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# Non-Parametric and Parametric Applications Measuring Efficiency in Health Care

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**Abstract.** This paper reviews 188 published papers on frontier efficiency measurement. The techniques used are mainly based on non-parametric data envelopment analysis, but there is increasing use of parametric techniques, such as stochastic frontier analysis. Applications both to hospitals and wider health care areas are reviewed and summarised, and some meta-type analysis undertaken. Results appear to confirm earlier findings that public provision demonstrates less variability than private. The paper is meant as a resource in itself, but also points to the future in terms of possible directions for research in efficiency measurement in health care and health.

**Keywords:** efficiency measurement, health care, parametric, non-parametric, stochastic frontiers, data envelopment analysis, health care

## 1. Introduction

In reviewing published applications of efficiency measurement in health care, this paper encompasses systematic searching of all available databases, as well as using contact lists such as Listserve and the Productivity Analysis Research Network. Papers are reviewed with a view to determining methods used, data used, models specified, sensitivity analysis employed, validity and robustness of techniques, results, and policy implications. Furthermore, results are summarised in a form of meta-analysis in order to synthesise results and draw out further implications.

An updated review in the area of health and health care is due, and is especially important given the lack of direction, and some would say confusion, in the area of efficiency measurement in health,[1] being in part due to the lack of information available to researchers on what has been undertaken so far. Until a researcher in the field examines the directions taken by their peers, it is difficult to place ones own work in context.

Given the above, it is hypothesised that much work undertaken and published in this area is of the nature of 'have software – will analyse', which may have resulted in research that has a weak underlying basis in sound economic theory. Findings on 'efficiency' may therefore have led to policy changes that are based upon invalid models and unreliable estimates of efficiency.

The consequences of the published research literature are drawn out for the theory and application of efficiency measurement in health care. There is, up to the end of 2002,[2] a published literature consisting of 188 journal papers and book chapters, helping to set in place robust foundations and guidelines for a research agenda for future research in this area. Future directions will involve such important factors as statistical analysis of results, as well as highlighting areas of analysis which require development, for example primary care, health promotion, or the production of health.

There are difficulties associated with trying to combine results in any way from different studies. Differences can arise for several reasons, including different data availability, model specification issues, estimation techniques, and data quality, to mention but a few, so results may not be strictly comparable. What is attempted here is the drawing out of trends from a large number of studies, associated problems with this must always be borne in mind.

As an appendix study findings are summarised, which will be a useful resource in itself.

## 2. Background

Hollingsworth et al. [71] reviewed the literature focusing on non-parametric measurement of efficiency in health care. Up to the end of 1997 there were 91 published studies and the paper concluded evidence from Europe and the USA suggested public rather than private provision appears more efficient, with the literature focussing on technical rather than allocative efficiency as health care inputs and outputs are difficult to value. The paper notes a rapid increase in the number of studies, the first published in 1983,[3] but over half being published between 1994 and 1997. Also, almost two thirds of studies made use of data envelopment analysis (DEA) alone, perhaps not surprising at the time given methodological and practical software developments [70]. A fifth of studies used

[1] A summary of arguments concerning economists' general confusion about efficiency can be found in Rice [129].

[2] The year 2002 is as complete as possible, given publication deadlines, and the time it takes certain databases to update.

[3] Although Wilson and Jadlow [163] do make use of LP techniques.

two stage analysis (DEA followed by some form of regression) to attempt to identify further determinants of efficiency.

In terms of area of application, almost two thirds were in hospitals and nursing homes in the USA. Although some papers looked at the efficiency of specific areas of secondary care, or primary care, in only a small number of studies was account made of the health status of individuals. The emphasis was always on measuring the efficiency of health care, rather than the efficiency of production of the health of the individual. Only a small number of studies tested different methods (for example weight restrictions, Malmquist techniques), or attempted validity measurement of model specification.

This paper builds on the earlier review, updating all the categories above, and adding in other studies using other efficiency measurement techniques, such as stochastic frontiers (SFA). These are increasingly used, but it is still DEA based methods which dominate the literature.

## 3. Applications

During the last twenty years, non-parametric and parametric methods have been increasingly employed to measure and analyse the productive performance of health care services. The health care sector is a unique area of application, and one in which the measurement of efficiency has burgeoned over the past few years. This section reviews the methodologies and results of studies which measure efficiency and productivity of health services.

First, some summary statistics are provided to give an overview of the extent of the literature. The total number of studies identified up to and including 2002 is 188. Around 70% of these studies publish quantifiable scores that can be analysed.[4] The earliest study is in 1983 [102] reflecting the relatively contemporary nature of the techniques. Several patterns emerge when undertaking some basic analysis of the studies. The first is the rapid increase in studies over recent years, with almost 80% of studies having reported in the last 10 years, see figure 1.

Figure 2 shows 50% of studies use DEA alone, this has fallen from over 60% in studies published up to 1997, as more complex analysis, such as using the efficiency score as the dependent variable in secondary regression analysis and applications of the Malmquist index, are now used more often. A quarter of studies use regression analysis in two stage analysis, typically to regress factors on the efficiency scores in

[4] A list of those references not specifically mentioned here can be obtained by contacting the author.

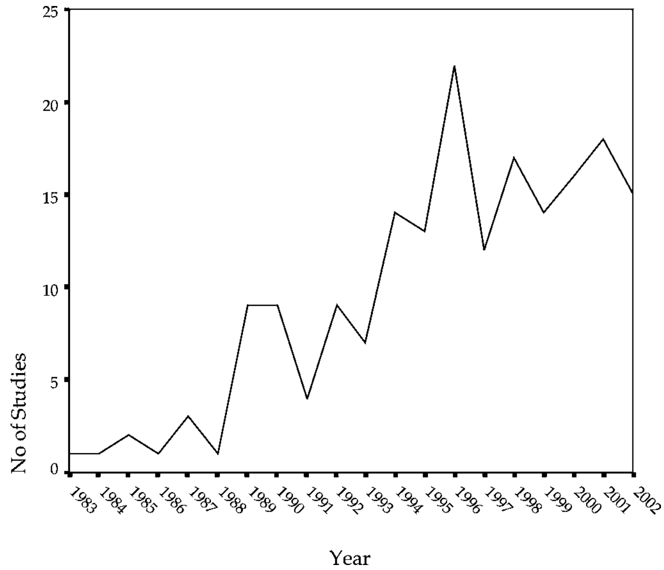


Figure 1. Number of efficiency studies 1983–2002.

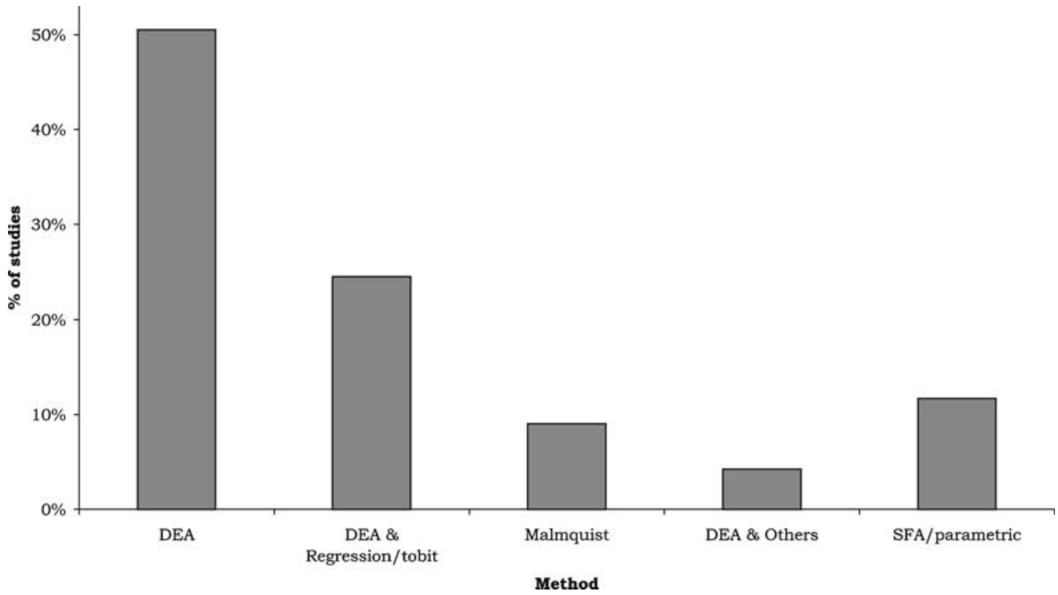


Figure 2. Methods used in reported studies.

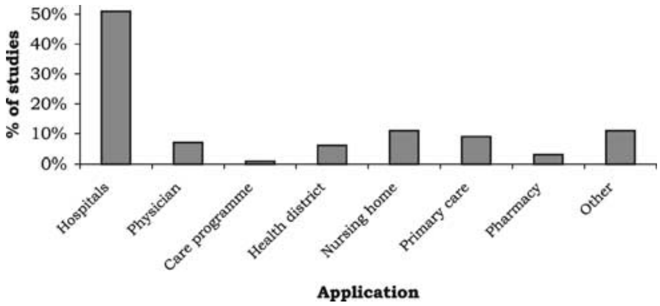


Figure 3. Areas of application.

an attempt to determine influences on efficiency. Malmquist techniques are used in 9% of studies, also SFA and other parametric frontier techniques are used in 12% of studies.

Figure 3 shows that over 60% of applications are in the area of secondary care and nursing home care. An increasing, but still small, number of studies investigate the efficiency of primary care delivery, and individual physician efficiency. This may simply reflect availability of data.

The output variables used in the analysis are almost entirely measures of physical activity, such as inpatient days or discharges. Only ten studies use *outcome* measures examining changes in health status of individuals treated. In terms of measuring outputs in hospitals (where it is recorded) there is an almost even split between inpatient days and inpatient cases. Input variables are mainly measures of staff and capital employed. Most of the results of the analysis are simple measures of technical efficiency. More recently there have been some studies reporting on productivity changes, although these must be viewed in their individual contexts. Although most studies are straightforward applications, a small number test methods such as weight restricted models and analysis of returns to scale. Similarly, a small number of studies use statistical or sensitivity analysis of results.

## 4. DEA applications in health care

Initially overall measures of efficiency in hospitals are concentrated on, before going on to examine the general health literature.

### *4.1. The hospital literature*

Details of the hospital efficiency studies can be found in the appendix and these show the type of hospital, country, number of hospitals in the sample, author(s) and efficiency scores. Most studies report results from the USA and can be categorised into different types of hospital. The main division can be made between public and private provision.[5] The public providers include Federal units, military Veteran's Administration (VA) units and Department of Defence (DoD) hospitals.

[5] Ownership definitions used here are: public – state owned/run firms; for profit-privately run; not-for-profit – in some cases are voluntary/charity run firms which serve the poor, but can also be privately run. However, health care not-for-profit firms obtain 90% of revenue from sales and receipts, are entitled to many tax exemptions and advantages, make a residual surplus and compete with for profit hospital firms.

Table 1
Summary statistics for hospital efficiency scores.

| | No. | Mean | Median | Standard deviation | Minimum |
|---|---|---|---|---|---|
| For profit | 4 | 0.801 | 0.855 | 0.130 | 0.61 |
| Not-for-profit | 11 | 0.824 | 0.874 | 0.115 | 0.60 |
| Public | 6 | 0.948 | 0.945 | 0.033 | 0.895 |
| Defence/VA | 5 | 0.898 | 0.92 | 0.052 | 0.82 |
| Non-teaching | 2 | 0.742 | 0.742 | 0.046 | 0.71 |
| Teaching | 2 | 0.71 | 0.71 | 0.085 | 0.65 |
| Acute/general | 24 | 0.84 | 0.852 | 0.086 | 0.65 |
| Non-specified | 14 | 0.85 | 0.861 | 0.101 | 0.70 |
| *All hospitals* | *68* | *0.844* | *0.87* | *0.099* | *0.60* |
| *USA Hospitals* | 48 | 0.834 | 0.86 | 0.104 | 0.60 |
| *EU hospitals* | 17 | 0.892 | 0.897 | 0.073 | 0.751 |
| *Non-USA/EU* | 3 | 0.799 | 0.74 | 0.116 | 0.724 |

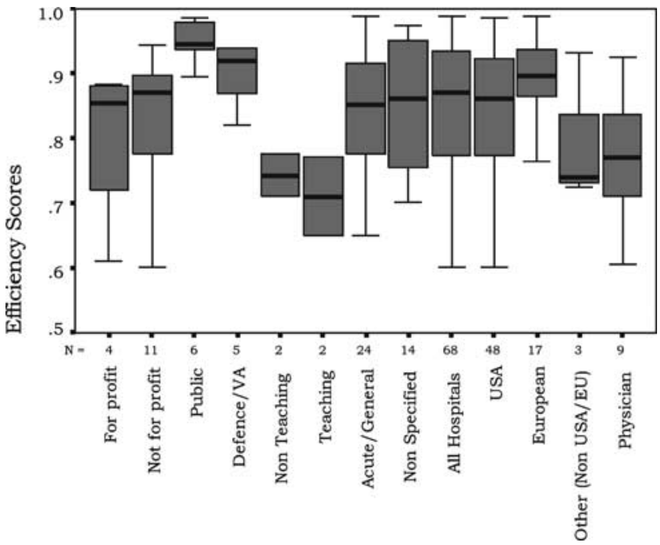


Figure 4. Boxplot of distribution of efficiency scores by category of hospital.

The summary statistics are shown in table 1, and a boxplot of the efficiency scores by hospital category is shown in figure 4. The mean efficiency across the whole sample is 0.84 (excluding the within hospital studies) and the median is 0.87.

Figure 4 summarises the results for each hospital type. The boxplot shows the median, quartiles, and extreme values for each hospital group, allowing us to see at a glance which hospital groups are more efficient and the range of scores. Comparing efficiency across the sector, public hospitals have the highest mean efficiency (0.95) and the highest median score (0.94), compared with not-for-profit (generally private) hospitals which have a lower mean efficiency (0.824) and a lower median score (0.874). Defence and Veterans' Administration (VA) hospitals (which are public in nature) also have a higher mean score (0.898) and a higher median score (0.92) than not-for-profit hospitals. Not-for-profit firms treat 70% of hospital patients in the USA [49] and these results correlate with comparisons made in individual studies where public and private provision are compared [61,99,154,155]. Examination of the standard deviation and minimum demonstrate the room for efficiency gain. For not-for-profit hospitals the standard deviation is 0.115 and the minimum 0.60, demonstrating considerable deviation from the mean of 0.824 and so substantial room for improvement. Potential efficiency gains are less obvious for public hospitals (standard deviation 0.033, minimum score 0.895 and mean of 0.95) and defence/VA hospitals (standard deviation 0.052, minimum 0.82 and mean of 0.898). There is also some potential for gain for Acute/general hospitals (standard deviation 0.086 and a minimum of 0.65), deviating from the mean of 0.84. The small sample of teaching hospitals shows non-teaching units to be more efficient (0.742 compared to 0.71).

To give some indication as to the efficiency of different means of health care delivery, the efficiency of hospitals across countries is compared. Most studies are from the USA where the average efficiency is 0.834, with a median of 0.86 and a minimum of 0.60. Here, the system is predominantly one of privately provided health care insurance, with a safety net of Medicaid and Medicare to cover the poor and elderly, respectively. In the European sample (including the UK, Finland, Greece, Austria, Belgium, Norway, Spain and France), where health care is characterised by public provision or social insurance, the average efficiency is 0.892, with a median of 0.897 and a minimum of 0.751. These results are higher than for the sample of USA hospitals, where there appears to be greater potential for efficiency gain, with a standard deviation of 0.104 and a minimum of 0.60 for the USA sample compared to 0.073 and 0.751 for the European sample.

The results, both that public provision seems to demonstrate less variability, and that European hospitals have higher average efficiency would seem to contradict the hypothesis that private market provision of services is more efficient than public provision of services. One explanation may be that health care is an unusual economic commodity. A second explanation could be methodological differences between the studies, for example differences in variables used or sample sizes leading to some studies potentially being more robust than others. It also may be the case that there is more 'slack' or spare capacity in the USA system. As a consequence results may be conditional upon heterogeneity of observations, rather than any real variations in efficiency. These factors suggest a need for caution in comparing results.

There are several studies looking at the efficiency of clinicians within hospitals, for example examining their ability to treat different cases under different payment regimes. Ozcan et al. [117] looks at 214 USA hospitals in 1989 in terms of stroke treatment. Those with more experience (100+ cases) are more efficient (0.81) than those with less experience (0.59–0.61). Harper [66] uses DEA and econometrics to measure the efficiency of 31 UK hospitals general surgery units for 1998/2000 data with estimates ranging from 0.876–0.938 in 1998/1999, and 0.849–0.930 in 1999/2000 with no widespread differences in units, with a small number of units performing poorly. Other examples include Hofmarcher et al. [69] who look at hospital wards in Austria and Puig-Junoy [127] looking at intensive care units in Spain.

*4.2. The general health literature*

There are several other health care areas in which DEA has been applied, although it should be borne in mind that there may be more scope for omitted variables, heterogeneous activities, or poor measurement. Details of the general health studies can be found in the appendix and show the type of organisation, country, number in the sample, author(s) and efficiency scores. The summary statistics are shown in table 2 and a boxplot of the distribution of efficiency scores in figure 5.

There is some coverage in the literature of more general health care administrative units: at the most general level, with general analysis on two levels – metropolitan and district health authorities and care programmes.

Examination of the statistics in table 2 and the boxplot of the distribution of scores in figure 5 demonstrates there is potential for efficiency gain. For Health Districts there is room for improvement, both in Europe and the USA (means of 0.839 and 0.742 and minimums of 0.80 and 0.50, respectively). There is also scope for efficiency gain in primary care where in Europe the mean is 0.817 compared to the USA mean of 0.648 where there is more potential for improvement (standard deviation 0.249 and minimum of 0.427). However, this may simply reflect the diverse nature of primary care delivery in the USA and Europe. A more valid

Table 2
Summary statistics for general health efficiency scores.

| | No. | Mean | Median | Standard deviation | Minimum |
|---|---|---|---|---|---|
| Care programme | 2 | 0.623 | 0.623 | 0.032 | 0.60 |
| Health districts EU | 4 | 0.839 | 0.838 | 0.04 | 0.80 |
| Health districts USA | 9 | 0.742 | 0.80 | 0.144 | 0.50 |
| Nursing homes EU | 4 | 0.765 | 0.75 | 0.079 | 0.70 |
| Nursing homes USA | 18 | 0.746 | 0.806 | 0.175 | 0.38 |
| Primary care EU | 5 | 0.817 | 0.79 | 0.117 | 0.675 |
| Primary care USA | 4 | 0.648 | 0.635 | 0.249 | 0.427 |

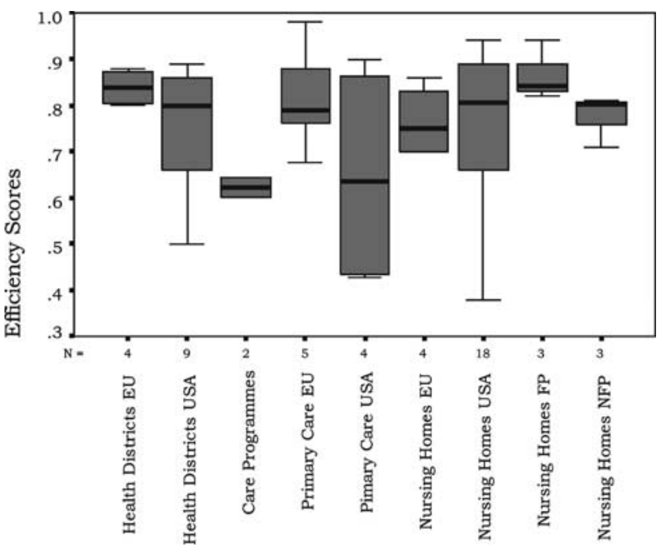


Figure 5. Boxplot of distribution of efficiency scores by general health.

comparison is of nursing homes. The USA and Europe seem similar in terms of variation (means 0.746 and 0.765, medians 0.806 and 0.75, respectively), but both demonstrate potential for improvement, with the minimum scores of 0.38 and 0.70 and standard deviations of 0.175 and 0.079. Figure 5 demonstrates that for profit nursing homes appear more efficient (mean 0.867, median 0.84, standard deviation 0.064, minimum 0.82) than not for profit homes (mean 0.774, median 0.803, standard deviation 0.058, minimum 0.71).

*4.3. Malmquist productivity applications*

A summary of Malmquist based productivity studies is provided in the appendix. The Malmquist index is the mean of two indices, measuring the change in efficiency from one period to the next, allowing a breakdown of efficiency changes over time (see [71] for more details on non-parametric methods). As with the SFA section which follows, summaries of results are provided individually, as direct meta type analysis is not appropriate due to small numbers, or methodological incompatibility.

Färe et al. [41] examine changes in productivity between 19 countries between 1974 and 1989. Two models are used, one using intermediate outputs (days and discharges), which shows little evidence of productivity growth, and one using health outcomes (life expectancy and infant mortality), which demonstrates some evidence of growth.

Giuffrida [56] uses Malmquist indices to estimate productivity changes for 90 UK FHSAs for the years 1990/1991 to 1994/1995. For the full model productivity change is 1.01, pure technical efficiency is 0.996, pure technical efficiency change is 1.003, technical change is 1.005, and scale change is 1.003. It is concluded there is a small productivity improvement due to technical and scale efficiency, not technology change. There is seen to be limited scope for productivity gain.

Burgess and Wilson [13] look at USA hospitals finding Federal hospitals to demonstrate a significant amount of technical regress while there are small changes in non-Federal units. Färe et al. [43] examine 17 Swedish public hospitals and find considerable variation in productivity across hospitals and time. Linna [83] uses Malmquist analysis alongside SFA on 42 hospitals in Finland (1988 to 1994) finding an annual average increase in productivity of 3 to 5%, due equally to cost efficiency and technical change.

Maniadakis et al. [91] use data from 75 Scottish acute hospitals from 1991/1992 to 1995/1996 and apply Malmquist indices to estimate productivity and quality changes, finding there was a productivity slowdown in the first year following NHS reforms, but productivity progress in subsequent years. Changes are dominated by technological change, with hospital efficiency changing little, and quality may have suffered at the expense of productivity. Maniadakis and Thanassoulis [92] look at the same 75 Scottish acute hospitals from 1991/1992 to 1995/1966 reporting productivity progress (0.928), and cost efficiency progress (0.912), made up of allocative efficiency progress, and technological regress, with overall gains being small. McCallion et al. [93] look at hospitals in Northern Ireland from 1986 to 1992 finding larger hospitals increase productivity by 2.31%, and smaller ones by 22.53%. Technological increase is outweighed by a decline in efficiency change for small hospitals. Scale efficiency falls. Sommersguter-Reichmann [148] looking at 22 Austrian hospitals from 1994 to 1998 (17 public non profit, 5 private non profit) finds an increase in productivity in the last two years (1.093 to 1.038) due to technology improvement, based on financing a new system. Zere et al. [167] look at productivity for 86 hospitals in South Africa in 1992/1993 finding it declined by 12%, due to technology regress, efficiency change was marginal.

Dismuke and Sena [37] use Malmquist indices (alongside SFA) on Portuguese district and central hospital diagnostic technology from 1992 to 1994 for cerebrovascular disorders and heart failure, finding productivity is related to the DRG system. The same authors [36] use Malmquist-Luenberger indices on this data finding technology has a positive impact on productivity when quality measures are included. Tambour [150] looks at 20 ophthalmology departments in Sweden from 1988 to 1993 concluding that overall the productivity change for the sector is positive and significant in all but one period. Average change in efficiency is positive but not significant, technology change is generally positive, with overall productivity change being driven by change in technology, for example medical technology, or administrative systems. Roos [131] looks at 865 ophthalmology patients in Sweden looking at daily living activity before and after surgery finding an increase of 74% for those not suffering from another eye disease.

Löthgren and Tambour [87] estimate productivity using a standard model and a network model for Swedish pharmacies. The standard model finds productivity progress at 0.914, efficiency change at 0.979, technology change at 0.934, and technical efficiency at 0.872. Färe et al. [42,44] examine the productivity of Swedish pharmacies, the second with the novel inclusion of quality variables. Färe et al. [45] introduce consumer satisfaction measures into the analysis of 74 Swedish pharmacies, finding they can impact on results, where price signals are unavailable.

*4.4. SFA and other parametric applications*

A summary of studies using SFA and other parametric techniques is provided in the appendix.

Bryce et al. [10] uses SFA and fixed effects regression (as well as DEA) on 585 HMOs in the USA on an unbalanced panel from 1985 to 1994, concluding that different models lead to different results, and model selection can influence efficiency ranking. Defelice and Bradford [35] use SFA on 1984 and 1985 data on USA primary care physicians from solo practices to large HMOs. They conclude that differences in efficiency are not due to solo or group practice, levels of inefficiency are similar.

Giuffrida and Gravelle [57] use SFA, corrected ordinary least squares (COLS), and canonical regression (as well as

DEA) on 90 UK FHSAs. COLS scores range from 0.868 to 0.915, stochastic frontier scores range from 0.872 to 0.982 and canonical scores range from 0.80 to 0.81 (DEA scores range from 0.904 to 0.994). They conclude scores are correlated within the different methods, but not as highly between the methods.

Folland and Hofler [50] use SFA on a sample of 791 US hospitals in 1985 concluding that group mean inefficiencies are robust to variations in methods, and that individual hospital ranks are not highly correlated, but not-for-profit hospitals were more efficient than for profit. Li and Rosenman [82] use SFA on a panel of 90 USA (Washington state) hospitals between 1988 and 1993 finding average inefficiency to be 33%, hospitals with a higher case mix index, or more beds, were less efficient, for profit hospitals were more efficient. Mobley [96] uses SFA (results used as part of tobit regression) on 1984 and 1990 data on 455 and 404 Californian (USA) hospitals serving Medicaid patients, commenting that distributional effects led to efficiency gains post reform (the 1982 California Medicaid Reform Act to increase competition and award contracts to more efficient providers) and that contracts were awarded to more efficient providers, but costs rose for public hospitals, as uncompensated care burdens rose. Zuckerman et al. [168] apply SFA to 1600 USA hospitals in 1986/1987 (28% public) finding for pooled data inefficiency of 0.132 for teaching, 0.135 for non-teaching, 0.141 for public, 0.144 for proprietary, and 0.129 for private not for profit. Potential inefficiency costs $31 billion.

Rosko [134] uses SFA then tobit on 1994 data on 3262 USA hospitals, using three error distributions. There is mean inefficiency ranging from 0.202 to 0.255 depending on the distribution of the error. It is concluded that inefficiency scores are robust with respect to assumptions regarding the distribution of the error term, and that for profit status is associated with increased inefficiency, with for profits being less efficient than not for profits. Rosko [135] using SFA and fixed effects models on an unbalanced panel of 1631 hospitals over the period 1990 to 1996 found a mean inefficiency score of 0.153 (range 0.125 to 0.175). Efficiency increased over the period, with an inverse relationship between HMO penetration and inefficiency, the same was the case with industry concentration. Inefficiency was positively related to for profit status. Rosko and Chilingerian [137] run SFA on 195 Pennsylvania (USA) acute care hospitals in 1989, finding inefficiency ranges from 3.5 to 17%. X efficiency increases with regulatory and payment pressure, but declines with competitive pressure. Inefficiency is also associated with industrial concentration. Rosko [136] uses SFA on 1966 USA short term community hospitals, finding inefficiency of 12.96%. Increases in managed care penetration, dependence on Medicare and Medicaid, being in multi-hospital system, location in a competitive area, and the pool of uncompensated care being greater are associated with less inefficiency. Not-for-profit ownership increased inefficiency.

Chirikos [30,31] uses SFA on 186 Florida hospitals (USA) from 1982 to 1993, and estimated efficiency rose 1.6% per year. Inefficiency levels are seen as high with costs exceeding the frontier by 15%. SFA is seen as yielding plausible estimates of efficiency, but caution needs to be exercised, not only in modelling inputs and outputs, but specifying the structure of the cost model (for example, the distribution of the efficiency term). SFA is most useful in tandem with other techniques. Chirikos and Sear [33] using the same sample of hospitals found SFA results ranging from 0.75 to 0.85, concluding that DEA and SFA yield convergent results overall, but divergent results for individual hospitals. Vitaliano and Toren [156] apply SFA to 219 general care hospitals in New York (USA) in 1991 (85% not for profit, 10% government, 5% for profit). Average inefficiency is 18%. Hospitals with larger Medicare populations are more efficient, hospitals with more than 300 beds are more efficient, and reimbursement restrictions may help. Unionisation seems to contribute to inefficiency.

Jacobs [77] uses SFA, OLS (and DEA) on a sample of up to 232 UK NHS hospital trusts. The OLS mean ranges from 0.541 to 0.611, the SFA mean from 0.645 to 0.936, and the DEA mean from 0.831 to 0.876. The author concludes differences across methods may be due to noise and data deficiencies, with actual scope for inefficiency savings being modest. Linna [83] uses SFA (and Malmquist indices) for 43 hospitals in Finland from 1988 to 1994. SFA scores were between 0.88 and 0.90, and were moderately correlated with Malmquist scores. Linna and Häkkinen [84] use SFA (and DEA) on a sample of 48 acute hospitals in Finland in 1994 finding SFA scores between 0.86 and 0.93, and DEA scores between 0.84 and 0.89, concluding that the choice of modelling affects results. A weight restricted DEA model was correlated with a parametric model. There was broad agreement across the models, which should be used together.

Wagstaff [157] uses SFA on 49 Spanish public hospitals from 1977 to 1981 estimating inefficiency on a cross section (1979) at 28%, stating it is likely that only 10% was actually inefficiency, and this may not be significant. Panel data suggests a third of variation may be inefficiency and inefficiency may be as high as 42% of average costs. It is concluded that more than one estimation technique should be applied. Wagstaff and López [158] using 1988 to 1991 data on 43 Spanish public and private hospitals find average inefficiency of 58%, with public hospitals having a higher level of inefficiency (75%) than private hospitals (56%). One explanation may be the fact that private hospitals can vary hours of work, and negotiate pay. There was mild evidence of economies of scope. Paul [123] estimates efficiency for public hospitals in Australia finding efficiency of 0.74, with higher results for larger facilities and acute facilities in urban areas. (As part of this study 15 nursing homes are also examined having efficiency of 0.684.)

Hofler and Rungeling [68] use SFA on 1985 data on 1079 nursing homes in the USA. They estimate allocative and technical inefficiency using homothetic production and cost frontiers. They find for profit homes to have lower costs, and in allocative inefficiency terms staff and capital are overcapitalised. Costs are 5.8% higher than efficient. Technical inefficiency is estimated at 2%, giving overall inefficiency of around 8%. They conclude that potential gains are small.

Dismuke and Sena [37] use SFA (and Malmquist indices) on Portuguese district and central hospital diagnostic technology from 1992 to 1994, for cerebrovascular disorders and heart failure, with alive and dead discharges as outputs. Technical efficiency increased for computerised axial tomography scanners, echocardiogram had declining technical efficiency in districts and increasing in central hospitals, and electrocardiogram was stable for central hospitals and declining for districts. It is noted that technical efficiency increases have not been accompanied by increases in quality. Bosmans and Fecher [9] use SFA and OLS on 1990 to 1991 data on Belgian inpatients affiliated to 2 main insurance organisations in 85 to 185 hospitals (depending on specialty). Efficiency by specialty was 0.778 for Ear, Nose and Throat, 0.615 for Respiratory, 0.536 for Circulatory, 0.621 for Digestive, 0.713 for Musculoskeletal, and 0.711 for Gynaecology. It is noted that public care is more efficient than private, and non-teaching more efficient than teaching, and regression shows size, area, ownership, and management are all related to efficiency.

Grytten and Rongen [64] use SFA (compared to a deterministic frontier) for Norwegian dental services from 1986–1992, with inefficiency ranging from 0.05 to 0.11 in the SFA model and 0.14 to 0.49 in the deterministic model.

Giuffrida et al. [58] use random and fixed effects models on 1989/1990 to 1994/1995 UK FHSA (primary care) data, both models suggesting economies of scale, but little evidence of economies of scope. Although inefficiency is treated cautiously in the paper, they estimate one high cost authority to be significantly above the mean. Gaynor and Pauly [53] estimate the efficiency of 6353 primary care physicians in the USA, using traditional and behavioural functions and estimating technical efficiency at 0.66, with coefficients similar across specifications. Incentives may affect quantity produced, but not technical efficiency. Relating compensation to productivity does not increase production.

Grosskopf et al. [59] use maximum likelihood estimation to estimate a frontier to assess nurse productivity in 91 community health facilities (not for profit, non-teaching hospitals) in California (USA) in 1983. Their results suggest over employment of registered nurses relative to licensed practical nurses, and also evidence of monopsony power. Okunade [107] uses seemingly unrelated regression to demonstrate technical change effects in USA pharmacies, for the period 1981–1990.

## 5. Summary and conclusions

Since the last review in this area [71], the number of studies which seek to measure health service efficiency and productivity has more than doubled. Research in this area should still be reviewed cautiously and the results of studies interpreted and used carefully. The inability to measure the *real* output of the health care industry, changes in health status and the low quality of available data still leads to problems. In addition, as Newhouse [101] notes, health industry studies may suffer from omitted variable bias. The techniques are still criticised, but are continuingly being refined. However, estimated results may still be sensitive to changes in the basic assumptions or specifications of the models used and the characteristics of the environment in which the units operate. Thus, the results may be valid only for the units under investigation, and not necessarily be generalizable.

Different modelling approaches have advantages and disadvantages and the choice of the most appropriate estimation method should depend on the type of organisations under investigation, the perspective taken and the quality of the available data. These issues are highlighted in the literature debating the WHO's use of cross country efficiency comparisons [76,162]. This is one area where efficiency measurement may have a direct policy impact, so a cautious approach is necessary. As well as refining methods, the means of making efficiency results useful in a practical setting needs careful attention [147]. Although steps are being taken in this direction there is still some way to go [75].

The use of models with restrictions placed upon the weights given to variables, in order to reflect underlying production models, or policy values, is also an interesting area, requiring further research to justify the use of such restrictions.

There is still room for the use of more advanced methods in efficiency measurement in the health and health care sector. Little sensitivity analysis or statistical testing has been undertaken, even though these advanced methods are under development [108,146]. The quality of data available for use may also be a problem to be addressed. Issues of model specification are important, and the use of the Bayesian approach to SFA may be useful in future work. Given the limitations of frontier techniques at present it may be that they are best employed in tandem, when possible, and if different methods suggest similar directions for results then the validity of such findings is enhanced.

Summary results here implying that rather than private provision of health care is more efficient should be viewed in the context that the studies in our sample may not be genuinely comparable. Nevertheless it is an important finding that public hospitals in general continue to demonstrate less variability than private hospitals, and it may also be important that European hospitals continue to show less variability than USA hospitals. Notwithstanding the caveats mentioned earlier regarding making comparisons across studies, and that perhaps work needs to be undertaken to think of ways of making efficiency studies comparable, these findings may have important policy implications for the organisational structure of health care delivery.

**Acknowledgement**

I am very grateful to Peter Smith for insightful comments on drafts of this paper.

## Appendix

Table 3
Summary of studies on non-parametric hospital efficiency.

| Hospital type | Country | Number | Author | Efficiency scores |
|---|---|---|---|---|
| *Federal/Defence/Veterans' Administration* | | | | |
| | USA | 284 | Bannick and Ozcan (1995) [3] | Defence mean: 0.87, VA mean: 0.78 |
| | USA | 89 | Burgess and Wilson (1993) [12] | Range: 0.93-0.97 |
| | USA | 2246 | Burgess and Wilson (1996) [14] | Efficiency scores, mean: VA 0.87, Non-Fed 0.82, FP 0.83, NFP 0.83 |
| | USA | 32 VA, 1413 non-VA | Burgess and Wilson (1998) [15] | Inefficiency: overall 13.6%; LG 11.2%; non profit 15.1%; profit 12%; VA 8.2% |
| | USA | 93 | Hao and Pegels (1994) [65] | Range: teaching 0.54–1, non-teaching 0.55–1 |
| | USA | 3780 | Ozcan and Bannick (1994) [111] | Means: army 0.94, air force 0.96, navy 0.91, Dept. of Defence 0.95 |
| *For profit/not-for-profit* | | | | |
| | USA | 160 | Bitran and Valor-Sabatier (1987) [5] | NFP mean: 0.60 |
| | USA | 360 | Ferrier and Valdmanis (1996) [46] | CE: 0.676, TE: 0.787, AE: 0.861, SE: 0.893 |
| | USA | 123 | Byrnes and Valdmanis (1994) [17] | AE: 0.73, TE: 0.84, SE: 0.94 |
| | USA | 82 | Grosskopf and Valdmanis (1987) [61] | Pooled, means: public 0.94, NFP 0.91 Separate, means: public 0.96, NFP 0.94 |
| | USA | 108 | Grosskopf and Valdmanis (1993) [62] | Range: case-mix adjusted 0.86–0.88, case-mix un-adjusted 0.85–0.86 |
| | USA | 60 | Morey et al. (1990) [99] | Public mean: 0.95, NFP mean: 0.65 |
| | USA | 85 | Ozcan et al. (1996) [116] | Overall mean: 0.65, FP: 0.61, NFP: 0.72 |
| | USA | 41 | Valdmanis (1990) [154] | Public: 0.98, NFP: 0.88 |
| | USA | 41 | Valdmanis (1992) [155] | Means, range: public 0.97–1, NFP 0.83-0.94; Scale efficiency: public 0.79–1, NFP 0.92–0.97 |
| *Acute* | | | | |
| | USA | 52 | Borden (1988) [8] | Mean scores range: 0.95–0.99 |
| | USA | 186 | Chirikos and Sear (2000) [33] | Mean: 0.801 |
| | USA | 189 | Chirikos and Sear (1994) [32] | Mean: 0.65 |
| | USA | 105 | Dittman et al. (1991) [38] | Range: 0.49–1 |
| | USA | 40 | Ozcan (1992) [109] | Mean range: 0.51-0.92 |
| | UK | 75 | Hollingsworth and Parkin (1995) [73] | Range: 0.63–1 |
| | UK | 23 | Kerr et al. (1999) [79] | Means: larger 0.94; smaller 0.82–0.91 |
| | Norway | 46 | Magnussen (1996) [89] | Mean range: 0.93–0.94 |
| | Spain | 94 | Dalmau-Matarrodona and Puig-Junoy (1998) [34] | Mean: 0.989 |
| | Finland | 48 | Linna and Häkkinen (1998) [84] | Efficiency scores between 0.84 and 0.89. Broad agreement with models |
| | UK | 75 | Parkin and Hollingsworth (1997) [122] | Mean range: 0.85–0.91 |
| *General* | | | | |
| | USA | 1535 | Ozcan and Lynch (1992) [113] | Mean: 0.88 |
| | USA | 80 | Chern and Wan (2000) [23] | Range: 0.76–0.8 |
| | USA/ Norway | 190/50 | Mobley and Magnussen (1998) [97] | TE: Norway 0.937, USA FP urban 0.884, USA NFP urban 0.936, USA NFP non-urban 0.917 |
| | Taiwan | 6 | Chang (1998) [20] | Range: 0.88–0.987 |
| | Greece | 98 | Athanassopoulos (1999) [2] | Production efficiency: means 0.67–0.86 Cost efficiency means: 0.62–0.72 |
| | Greece | 91 | Giokas (2001) [55] | Mean: 0.751 |
| | UK | 232 | Jacobs (2001) [77] | Mean range: 0.645–0.936 |
| | UK | 27 | Tsai and Molinero (2002) [152] | Mean: 0.938 |

Table 3
Continued.

| Hospital type | Country | Number | Author | Efficiency scores |
|---|---|---|---|---|
| | UK | 23 | McCallion et al. (1999) [95] | Means: CE: large 0.672 small 0.601; AE: large 0.715, small 0.713; TE: large 0.939, small 0.842; SE: large 0.949; small 0.913 |
| | UK | 23 | McKillop et al. (1999) [94] | Range: large 0.933–0.951, small 0.842–0.909 |
| | Turkey | – | Sahin and Ozcan (2000) [139] | Mean: 0.879 |
| | Spain | 75 | Lopez-Valcarcel and Barber Perez (1996) [86] | Overall range: 0.92–0.95 Overall scale: 0.96–0.98 |
| *Non-specific* | | | | |
| | USA | 360 | Ferrier and Valdmanis (1996) [46] | CE: 0.68, TE: 0.79, AE: 0.87, SE: 0.89 |
| | USA | 123 | Byrnes and Valdmanis (1989) [16] | NFP: TE: 0.87, AE: 0.83, OE: 0.72 |
| | USA | 27 | Morey (2000) [100] | Mean: 0.906 |
| | USA | 27 | O'Neill (1998) [106] | Non-teaching SPE: 1.25 Teaching SPE: 1.15 |
| | USA | 7 | Sherman (1984) [145] | Range: 0.88–1 |
| | USA | 55 | Maindiratta (1990) [90] | Efficiency range: 0.51–1 Scale efficiency range: 0.51–1 |
| | USA | 105 | Morey and Dittman (1996) [98] | Mean: 0.95 |
| | USA | 16 | Nunamaker (1983) [102] | Range: 0.91–1 |
| | USA | 170 | White and Ozcan (1996) [161] | Church: 0.81, secular: 0.76 |
| | USA | 20 | Harris (2000) [67] | Range: 0.81–0.85 |
| | USA | 236 teaching, 556 non-teaching | Grosskopf et al. (2001) [60] | Non-teaching: 0.71, teaching 0.65 |
| | USA | 22 | Young (1992) [165] | Range: 0.40–1 |
| | Canada | 168 | Gruca and Nath (2001) [63] | Means: secular 0.75, religious 0.67, govt 0.70, rural 0.77; urban 0.72, small 0.77, large 0.69 |
| | Belgium | 34 | Beguin (2001) [4] | Range: 0.39–0.54 (FDH) |
| | Spain | 132 and 149 | Prior and Sola (2000) [126] | Means: diversified 0.89 and 0.93, specialised: 0.87 and 0.88 |
| | Spain | 50 | Prior (1996) [125] | Inefficiency: 3% |
| | South Africa | 86 | Zere et al. (2001) [167] | Mean: 0.74 |
| | Jordan | 15 | Al-Shammari (1999) [1]; Sarkis and Talluri (2002) [141] | Means 0.867–0.977 [1]; 0.688–0.884 [141] |
| *Within hospital* | | | | |
| | USA | 36 physicians | Chilingerian (1989) [24] | Mean: 0.91 |
| | USA | 36 physicians | Chilingerian (1994) [25] | Surgeons: 0.72–1, interns: 0.63–1 |
| | USA | 36 physicians | Chilingerian (1995) [26] | Pure TE: 0.90–0.95, TE/SE: 0.80–0.89 |
| | USA | 326 physicians | Chilingerian and Sherman (1997) [29] | Range: 0.21–1 |
| | USA | 15 physicians | Chilingerian and Sherman (1990) [27] | Range: 0.54–1 |
| | USA | 326 physicians | Chilingerian and Sherman (1996) [28] | Range: 0.4–1 |
| | USA | 160 physicians | Ozcan (1998) [117] | Mean: 0.796 |
| | USA | 9 obstetric depts | Finkler and Wirtschafter (1998) [47] | Range: 0.64–1 |
| | Spain | 16 ICU | Puig-Junoy (1998) [127] | TE: 0.837 |
| | – | 127 cataract patients | Roos and Lundström (1998) [132] | Index scores: before surgery 0.98, after surgery 1.57 |
| | UK | 31 General surgery units | Harper (2001) [66] | Range: 0.876–0.938 |
| | Austria | 31 wards | Hofmarcher et al. (2002) [69] | Using discharges and IPD: average 0.95–0.965; using points system: average 0.65–0.73 |
| | Taiwan | 57 nursing units | Wan et al. (2002) [159] | Nursing hours model: 0.96; costs model: 0.97 |

[a] VA – veterans administration; LG – local government; FP – for profit; NFP – not-for-profit; Non-Fed – non-federal; CE – cost efficiency; TE – technical efficiency; AE – allocative efficiency; SE – scale efficiency; SPE – super efficiency.

Table 4
Summary of studies on non-parametric general health organisation efficiency.

| Organisation type | Country | Number | Author | Efficiency scores |
|---|---|---|---|---|
| *Countries* | OECD | – | Puig-Junoy (1998) [128] | TE: increases 0.59–0.72 |
| *Health districts* | USA | 319 | Ozcan (1995) [110] | Range: 0.72–1 |
| | USA | 314 | Wang et al. (1999) [160] | Range: 0.74–0.89 |
| | USA | 298 | Ozcan et al. (1996) [119] | Range: 0.79–0.90 |
| | USA | 25 | Ozcan and Cotter (1994) [112] | Govt 0.8, joint: 0.5, private NFP: 0.57 |
| | USA | 28 | Rosenman et al. (1997) [133] | Mean FP: 0.68, mean NFP: 0.66 |
| | Sweden | 26 | Gerdtham et al. (1999) [54] | Inefficiency: 13% |
| | UK | 15 | Hollingsworth and Parkin (1995) [73] | Range: 0.76–1 |
| | UK | 15 | Parkin and Hollingsworth (1997) [122] | Range: 0.72–1 |
| | UK | 189 | Thanassoulis et al. (1996) [151] | Range: 0.60–1 |
| | UK | 85 | Salinas-Jiménez and Smith (1996) [140] | Range: 0.73–1 |
| *Care programmes* | USA | 54 | Schinnar et al. (1990) [142] | Range: 0.62–0.67 |
| | USA | 40 | Yeh et al. (1997) [164] | Overall mean: 0.60 |
| *Primary care* | USA | 159 | Sexton et al. (1989) [143] | Range: 0.66–1 |
| | USA | 39 | Tyler et al. (1995) [153] | Mean: 0.44 |
| | USA | 36 | Rollins et al. (2001 [130] | 0.801–0.994 |
| | USA | 249 | Draper et al. (2000) [39] | Mean: 0.427 |
| | Finland | 202 | Luoma et al. (1996) [88] | Mean: 0.88 |
| | Spain | 10 | Pina and Torres (1992) [124] | Range: 0.58–1 |
| | UK | 90 | Giuffrida and Gravelle (2001) [57] | TE: 0.98 |
| | UK | 52 | Szczepura et al. (1993) [149] | Range: 0.35–1 |
| | Greece | 133 | Zavras et al. (2002) [166] | Range 0.66–0.808 |
| *Nursing homes* | USA | 140 | Chattopadhyay and Heffley (1994) [21] | Mean: 0.90 |
| | USA | 140 | Chattopadhyay and Ray (1996) [22] | Mean NFP: 0.81, mean FP: 0.94 |
| | USA | 372 | Fried et al. (1998) [52] | Skilled home: 0.38; intermediate 0.42; diversified 0.46. |
| | USA | 22 | Kleinsorge and Karney (1992) [80] | Range: 0.71–1 |
| | USA | 184 | Nyman and Bricker (1989) [103] | Mean: 0.89 |
| | USA | 296 | Nyman et al. (1990) [104] | Mean: 0.93 |
| | USA | 52 | Sexton et al. (1989) [144] | Means range: 0.76–0.78 |
| | USA | 324 | Ozcan et al. (1998) [118] | Means: FP 0.84, NFP 0.803 |
| | USA | 104 | Fizel and Nunnikhoven (1993) [48] | Means (all FP): overall 0.66, chain 0.71, independent 0.62 |
| | USA | 461 | Rosko et al. (1995) [138] | Means: FP 0.82, NFP 0.71 |
| | USA | 990 | Fried et al. (2002) [51] | With SFA as 3 stage method, mean 0.905. |
| | Netherlands | 232 | Kooreman (1994) [81] | CRS mean: 0.80, COD mean: 0.94 |
| | Netherlands | – | Blank et al. (1996) [7] | Mean: 0.70 |
| | Finland | 64 | Björkgren et al. (2001) [6] | Means: CE 0.74–0.77, TE 0.85–0.87, AE 0.84–0.89, SE 0.92–0.93 |
| | Norway | 471 | Erlandsen and Førsund (2002) [40] | Input saving 0.76, outupt increase 0.78, technical productivity 0.70, scale 0.90–0.93 |
| *Dialysis* | USA | 791 facilities | Ozgen and Ozcan (2002) [120] | TE of inefficient facilities 0.79 |
| *Mechanical ventilation* | USA | 62 hospitals, 7961 patients | O'Neal et al. (2002) [105] | IPD: 0.527, discharges: 0.491 |
| *Sinusitis treatment* | USA | 178 physicians | Pai et al. (2000) [121] | Inefficient physicians: 0.71 (metropolitan 0.75, rural 0.66) |
| | USA | 176 physicians | Ozcan et al. (2002) [115] | Inefficient generalists: 0.71; inefficient specialists: 0.73 |
| *Organ procurement* | USA | 64 | Ozcan et al. (1999) [114] | Overall mean: 0.843 |

Table 4
Continued.

| Organisation type | Country | Number | Author | Efficiency scores |
|---|---|---|---|---|
| *Stroke treatment* | USA | 214 | Ozcan (1998) [118] | Means: more experience 0.81, less experience 0.59–0.61 |
| *Dental services* | UK | 100 | Buck (2000) [11] | CRS mean: 0.635, VRS mean: 0.673 |
| | Finland | 228 | Linna et al. (2002) [85] | Primal efficiency: mean 0.72–0.81 Cost efficiency: mean 0.62–0.79 |
| *Neonatal care* | UK | 49 | Hollingsworth and Parkin (2001) [74] | Mean: 0.723 |
| *Screening* | UK | 64 | Johnston and Gerard (2001) [78] | Mean: 0.821 |
| *Immunisation* | Australia | 23 local authorities | Hollingsworth et al. (2002) [72] | Cost efficiency: 0.689 (rural), 0.816 (urban); productive efficiency: 0.706 (rural), 0.804 (urban) |
| *Pharmacies* | USA | 68 | Capettini et al. (1985) [19] | Range: 0.44–0.98 |

[a] FP – for profit; NFP – not-for-profit; CRS – constant returns to scale; COD – constant or decreasing returns.

Table 5
Summary of studies on productivity (Malmquist) analysis.

| Organisation type | Country | No of units | Author | Results |
|---|---|---|---|---|
| *General health* | International | 19 | Färe et al. (1997) [41] | Some evidence of productivity growth when using outcomes rather than outputs |
| *Primary care* | USA | 585 | Bryce et al. (2000) [10] | Different models lead to different results |
| | UK | 90 | Giuffrida (1999) [56] | There is a small productivity improvement, but little scope for more |
| *Opthalmology* | Sweden | 20 | Tambour (1997) [150] | Positive changes in productivity |
| *Hospital* | USA | 1545 | Burgess and Wilson (1995) [13] | Technical regress in Federal Units |
| | USA | 186 | Chirikos and Sear (2000) [33] | Convergent results to DEA for industry, divergent for individual hospitals |
| | UK | 232 | Jacobs (2001) [77] | Differences across methods (DEA and OLS) may be due to noise/data deficiencies. Inefficiency savings may be modest |
| | UK | 75 | Maniadakis et al. (1999) [91] | Productivity progress is dominated by technological change |
| | UK | 75 | Maniadakis and Thanassoulis (2000) [92] | There is cost efficiency and allocative efficiency progress |
| | UK | – | McCallion et al. (2000) [93] | Smaller hospitals increase productivity more than large hospitals |
| | Austria | 22 | Sommersguter-Reichmann (2000) [148] | Productivity increases due to technology improvement |
| | Finland | 43 | Linna (1998) [83] | Scores are moderately correlated with Malmquist scores |
| | Sweden | 17 | Färe et al. (1994) [43] | Variation in productivity |
| | South Africa | 86 | Zere et al. (2001) [167] | Productivity declined 12%, driven by technology regress |
| *Diagnostic technology* | Portugal | 62, 136 disharges | Dismuke and Sena [36] | Prospective payment systems have positive impact on productivity, where a measure of quality is included |
| *Ophthalmology* | Sweden | 20 | Tambour (1997) [18] | Overall productivity change is driven by changes in technology |
| | Sweden | 34 departments | Roos (2002) [131] | |
| *Dental pharmacy* | Norway | 14 | Grytten and Rongen (2000) [64] | Inefficiency ranges from 0.05 to 0.11 |
| | Sweden | – | Löthgren and Tambour (1999) [87] | Productivity progress |
| | Sweden | 74 | Färe et al. (2002) [45] | Improvement overall, consumer satisfaction can affect results |
| | Sweden | 42 | Färe et al. (1992) [42] | Over nine time periods, there were seven periods of improvement and two of regress |
| | Sweden | 257 | Färe et al. (1995) [44] | Quality matters when measuring productivity change |

Table 6
Summary of studies using SFA/parametric techniques.

| Organisation type | Country | No of units | Author | Results |
|---|---|---|---|---|
| *Hospitals* | USA | 90 | Li and Rosenman (2001) [82] | Average inefficiency 33% |
| | USA | 186 | Chirikos (1998/1999, 1998) [30,31] | Inefficiency 15% |
| | USA | 91 | Grosskopf et al. (1990) [59] | Evidence of monopsony power |
| | USA | 3262 | Rosko (1999) [134] | Mean inefficiency 0.202–0.255 |
| | USA | 1631 | Rosko (2001) [135] | Mean inefficiency: 0.153 |
| | USA | 1966 | Rosko (2001) [136] | Inefficiency 12.96% |
| | USA | 195 | Rosko and Chilingerian (1999) [137] | Inefficiency range: 3.5 to 17% |
| | USA | 455 and 404 | Mobley (1998) [96] | Distributional effects led to post reform efficiency gains |
| | USA | 219 | Vitaliano and Toren (1996) [156] | Average inefficiency 18% |
| | USA | 1600 | Zuckerman et al. (1994) [168] | Inefficiency 0.132 for teaching, 0.135 for non-teaching, 0.141 for public, 0.144 for proprietary, 0.129 for private NFP |
| | USA | 791 | Folland and Hofler (2001) [50] | Not for profit more efficient than for profit |
| | Australia | 208 | Paul (2002) [123] | Higher results for larger facilities and acute facilities in urban areas. Efficiency higher with greater capital base, and lower with higher levels of personal care |
| | Spain | 49 | Wagstaff (1989) [157] | Inefficiency 28% (only 10% actual inefficiency) |
| | Spain | 43 | Wagstaff and López (1996) [158] | Inefficiency 58%, public more inefficient than private |
| | Finland | 48 | Linna and Häkkinen (1998) [84] | Efficiency scores between 0.86 and 0.93. Broad agreement with DEA models |
| | Finland | 43 | Linna (1998) [83] | Scores are moderately correlated with Malmquist scores |
| *Nursing homes* | USA | 1079 | Hofler and Rungeling (1994) [68] | Allocative inefficieny 5.8%; technical inefficiency 2% |
| *Primary care* | USA | – | Defelice and Bradford (1997) [35] | Levels of inefficiency are similar between solo and group practices |
| | USA | 6353 | Gaynor and Pauly (1990) [53] | TE: 0.66 |
| | UK | 90 | Giuffrida and Gravelle (2001) [57] | Stochastic scores are correlated within methods, but not highly between methods (COLS and DEA) |
| *Diagnostic technology* | Portugal | – | Dismuke and Sena (1999) [37] | SFA and Malmquist, with SFA results finding differing efficiency levels for differing technologies |
| *Specialties* | Belgium | – | Bosmans and Fecher (1995) [9] | Public care is more efficient, non-teaching hospitals more efficient than teaching |
| *Pharmacy* | USA | – | Okunade (2001) [107] | Biased and pure technical change effects |

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