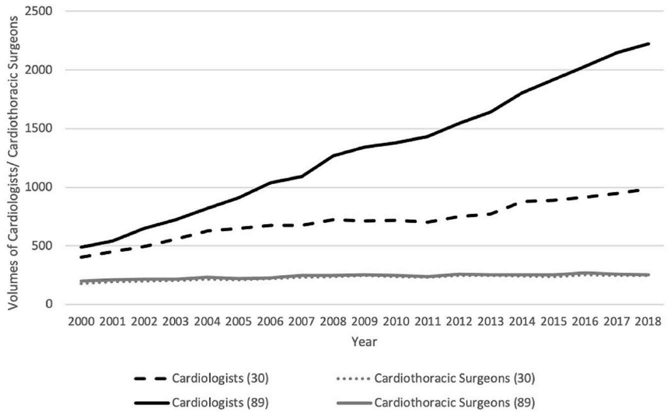


**Fig. 2.** Cardiologist and Cardiothoracic surgeons
*Notes*: Fig. 2 shows the number of cardiologists and cardiothoracic surgeons recorded in the HES data relating to the procedures of interest. The count of total NHS cardiothoracic surgeons, not shown here, is higher than the represented in the figure, as other hospitals also employ cardiothoracic surgeons who perform other cardiothoracic surgeries, but not CABG. For those cardiothoracic surgeons linked to CABG, they are only present in the sub-group of 30 hospitals where both PCI and CABG is done, hence their headcount overlaps for the samples of 89 and 30 hospitals.
Source: HES data.

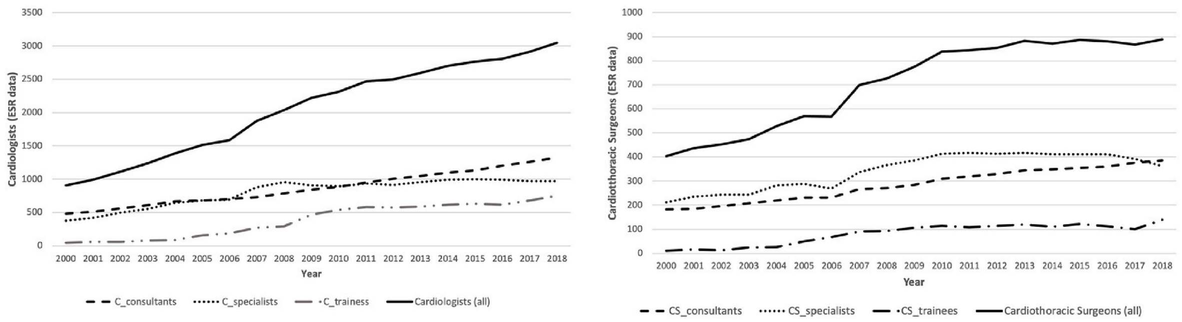
Post-2012 we maintain the geographical definition of the PCT, to allow for consistency in our geographical delimitation. After accounting for hospital mergers and excluding hospitals with exceptionally low volumes (with volumes of either PCI or CABG below 50 procedures per year, less than one intervention per week) are removed. The final dataset identifies 89 hospitals across the period 2000–2018 undertaking sufficient volume of PCI and/or CABG, representing the complete set of hospitals performing the vast majority of these procedures, and in sufficient numbers to analyse statistically within the English NHS. Of these 89 hospitals, a subgroup of 30 hospitals perform both surgeries (PCI and CABG), while the remainder of 59 hospitals only perform PCI.

Fig. 1 shows the volumes for PCI and CABG for all 89 hospitals performing PCI or CABG, and also the volumes for the subgroup of hospitals that perform both PCI and CABG. We are interested in the mature phase of technology uptake to document the changes in workforce that take place after substitution of one technology for another has stabilised. To do so we focus on the period 2000–2018, given that the initial substitution phase in the UK has been documented in McGuire et al. (2010) who analyse the substitution phase of these technologies in earlier stages of diffusion. The period 2000–2018 we take to represent a maturing phase of PCI adoption, and believe this more settled phase is where sustained labour impacts will be experienced. While the average annual rate of growth for PCI was 7.17% during the period 2000–2018, it was −1.40% for CABG, suggesting that as PCI matures the demand for CABG is significantly reduced. Similarly, the 30 hospital subgroup shows an average annual rate of growth for PCI of 4.34% during the period 2000–2018, and a 1.37% decrease for CABG. Fig. 1 presents the increase in PCI volumes across all hospitals performing this procedure, with a sustained increase in the use of this technology. The picture is different for the subgroup of 30 hospitals that perform both technologies, with an increase in volumes between 2000 and 2005, and relative stable volumes of PCI afterwards. This suggests specialisation in PCI is taking place where the increase in volume is driven by those hospitals that only perform PCI. However, our interest also lies on the subgroup of hospital providers that do both, as this allows examining the labour dynamics between two surgical staff groups.

### 3.2. *Workforce trends*

HES also includes an anonymised consultant code for the consultant in charge performing the intervention. Based on this information, we also compute the count of consultants per hospital and year associated

(a) Cardiologists - All hospitals (b) Cardiothoracic Surgeons - All hospitals



(c) Cardiologists - PCI/CABG (d) Cardiothoracic Surgeons - PCI/CABG

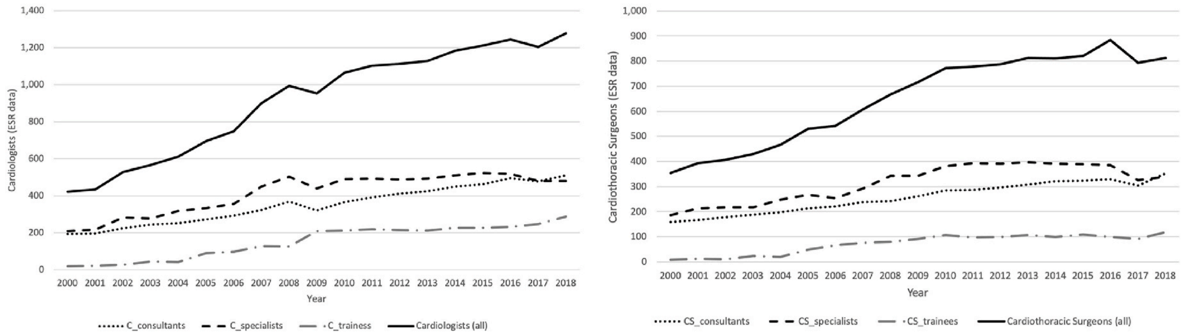


**Fig. 3.** Workforce by Seniority Levels (a) Cardiologists - All hospitals (b) Cardiothoracic Surgeons - All hospitals.
Source: ESR data (c) Cardiologist - sample of hospitals doing PCI/CABG (d) Cardiothoracic Surgeons - sample of hospitals doing PCI/CABG.

with each intervention. We distinguish between cardiologists, who perform PCI in a catheterisation laboratory, and cardiothoracic surgeons who perform CABG in an operating theatre (Gray et al., 2000; Molina and Heng, 2009). Fig. 2 shows the count of cardiologists and cardiothoracic surgeons in our dataset performing PCI and CABG, respectively, and for both the whole sample of 89 hospitals performing any of the surgical procedures and the subgroup of 30 hospitals performing both PCI and CABG. The number of cardiologists performing PCI increased over the period, with an average annual rate of growth of 8.9%, while the number of cardiothoracic surgeons performing CABG did not fall significantly, but remained relatively stable. Similarly to the 89 hospital group, the number of cardiologists performing PCI within the 30 hospital subgroup also increased over the period, with an average annual rate of growth of 5.2%, while the number of cardiothoracic surgeons performing CABG remained relatively stable.

Although HES data allows identifying the consultant in charge for each PCI and CABG, we are not able to distinguish across seniority levels of surgeons. This may be important as trends across seniority levels in cardiology and cardiothoracic surgery may reveal dynamics by staff grade that indicate the direction of any labour adjustment. Both cardiothoracic surgeons and cardiologists work in teams led by a consultant but with various junior physicians below them. Therefore, to complement the HES data on consultant count we exploit information available from the NHS Electronic Staff Record (ESR) that reports data on the total count of all NHS staff by staff grade and workplace. Unlike the HES data, the ESR data does not tie the exact treatments or procedures undertaken to individual staff. The staff numbers relating to cardiologists and cardiothoracic surgeons extracted from the ESR by default were larger than the counts retrieved from HES data given that these include all cardiologists and cardiothoracic surgeons, and not only those undertaking PCI and CABG respectively. When looking at counts in HES compared to ESR, HES data accounts for 76% of ESR cardiologist counts and 40% of cardiothoracic surgeons. Cardiothoracic surgeons cover not solely those only undertaking cardiac procedures but also those dealing generally with the thorax, which explains this slightly lower percentage. This is entirely consistent with the fact that through the HES database we only identify the sub-set of actual consultants who undertake PCI or CABG, while the ESR database covers all cardiologists and cardiothoracic surgeons.

Fig. 3 shows the increase in cardiologists and cardiothoracic surgeons by seniority level based on ESR counts: consultants, specialists and trainees. Specialists include all those below consultant level; Associate Specialist, Specialty Doctor, Staff Grade and Specialty Registrar. Trainees include those classed as Core Medical Training, Foundation Doctor Year 1 and Year 2). Graphs (a) and (b) show the counts for cardiologists and cardiothoracic surgeons, respectively, for the sample of all 89 hospitals from 2000 to 2018. The average annual growth rate was 7.05% for all cardiologists; slightly less than the growth in cardiologists known to perform PCI (as shown in Fig. 2). In contrast with Fig. 2, which showed a stable count of cardiothoracic surgeons performing CABG, Graph (b) shows an average annual growth rate of 4.62% in this specialty for the 89 hospital sample. Graphs (c) and (d) show the counts for the sample of 30 hospital sample. Graph (c) indicates an average annual growth rate of 5.52% for all cardiologists, slightly greater than the growth of cardiologists known to perform PCI (as shown in Fig. 2). In contrast with Fig. 2, which showed a stable count of cardiothoracic surgeons performing CABG, Graph (d) shows an average annual growth rate of 2.49% within the 30 hospital sample. The increasing numbers for all cardiothoracic surgeons is especially striking from 2006 onwards given the markedly decreasing trend in CABG volumes in the second half of our study period. This suggests the increase in cardiothoracic surgeons may be driven by an increased volume of surgical procedures other than CABG performed by this specialty group.

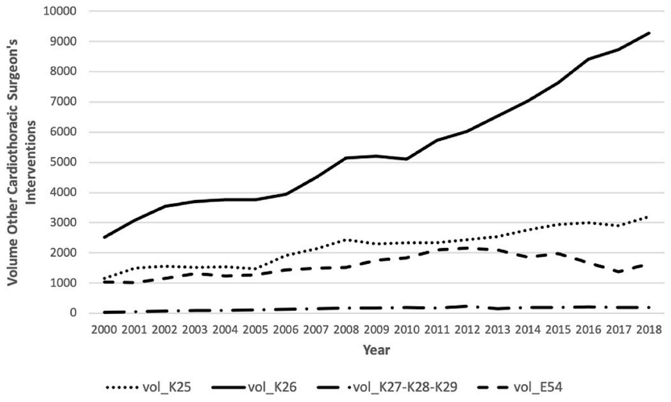


**Fig. 4.** Volume non-CABG interventions by Cardiothoracic Surgeons.
Source: HES data.

### 3.3. *Volumes for other cardiothoracic surgeries*

The replacement of CABG by PCI is postulated to give rise to cardiothoracic surgeons increasing the volume of other cardiac procedures. Using the anonymised consultant code for cardiothoracic surgeons available in HES, we identify all individual procedures performed by senior cardiothoracic surgeons. We track all their surgical volume for all operations other than CABG activity. We focus on the list of the main operations that fall into the remit of cardiothoracic surgeons as specified by the Royal College of Surgeons (Royal College of Surgeons of England, 2022). The list of included cardiothoracic surgeries are valve replacement, pneumonectomy, wedge resection and lobectomy. CABG and valve replacement are cardiac procedures, which is where our explicit interest lies as both act as direct cardiac competitors. While pneumonectomy, wedge resection and lobectomy are all thoracic procedures, we still consider them below due to the potential leverage cardiothoracic surgeons may have to compensate volumes with non-cardiac procedures. All surgical volumes related to these alternative procedures were identified by their specific OPCS-4 procedure code. See Table A1 in the Appendix for a list of OPCS-4 codes used to extract the data.Fig. 4 shows the volume of these other cardiothoracic surgeons interventions. While all procedures are increasing over time, among the cardiac surgeries aortic valve replacement (K26) shows the highest volume increase, followed by mitral valve replacement (K25), fol-lowed by all other procedures (K27 to K29). Thoracic procedures (lung interventions coded E54) show a more stable trend. Such increases could reflect a shift in the composition of surgical interventions performed by cardiothoracic surgeons as their CABG load decreases.

### 3.4. *Control variables*

In addition to the measures on procedure-specific volumes and count of doctors, our data includes a number of controls that capture patient and provider mix. We use HES data to compute hospital-averaged information on case-mix such as the percentage of male patients, percentage of emergency procedures, Charlson Comorbidity Index (CCI), Index of Multiple Deprivation (IMD) of the area where the patient resides, and age. We also include a number of hospital characteristics such as whether they have foundation trust status, bed occupancy rates, the total number of sites which the hospital trust occupies for health care service delivery and total annual admission per year. In some specifications we also include the volume of statins (used for primary and secondary prevention for cardiovascular disease) in each PCT to control for the use of alternative non-surgical technologies that may reduce the need for PCI or CABG. Table A2 in the Appendix lists the variables used, their definition and provides some descriptive statistics.

## 4. Empirical strategy

### 4.1. PCI diffusion

We first establish any interaction in place between PCI and CABG, as PCI enters its mature diffusion phase. We draw on Cutler and Huckman (2003) and McGuire et al. (2010) and use the following empirical specification:

$$\frac{CABG}{pop45_{it}} = \alpha + \beta_1 \frac{PCI}{pop45_{it}} + (\beta_s - \beta_1)\left[\frac{PCI}{pop45_{it}} * TimePeriod\right] + \gamma X_{it} + T_t + C_i + U_{it} \tag{1}$$

where the dependent variable is the population-adjusted CABG volume by hospital $i$ at year $t$ and the main explanatory variable is population-adjusted PCI volume. We also interact the population-adjusted PCI volume with a vector of time indicators (Year Periods: 2000–2004, 2005–2009, 2010–2014 and 2015–2018). These periods were decided based on the evolution of PCI/CABG to differentiate between periods of clear divergence between these technologies, as seen in Fig. 1. By using time-varying coefficients we allow the interaction between PCI and CABG to fluctuate over time. Through Equation (1) we are able to quantify the elasticity of substitution or complementarity between CABG and PCI, as PCI matures as a technology. We interpret the results in the same manner as Cutler and Huckman (2003) with the $\beta$ coefficients on the PCI and time interactions reflecting the change in the degree of substitution (complementarity) over the study period if the coefficient is negative (positive). As Cutler and Huckman (2003) state the overall level of substitution, taken as the sum of the base PCI coefficient and the relevant interaction term may well be biased if unobservables affect the relationship between CABG and PCI. However, the change in the degree of substitution or complementarity over time, as given by the $\beta'$s on the interaction terms will remain unbiased on the assumption that the degree of any bias in the overall level of substitution does not change over time; put simply that any unobservable relationship affecting PCI and CABG does not change over time. Even if this is considered a restrictive assumption, it remains likely that any existent bias will affect the levels of substitution more than their rates of change. This allows focus on the degree of substitution or complementarity over time as captured by the $\beta'$s on the interaction terms, noting that we only wish to identify broad trends here in any case.[2]

We also include a set of control variables $X_{it}$ (hospital-averaged patient case-mix and hospital characteristics as defined in Section 3), year fixed-effects $T_t$, hospital fixed-effect $c_i$ and the disturbance term $u_{it}$. Additionally, we explicitly examine the role that statins, a potential medical substitute for procedure interventions, may have on the diffusion of PCI, and whether this introduced a distortionary effect on the relationship between PCI and CABG.

#### 4.1.1. PCI indication creep

We also specifically consider the potential indication creep of PCI, whereby PCI is performed in older and sicker patients as surgeons become more familiar with the technology. The indication creep specification is as follows:

$$\begin{aligned} \frac{CABG}{pop_{it}} &= \alpha + \beta_1 \frac{PCI}{pop_{it}} + (\beta_s - \beta_1)\left[\frac{PCI}{pop_{it}} * (t\varepsilon s)\right] + \beta_2 Charlson_{it} \\ &\quad + (\beta_s - \beta_1)\left[Charlson_{it} * (t\varepsilon s)\right] + \gamma X_{it} + T_t + C_i + U_{it} \end{aligned} \tag{2}$$

where CABG and PCI are now population-adjusted to different age groups (55–64, 65–74, 75+) in order to test whether PCI was progressively performed in older patients. Subscript $i$ indicates hospital and $t$ year. PCI and CABG volumes are also interacted with the time dummies defined in Section 4.1 to examine whether there exist differences for the indication creep over time, again assuming that if unobservables result in bias between CABG and PCI, this bias is constant over time allowing the interaction terms to exhibit the degree of within age group substitutability (complementarity) changes, and again noting we are only interested in identifying broad trends here. In addition to differentiating the expansion of PCI across older patient groups, PCI may also be performed in sicker patients. To proxy for patient severity we use the Charlson index to account for comorbidities. We calculate the average CCI score seen in patients at hospital $i$ and year $t$ and we interact it with time periods. Fig. 1 in the Appendix shows the changing composition of patient profiles over time, comparing PCI with CABG. Figure (a) shows that CABG is performed on patients that are older compared to the age profile for those in the PCI group. Figure (b) shows patients in the CABG group had higher CCI during the first half of our study period, but this trend reversed slightly from 2010 onwards and PCI patients showed a marginally higher CCI. These graphs only show aggregated national averages per year, and our analysis will exploit the variation per hospital-year and provide confirmation on whether there exist changes in patient-mix in terms of age and CCI.

### 4.2. Workforce elasticity of substitution

Our primary empirical focus is to examine the labour implications following PCI diffusion. As PCI overtakes CABG, and cardiothoracic surgeons experience a decrease in CABG volumes we first quantify the responsiveness of cadiothoracic surgeons to the increased number of cardiologists through the following empirical strategy:

$$CS_{it} = \alpha + \beta_1 C_{it} + \gamma X_{it} + T_t + c_i + u_{it} \tag{3}$$

where the dependent variable $CS_{it}$ is the number of cardiothoracic surgeons per hospital trust $i$ and year $t$. $C_{it}$ is the number of cardiologists adjusted by population at risk in hospital trust $i$ and year $t$. Both $CS_{it}$ and $C_{it}$ are adjusted by the population at risk (patients aged$\geq$45). We also include a set of control variables $X_{it}$ (as defined above), year fixed-effects $T_t$ and the error term which consists of an unobserved hospital fixed-effect $c_i$ and the disturbance term.

$u_{it}$. During the period of analysis, 2000–2018, there were policy changes in the hospital sector (introduction of a fixed-price reimbursement system, quasi-market competition and waiting time targets). These were NHS-wide policies common across all hospital providers and are picked up by our year and hospital fixed-effects. The underlying assumption in Equation (3) is that any changes in workforce composition will reflect adjustments brought about by the use of PCI, a medical technology that largely replaced the use of CABG, and hence reduced activity volumes for cardiothoracic surgeons.

### 4.3. Cardiothoracic surgery displacement

Our descriptive analysis shows a decrease in CABG volume over time, while the number of cardiothoracic surgeons performing CABG remains stable. Indeed, there is also a simultaneous increase in the aggregate number of cardiothoracic surgeons even as CABG volume decreases (see Figs. 2 and 3). This in itself is compatible with an increasing volume of other cardiac surgeries that this workforce group undertakes (as per Fig. 1). We now empirically analyse potential replacement activity undertaken by these cardiothoracic surgeons as

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[2] Obviously if the unobservable factor is insignificant in explaining dependent variation it may be ignored. If on the other hand it is important, then bias will be imparted in the $\beta'$s on the interaction terms. However if this bias is constant then the expected values of these $\beta'$s, representing the change in the substitution values, will be unbiased. Following Cutler and Huckman (2003) note that E($\beta_s$ - $\beta_1$) in Eq (2) will be unaffected by a constant bias as E($\beta_s = \beta_s$, *true* + E(bias), where$\beta_s$, *true* is the true $\beta$ value and similarly $\beta_1 = \beta_1$, *true* + E (bias), such that E($\beta_s$ - $\beta_1$) will not be biased.

CABG volumes decline in response to volume increases in PCI. This analysis provides some explanation of what happens to cardiothoracic workload as PCI increases over time. For each consultant performing CABG identified in our sample over the study period, we track the volumes of all other surgical activity they undertake in a given year to consider whether CABG consultants respond to increases in PCI replacing CABG for other procedures. We consider the following specification at the consultant level:

$$\frac{otherCS}{pop45_{ijt}} = \alpha + \beta_1 \frac{PCI}{pop45_{it}} + (\beta_s - \beta_1)\left[\frac{PCI}{pop45_{it}} * (t\epsilon s)\right] + \gamma X_{it} + T_t + C_i + U_{ijt} \tag{4}$$

where the population-adjusted volume of other cardiothoracic surgical interventions (*otherCS*) performed by consultant *j* based in hospital *i* at time *t* is regressed on the volume of PCI interventions (adjusted for population at risk) performed at hospital *i* in the same year, also including interaction terms between the time periods and PCI volumes. The other cardio-thoracic volumes considered are valve replacement (mitral-K25, aortic-K26, tricuspid-K27, pulmonary-K28 and heart-K29) and lung interventions (pneumonectomy, wedge resection and lobectomy - E54).

## 5. Results

### 5.1. Diffusion of a mature technology

We first estimate the degree of substitution/complementarity between our two technologies through estimating Equation (1), using fixed-effects panel data methods. In this estimation, which is similar in specification to Cutler and Huckman (2003), the dependent variable is the volume of CABG over the population aged 45 and above (in 1000s) and the main explanatory variable is the corresponding measure for PCI. The results reported in Table 1, column (1) give the estimates for the whole sample of hospital providers which may supply both treatments or PCI and CABG separately, 89 hospital providers, and column (2) for the subsample of 30 hospital providers performing both procedures, for the period 2000–2018. The analysis using all hospitals provides an insight into the diffusion of the technology at the system level, whereas the analysis using the sample of hospitals that perform both surgeries is indicative of differences in uptake in a setting where both technologies compete directly. PCI volume is also interacted with the time dummies for the different diffusion periods as defined above. Each interaction term with a given time period represents the change in the coefficient of the CABG rate relative to 2000–2004 (our baseline). The coefficient on the PCI variable reports the overall degree of substitutability or complementarity, and as noted may potentially be biased. The interaction terms, used to indicate the change in the value of substitutability or complementarity within over time, will be unbiased if the bias between unobservables affecting CABG and PCI is constant over time.

It is these interaction terms we are interested in, given our focus is on how the relationship in CABG and PCI changes over time, as ultimately we wish to consider the impact of these volume changes on labour inputs. The estimates for the interaction terms are negative and statistically significant (relative to our reference period of 2000–2004) showing that the degree of substitutability between CABG and PCI generally strengthens over time. Again, this is in line with prior expectations, as PCI is increasingly rolled out to riskier patients. The coefficients of the interactions, which reflect marginal rates of change, are negative and increase by 0.09 over time. This confirms that, despite the existing complementarity between the technologies indicated by the coefficient of the PCI variable, there exits substitution that strengthens as PCI becomes the dominant technology.

In columns (3) and (4) we also include the log of statins, as a further (prescription) technology introduced into this patient population for the treatment of coronary heart dis-ease. However, the sample now only covers the period 2008–2018 given data restrictions on prescription information which was only available over this period. Statins prescriptions are negative and statistically significant (column (3) and (4)) indicating that statins are also substitutes for CABG. Although again subject to potential bias, we merely wished to describe the potential relationship between statins and CABG here, which appears to be one of substitutability. There is no reason to believe that the introduction of

**Table 1**
Technology diffusion: Basecase results.

| Dep.Var: CABG/45+ | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| PCI/45+ | 0.204*** | 0.184*** | 0.247*** | 0.214*** |
| | (0.049) | (0.059) | (0.070) | (0.085) |
| PCI/45+*(2005–2009) | −0.061*** | −0.054** | | |
| | (0.011) | (0.021) | | |
| PCI/45+*(2010–2014) | −0.156*** | −0.181*** | | |
| | (0.024) | (0.030) | | |
| PCI/45+*(2015–2018) | −0.155*** | −0.126*** | | |
| | (0.023) | (0.034) | | |
| 2005–2009 | −0.426*** | −0.122 | | |
| | (1.140) | (0.470) | | |
| 2010–2014 | −0.366* | 1.151 | | |
| | (0.209) | (0.694) | | |
| 2015–2018 | −0.787** | −0.065 | | |
| | (0.331) | (0.788) | | |
| Log Statins | | | −2.308* | −2.961* |
| | | | (1.169) | (1.563) |
| No. Hospitals | 89 | 30 | 83 | 29 |
| N | 1359 | 531 | 772 | 285 |
| Time fixed-effects (FE) | Yes | Yes | Yes | Yes |
| Hospital FE | Yes | Yes | Yes | Yes |
| Controls Patients | Yes | Yes | Yes | Yes |
| Controls Hospital | Yes | Yes | Yes | Yes |
| $R^2$ | 0.508 | 0.576 | 0.438 | 0.571 |
| Years | 2000–2018 | 2000–2018 | 2008–2018 | 2008–2018 |

*Notes:* Robust standard errors in parentheses. Significance levels: ***$p<0.01$, **$p<0.05$, *$p<0.1$. Control variables: percentage of male patients, percentage of emergency procedures, charlson morbidity index, Index of Multiple Deprivation of the area where the patient resides, mean age, percentage of population over 45 by PCT, bed occupancy rate, total number of admissions, total number of sites and foundation trust dummy. For models (1) and (2), the time FE are period dummies and for models (3) and (4), the time FE are year dummies because there are no interactions. Reference period 2000–2004.

**Table 2**
Technology Diffusion: Area level analysis.

| Dep.Var: CABG/45+ | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| PCI/45+ | 0.201*** | 0.182*** | 0.0526 | 0.0370 |
| | (0.0145) | (0.0218) | (0.0586) | (0.0904) |
| PCI/45+*(2005–2009) | −0.0579*** | −0.0490*** | | |
| | (0.00545) | (0.00712) | | |
| PCI/45+*(2010–2014) | −0.125*** | −0.117*** | | |
| | (0.00610) | (0.00931) | | |
| PCI/45+*(2015–2018) | −0.166*** | −0.160*** | | |
| | (0.00626) | (0.0105) | | |
| 2005–2009 | −60.24* | −62.85 | | |
| | (32.85) | (44.55) | | |
| 2010–2014 | −2.714 | 63.20 | | |
| | (37.17) | (57.14) | | |
| 2015–2018 | 10.93 | 142.3* | | |
| | (46.37) | (71.26) | | |
| Log Statins | | | −578.9 | −2327*** |
| | | | (753.3) | (529.8) |
| No. Hospitals | 89 | 30 | 83 | 29 |
| N | 1359 | 531 | 772 | 285 |
| Period fixed-effects | Yes | Yes | Yes | Yes |
| Provider fixed-effects | Yes | Yes | Yes | Yes |
| Controls Patients | Yes | Yes | Yes | Yes |
| Controls Providers | Yes | Yes | Yes | Yes |
| R-squared | 0.778 | 0.763 | 0.425 | 0.621 |
| Years | 2000–2012 | 2000–2012 | 2008–2012 | 2008–2012 |

*Notes:* See Table 1 for list of controls included. CABG and PCI volumes are computed at the area level. Control variables are averaged at the hospital level. Reference period 2000–2004. Robust standard errors in parentheses. . Significance levels: *** p < 0.01, ** p < 0.05, * p < 0.1.

statins will change the underlying strengthening substitutability between CABG and PCI. Results with the full set of control variables is given in Table A3 in the Appendix.

Given that some providers offer both types of procedures, whereas other providers focus exclusively on PCI, there could be some area dynamics in that CABG providers operating in specific markets would retain volumes at the expense of PCI. To partly address this concern, we have included in the specification outlined in Equation (1) a variable that controls for dynamics at the regional market level. For each hospital provider we count the number of hospitals doing CABG in a 30-mile radius, excluding the hospital's own CABG capabilities (if the hospital provides both services). The rationale for including this variable is that if more hospitals are performing CABG in the area, there is an increased probability of selection into CABG. We present the results in Table A4 in the Appendix. Adding this variable to Equation (1) does not change the results and remains statistically insignificant in the main specification.

We have considered the aggregate impact of market competition for patients at the hospital level above to account for area dynamics. We next consider the potential impact of volume changes, as opposed to using the count of competitors. This approach will identify area-level dynamics if the increase in PCI leads a to redistribution of CABG volumes at the regional market level. We estimate Equation (1) using area-level definitions for the CABG and PCI variables. In this specification the volume variables are defined as $CABG/pop45_{at}$ and $PCI/pop45_{at}$, where the subscript a refers to the area where the hospital trust is located. For each hospital provider, we define the area based on the 30-miles radius from the location of the hospital and define the volume of CABG and PCI supplied in this area for the surrounding providers within this area (excluding the hospital's own volumes). The 30-miles radius definition has been widely used in the literature to delimit markets (Gaynor et al., 2012; Bloom et al., 2015). Results are presented in Table 2. The point estimates for the interaction terms are slightly larger than those presented in Table 1, confirming the substitutability effect between CABG and PCI over time. The results also indicate a certain degree of area spillovers between these technologies beyond the existing substitution effect at the individual provider, suggesting additional market area adjustments to increases in PCI.

The results in the basecase presented in Table 1 include all PCI and CABG cases for all admission methods, being elective or emergency arrivals. We further examine whether differences arise for elective patients, given that elective admissions allow for extended planning of the procedures and additional time to consider which surgical type to perform. Results are presented in Table A5 in the Appendix and are very similar to the basecase. This suggests very little influence on the admission method, with pathways of care becoming more established over time irrespective of case urgency.

We also undertake a final check on the robustness of our results. As patients are referred for treatment by their GPs, waiting times could influence which surgery the patient will receive. We only observe the referring GP practice but not the cardiology service to which the patient was referred to. The decision on the type of procedure will be internally determined by doctors at the hospital level, but we do not observe how the decision making is done. We are only able to use volumes of PCI and CABG as measure of patient flows. However, to see if referral to a cardiology service and the accompanied waiting time affects patient flows, we have also estimated Equation (1) controlling for average patient waiting time in a given hospital. Results are available in Table A6 in the Appendix. The mean waiting time variable is not statistically significant and shows there is no impact on CABG volumes.

### 5.1.1. *Indication creep*

To capture the impact of indication creep through the use of PCI in increasingly more diseased patient groups, Table 3 presents the results of regressing the volume of CABG undertaken in increasingly elderly age groups against the use of PCI in those age groups, including interacting PCI volumes for that age group with time interactions and a Charlson comorbidity index (CCI), reflecting higher degrees of comorbidity in patients, also interacted with time periods. We use the sample that includes the 30 hospital providers as it allows direct comparison of the interaction between these two surgical techniques, PCI and CABG. Each column represents a patient group of different age (55–64, 65–74 and 75+) and the PCI volume is again interacted with time dummies.

In line with our general results in Table 1, these results show general growing substitutability between the procedures. As shown by the PCI age group time interactions, this is consistent with PCI indication creep. This is also consistent with findings in Tu et al. (1997) and Cutler and

Huckman (2003), who also assessed the impact of PCI use as demand expanded to more elderly patients. The estimates for the CCI are over-all weaker, with only the youngest age group revealing a fall in CABG rates as comorbidities increase. The over-all takeaway is that there is a decreasing rate of CABG use in elderly patients over time, supportive of indication creep if ageing is assumed to be a risk factor in this population.

### 5.2. Technology diffusion and workforce effects

As our analysis suggests during the mature phase of PCI diffusion, PCI and CABG interact as substitutable technologies over time. Our primary question of whether cardiothoracic surgeons reallocate their tasks as their CABG volumes significantly reduced remains. In this section we explore any adjustments of the skill-mix involved in PCI and CABG. We first estimate the workforce elasticity between cardiothoracic surgeons and cardiologists. Results are presented in Table 4. Column (1) provides the estimated coefficient using the sample that includes all hospital providers. This estimate suggests that an increase of 10 cardiologists per 1000 inhabitants, increases the number of cardiothoracic surgeons by 0.5 per 1000 inhabitants. This estimate quantifies the system-wide effect of the workforce adjustment. In column (2) we present the results using the subsample of hospitals that do both PCI and CABG. The estimated effect indicates that an increase of 10 cardiologists per 1000 inhabitants, increases the number of cardiothoracic surgeons by 0.8 per 1000 inhabitants. This effect is larger than in column (1) as the effect is mediated by a more direct comparison between surgical specialties that compete within the same hospitals.

#### 5.2.1. Workforce elasticity using ESR data

As further robustness check, and to give some precision to workforce composition effects, Table 5 presents the estimates of using ESR workforce counts, instead of workforce counts obtained from HES data. Results in Table 5 follow the specification of Table 4. As discussed in Section 3, ESR data records all cardiologists and cardiothoracic surgeons working in the NHS, but it returns a larger count of workforce because it accounts for all cardiologists and cardiothoracic surgeons, not only those performing PCI or CABG. While we cannot link the individual

**Table 3**

PCI indication creep.

| Dep. Var: | (1) | (2) | (3) |
|---|---|---|---|
| | CABG/55-64 | CABG/65-74 | CABG/75+ |
| PCI/55-64 | 0.243*** | | |
| | (0.044) | | |
| PCI/55–64*(2005–2009) | −0.130*** | | |
| | (0.016) | | |
| PCI/55–64*(2010–2014) | −0.214*** | | |
| | (0.043) | | |
| PCI/55–64*(2015–2018) | −0.144*** | | |
| | (0.022) | | |
| PCI/65-74 | | 0.305*** | |
| | | (0.060) | |
| PCI/65–74*(2005–2009) | | −0.108*** | |
| | | (0.023) | |
| PCI/65–74*(2010–2014) | | −0.279*** | |
| | | (0.024) | |
| PCI/65–74*(2015–2018) | | −0.123* | |
| | | (0.063) | |
| PCI/75+ | | | 0.304*** |
| | | | (0.078) |
| PCI/75+*(2005–2009) | | | −0.018 |
| | | | (0.029) |
| PCI/75+*(2010–2014) | | | −0.132** |
| | | | (0.060) |
| PCI/75+*(2015–2018) | | | −0.120*** |
| | | | (0.041) |
| Charlson | −4.766** | −2.806 | 2.258 |
| | (1.871) | (3.065) | (2.575) |
| Charlson*(2005–2009) | 2.632 | 1.683 | −1.520 |
| | (1.988) | (3.202) | (3.107) |
| Charlson*(2010–2014) | 3.429* | 1.725 | −3.572 |
| | (1.847) | (2.983) | (2.393) |
| Charlson*(2015–2018) | 3.757 | 3.388 | −3.351 |
| | (2.909) | (5.110) | (3.372) |
| 2005–2009 | −1.079 | −1.276 | 1.622 |
| | (1.134) | (2.095) | (2.009) |
| 2010–2014 | −0.928 | 0.917 | 5.232*** |
| | (1.392) | (2.086) | (1.624) |
| 2015–2018 | −2.373 | −4.967 | 3.599 |
| | (3.182) | (6.983) | (3.811) |
| No. Hospitals | 30 | 30 | 30 |
| N | 528 | 528 | 528 |
| Year FE | Yes | Yes | Yes |
| Hospital FE | Yes | Yes | Yes |
| Controls Patients | Yes | Yes | Yes |
| Controls Hospitals | Yes | Yes | Yes |
| R2 | 0.665 | 0.609 | 0.505 |
| Year | 2000–2018 | 2000–2018 | 2000–2018 |

*Notes:* See *Notes* in Table 1. Reference period is 2000–2004 for the time interactions. Robust standard errors in parentheses. . Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

**Table 4**
Workforce Elasticity: PCI & CABG hospitals.

| | (1) | (2) |
|---|---|---|
| Dep. Var: CS over pop45+ (per 1000 inhabitants) | | |
| Cardiologist over pop45+ (per 1000 inhabitants) | 0.053**<br>(0.020) | 0.083***<br>(0.032) |
| No. Hospitals | 89 | 30 |
| N | 1359 | 531 |
| Year FE | Yes | Yes |
| Hospital FE | Yes | Yes |
| Controls Patients | Yes | Yes |
| Controls Hospitals | Yes | Yes |
| Years | 2000–2018 | 2000–2018 |

*Notes:* Robust standard errors in parentheses. Significance levels: ***p < 0.01, **p < 0.05, *p < 0.1. CS refers to Cardiothoracic surgeons. CS and cardiologists are counts per 1000 inhab-itants. Control variables included are: percentage of male patients, percentage of emergency procedures, charlson morbidity index, Index of Multiple Deprivation of the area where the pa-tient resides, mean age, percentage of population over 45 by PCT, bed occupancy rate, total number of admissions, total number of sites, and foundation trust dummy.

workforce data from the ESR to the treatment procedures we analyse, as we do for HES data, the ESR data do have detailed data on workforce seniority levels that allows us to break down the impact of the maturing use of PCI by staff grade, as there are data on counts of consultants (attending or chief resident physician), specialists (residents) and trainees (fellows) at individual hospital provider and year level.

Table 5 reports on staffing levels for the 89 hospital providers in columns (1) to (4) and for the 30 hospital providers (performing both CABG and PCI) in columns (5) to (8). Results show statistically insignificant effects for all workforce but also by seniority. This may be explained by the differences between HES workforce count, which reflects the accurate count of physicians performing PCI or CABG, compared to ESR, which has the total count of physicians in these two surgical specialties, and therefore the results may be downward biased. As a result, the ESR data is not informative of any dynamics happening by seniority level.

### *5.3. Cardiothoracic surgeons' response to decreased CABG as a result of increasing PCI uptake*

Despite a decline in CABG volumes, the number of cardiothoracic surgeons performing CABG has remained stable, and we would expect individual consultant productivity for cardiothoracic surgeons to decrease. Instead, we observe an increase in volumes of the other cardiac procedures that cardiothoracic surgeons perform. In order to investigate any replacement activity in response to increases in PCI, we examine the level of substitution across alternative interventions undertaken by cardiothoracic surgeons in response to increasing PCI volumes replacing CABG. Table 6 presents the estimates of a pooled OLS with year and hospital fixed-effects at the consultant level, where other cardiothoracic procedures are regressed on the hospital volume of PCI and interacted with time dummies. As explained in the data section, the other main interventions that cardiothoracic surgeons perform are valve replacement (mitral-K25, aortic-K26, tricuspid-K27, pulmonary-K28 and heart-K29) and lung interventions (pneumonectomy, wedge resection and lobectomy - E54). Table 6 shows the estimates only for the consultants identified in HES as performing CABG, observed in the sample of the 30 hospitals performing both PCI and CABG.

Column (1) shows the results aggregating all valve replacement procedures (K25 to K29). We are interested in the interaction terms as these indicate the level of substitution between the increase in PCI volumes and non-CABG volumes. The interaction terms are positive and statistically significant for the third (2010–2014) and fourth (2015–2018) period. This indicates that increases in PCI volumes in the hospital where the CABG surgeon practices lead to higher volumes of other cardiothoracic procedures. Columns (2) to (4) show the results when separating valve replacement surgeries according to procedures with higher volumes, K25 and K26, and all other procedures (K27 to K29). Results for K25 and K26 are consistent with those in Column (1). On the contrary, results in Column (4) show higher PCI volumes reducing volumes of other valve replacement surgeries. Column (5) shows the results for lung surgeries. None of the relevant point estimates

**Table 5**
Workforce Elasticity: PCI & CABG hospitals - ESR data.

| Dep. Var: CS | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | All | Consultants | Specialists | Trainees | All | Consultants | Specialists | Trainees |
| Cardiologist All | 0.112<br>(0.115) | | | | 0.060<br>(0.095) | | | |
| Cardiologist Consultants | | 0.063<br>(0.061) | | | | 0.014<br>(0.053) | | |
| Cardiologist Specialists | | | 0.146<br>(0.157) | | | | 0.088<br>(0.138) | |
| Cardiologist Trainees | | | | 0.086<br>(0.063) | | | | 0.092<br>(0.067) |
| No. Hospitals | 89 | 89 | 89 | 89 | 30 | 30 | 30 | 30 |
| N | 1359 | 1359 | 1359 | 1359 | 531 | 531 | 531 | 531 |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Hospital FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Controls Patients | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Controls Hospitals | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Years | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 |

*Notes:* Robust standard errors in parentheses. Significance levels: ***p < 0.01, **p < 0.05, *p < 0.1. CS refers to Cardiothoracic surgeons. CS and cardiologists are counts per 1000 inhabitants. Control variables included are: percentage of male patients, percentage of emergency procedures, charlson morbidity index, Index of Multiple Deprivation of the area where the patient resides, mean age, percentage of population over 45 by PCT, bed occupancy rate, total number of admissions, total number of sites, and foundation trust dummy.

**Table 6**
CABG displacement.

| Dep Vars: | (1)<br>K25–K29 | (2)<br>K25 | (3)<br>K26 | (4)<br>K27,K28& K29 | (5)<br>E54 |
|---|---|---|---|---|---|
| PCI/45+ | −0.0024 | −0.0013 | −0.0011 | −4.19e-05 | −0.0013 |
| | (0.0030) | (0.0010) | (0.0021) | (4.75e-05) | (0.0012) |
| PCI/45+*(2005–2009) | 0.0003 | 6.85e-05 | 0.0003 | −3.52e-05 | −6.02e-05 |
| | (0.0015) | (0.0005) | (0.0010) | (3.18e-05) | (0.0004) |
| PCI/45+*(2010–2014) | 0.0043** | 0.0018*** | 0.0027** | −0.0002*** | 0.0016 |
| | (0.0016) | (0.0004) | (0.0013) | (6.97e-05) | (0.0012) |
| PCI/45+*(2015–2018) | 0.0077*** | 0.0035*** | 0.0042*** | −2.91e-05 | 0.0009 |
| | (0.0023) | (0.0008) | (0.0014) | (0.0001) | (0.0007) |
| 2005–2009 | 0.0467 | 0.0231 | 0.0204 | 0.0033*** | 0.0423** |
| | (0.0429) | (0.0143) | (0.0295) | (0.0012) | (0.0189) |
| 2010–2014 | −0.0114 | −0.0009 | −0.0172 | 0.0067** | 0.0369 |
| | (0.0534) | (0.0181) | (0.0376) | (0.0025) | (0.0255) |
| 2015–2018 | −0.0514 | −0.0159 | −0.0401 | 0.0046 | 0.0330 |
| | (0.0634) | (0.0220) | (0.0418) | (0.0029) | (0.0257) |
| No. Hospitals | 30 | 30 | 30 | 30 | 30 |
| N | 4496 | 4496 | 4496 | 4496 | 4496 |
| Time FE | Yes | Yes | Yes | Yes | Yes |
| Hospital FE | Yes | Yes | Yes | Yes | Yes |
| Controls Patients | Yes | Yes | Yes | Yes | Yes |
| Controls Hospital | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.293 | 0.133 | 0.303 | 0.106 | 0.178 |
| Years | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 | 2000–2018 |

*Notes:* See *Notes* in Table 1 for controls included. Standard errors (in parentheses) clustered at the hospital level. Significance levels: ***p < 0.01, **p < 0.05, *p < 0.1. The same consultant may practice in different hospital providers. This prevented us from using a fixed-effects panel model. Estimates obtained using a pooled OLS with year and hospital fixed-effects.

are statistically significant.

Overall, the results suggest that increased volumes of PCI (which are associated with lower volumes of CABG) lead to changes in volumes of the other cardiothoracic volumes. This reinforces the idea that as CABG decreases, and with a relatively stable number of cardiothoracic surgeons over time, the reduction in CABG volume is substituted by an increasing volume of valve replacements, a type of surgical procedures within the remit of the cardiothoracic surgical specialty.

## 6. Discussion and conclusion

The objective of this paper was to consider the full impact of a maturing new technology on health care workforce composition in the context of the English NHS. We compare two competing technologies for treating cardiovascular disease: CABG, an open procedure introduced as an initial treatment for coronary heart disease, and PCI, a less invasive and cheaper procedure for the treatment of this disease introduced into the NHS later. Each of these surgical technologies are performed by a different set of physicians in the NHS. CABG is performed by cardiothoracic surgeons and PCI by cardiologists. This allows us to examine changes in the medical workforce arising from technology change. We use two major UK administrative databases to undertake our analysis: the Hospital Episodes Statistics (HES) and the NHS Electronic Staff Records (ESR). HES allows specific identification of the consultants (cardiologists and cardiothoracic surgeons) undertaking PCI or CABG procedures. While ESR data identifies all NHS cardiologists and cardiothoracic surgeons, providing greater detail on staffing levels by seniority levels, but not explicitly linking the individual staff to specific operations.

Our results indicate substitution between PCI and CABG in the mature phase of diffusion, with PCI largely reducing CABG volume and being performed over older and sicker patients. There is also a positive workforce elasticity between cardiologists performing PCI and cardiothoracic surgeons performing CABG. Our analysis also covered the replacement of activity of cardiothoracic surgeons, as PCI volume increases (and CABG volume is reduced) surgeons increase activity for other cardiac interventions, especially for the case of valve re-placement interventions. We provide a quantification of the differential effects of changes in PCI on CABG and non-CABG volumes. Focusing on the last stage of diffusion in our study period (2015–2018) our estimates indicate that an increase in 100 PCI surgeries per 1000 population at risk leads to a decrease of CABG by 12.6 surgeries (See Column (2) in Table 1). Similarly, an increase in 100 PCI surgeries will lead to an increase in 0.77 non-CABG surgeries (valve replacement surgeries, see Column (1) in Table 6). Despite the increase in non-CABG procedures by cardiothoracic surgeons, this effect does not offset the decrease in CABG volumes. This accounts for the levelling off in the employment of cardiothoracic surgeons, rather than any decrease that might have been expected to follow the decrease in CABG rates. Whether this increase in the volume of other cardiac treatments reflects a compensating mechanism in the form of supplier-induced demand or merely the ability of these surgeons to address pent-up demand in other treatment areas is something our data does not allow us to address.

Little is known about the substitution of workforce across the health care sector, and there is little knowledge relating to the technology-labour substitution. If technology is a major driver of health care expenditure growth, examining general impacts of new technology uptake on staffing levels and composition is key to understand future workforce planning. This is ever more important given the long-standing workforce shortages present in the NHS and across healthcare systems worldwide. Further research is required to validate our findings across other areas of technology, and across a wider range of staffing categories. Data restrictions on staffing levels prevented investigation of the latter in our case.

Overall, our results suggest that, at least in this area of health care, new technology up-take and diffusion does affect the skill mix of the medical workforce as that technology matures. While our results are confined to specific, although highly prevalent technologies, it appears that the complex regulation of staffing and specialty mix is even further complicated once account is taken for the impact of new technology on the hospital production process. Skilled medical staff, at least, appear to be able to substitute new tasks in adjusting to exogenous technology change. This, along with the expansion of the new technology, helps explain why technology up-take fuels increasing health care expenditure.

## Funding statement

The research was funded by The Health Foundation (Efficiency Research Program), Award Reference Number 7432.

## CRediT authorship contribution statement

**L. Maynou:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **A. McGuire:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **V. Serra-Sastre:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

## Acknowledgments

This paper was produced using HES provided by NHS Digital under Data Sharing Agreement (DSA) NIC-354497-V2J9P. This paper has been screened to ensure no confidential information is revealed. We thank participants at the Health Economics Study Group in Aberdeen, Jornadas AES organised by the Asociación Española Economía de la Salud, Simposio de la Asociación Española de Economía, Taller EvaluAES, European Health Economics Association at the University of Maastricht, Department of Health Policy Seminar Series LSE, Departament d'Economia Universitat Jaume I, Health Economics, Econometrics and Data Group Seminar Series at University of York, CRES at Universitat Pompeu Fabra, NHS Improvement and comments received by the Advisory Committee of the Efficiency Research Program. This work was supported by the Efficiency Research Program funded by The Health Foundation, Award Reference Number 7432. Laia Maynou is funded by the Spanish Ministry of Science, Innovation and Universities (PID2022-138866OB-I00 and CNS2023-144351).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2024.117014.

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