Choice and Competition Between Adult Congenital Heart Disease Centers

Evidence of Considerable Geographical Disparities and Association With Clinical or Academic Results

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Background—Although concentrating adult congenital heart disease services at high-volume centers has been widely advocated, the potential beneficial effects of competition and patient choice have received relatively little attention. We aimed to assess the degree of patient choice and competition between adult congenital heart disease units and to investigate whether competition indices correlate with clinical quality or research output.

Methods and Results—Competition between the 10 major adult congenital heart disease units in England was evaluated based on the Herfindahl–Hirschman Index, representing the sum of squared market shares of individual units. In addition, to account for geography and feasible access, we calculated spatial indices of competition based on travel time by road. These indices were correlated with 30-day mortality postpulmonary valve replacement in adult patients (as obtained from the National Central Cardiac Audit Database) and the aggregate research impact factors of individual centers. On a national level, a high level of competition without obvious dominant players was found (Herfindahl–Hirschman Index between 0.107 and 0.013). When accounting for geography, however, important disparities in patient choice and competition faced by individual centers emerged. The degree of local competition was correlated significantly with clinical outcomes and research output. In contrast, no association between center volume and outcome could be established.

Conclusions—Beyond the usual focus on concentrating services at high-volume centers, the potentially beneficial effects of competition should not be ignored. Therefore, policymakers should consider fostering a competitive environment for adult congenital heart disease centers or at least avoiding creating government-granted monopolies in the field.

Key Words: economic competition • heart defects, congenital • hospitals, high-volume • pulmonary valve • research • survival

In the current era, the vast majority of patients born with congenital heart disease (CHD) in developed countries survive to adulthood, most of them living relatively normal lives with good long-term survival prospects. However, challenges in providing optimal care for a growing number of adults with CHD (ACHD) remain. These include the provision and implementation of guidelines, the measurement of quality of care, and—particularly relevant to health policy—the question of whether ACHD services should be consolidated. Large supraregional ACHD centers may profit from larger patient and procedure numbers, improved provider expertise, as well as the effects of economies of scale and potentially more investment in technology and human capital. Although appealing and conceivably beneficial, it should be recognized that concentrating services is not costless. If services are to be planned and regulated, there is potential for excessive regulation and the development of unhealthy relationships between regulators and the regulated. If managed inappropriately, bureaucratic control may distort incentives and lead to a compromise of high-quality care in some areas. Ultimately, this can lead to a “process of monopoly creation and monopoly protection.” In contrast to service centralization, insufficient attention has been paid to the potential beneficial effects of competition in the field of CHD. Evidence is accumulating that competition under a payment model can provide incentives and attract patients to improve quality, but such data in patients with CHD are lacking at present. Furthermore, competition is linked inherently to choice and patient autonomy, which are desirable ends.

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WHAT IS KNOWN

• Larger center volumes are assumed to be associated with better clinical results and superior research output in the setting of rare conditions such as adult congenital heart disease.

WHAT THE STUDY ADDS

• There is wide variation in patient choice and spatial competition among adult congenital heart disease centers in England.
• We found no association between center volume and clinical or academic results could be established in the current study.
• Higher spatial competition faced by individual adult congenital heart disease centers was associated with lower 30-day mortality after pulmonary valve replacement and superior cumulative research output.

in their own right. The current study aims to explore a possible association between degree of competition and clinical or academic results. It takes the patient perspective by assessing choice, as well as the perspective of providers by estimating the degree of competition faced by individual centers and correlates indices of market concentration with operative mortality and the cumulative impact points generated through original publications between 2009 and 2011.

Methods

This cross-sectional study is based on publically available data on ACHD centers in England, as well as information on general practitioner (GP) addresses and geographical data. A detailed list of data sources and relevant references is presented in the Data Supplement Appendix (Table AI in the Data Supplement). To define feasible access for patients and market areas for measuring competition, travel times along the road network were used. Travel times to individual ACHD centers were calculated using a web-based route planner, whereby the starting points were centered on GP addresses. Because estimated travel time may vary depending on the date and time of travel (eg, weekday versus weekend and certain rush hour times), the time of travel was arbitrarily set to Monday 9 AM for all queries. Addresses of GPs were used as a starting point for analysis because GPs act as gatekeepers in the English National Health System (NHS) and have a substantial role in referring patients and dictating patient flows. Centering the analysis on GP addresses is in accordance with previous studies. Because the study is based on publically available data, approval by a local ethics committee was not required.

Measures of Competition

The most widely used index of competition is the Herfindahl–Hirschman Index (HHI). This parameter is defined as the sum of squared market shares of providers and is used here to assess the countrywide degree of market concentration. This is based on adult operation and catheter procedure numbers in 2009 to 2011 as reported by the Central Cardiac Audit Database. Adult operations included all procedures with cardiopulmonary bypass in adult patients with CHD as reported by the Central Cardiac Audit Database. In addition, the HHI was also calculated for adult surgical pulmonary valve replacements, adult catheter interventions, as well as interventional atrial septal defect closures in adults. The market share (ie, the relative contribution of each center to all procedures nationwide) was defined as the number of patients with the condition treated at the respective center divided by the total number of procedures. The HHI was specifically calculated as:

\[ \text{HHI} = \sum_i \left( \frac{\text{No. of procedures at center } i}{\text{Total number of procedures}} \right)^2 \]

where \( n \) is the total number of centers.

Regarding spatial competition, a modified version of the HHI was used as the individual market shares of providers for various geographic areas is not available because of a lack of countrywide patient-level data. To calculate the degree of spatial competition, the relevant market (catchment) areas based on geography and feasible travel time for patients were estimated first. Subsequently, based on the calculated market segments, indices of competition were computed. To this end, the inverse of the number of providers was used as a surrogate for HHI. These 2 measures are equivalent if all providers have the same market share (an assumption that seems reasonable given the low grade of market concentration overall). Defining catchment areas by calculating boundaries for 120-minute drive time around each center was our preferred approach. However, because this drive time is to some degree chosen arbitrarily, we also performed analyses with 90- and 180-minute drive time sectors of access (results in the Data Supplement Appendix). Specifically, the spatial competition indices (SCI) were calculated as follows:

\[ \text{SCI} = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{d_i} \]

where \( i \) is the number of GP addresses within the predefined travel time from the ACHD center and \( n \) represents the number of ACHD centers within the same predefined travel time from the 1st GP address.

\[ \text{SCI}_{\text{distance-weighted}} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{d_i} \right) \]

where \( i \) represents the number of GP addresses within the predefined travel time from the ACHD center, \( n \) represents the number of ACHD centers within the same predefined travel time from the 1st GP address, and \( d_i \) is the travel time between the 1st GP address and ACHD center \( n \) under consideration.

The SCI corresponds to the average of the inverse number of ACHD centers within a given travel time of all GPs in the ACHD centers’ market area. For example, one could imagine an ACHD center with 4 hypothetical GPs within a 2-hour travel time, each of which have 4 ACHD centers within the same travel time, respectively. The corresponding SCI for this center would be:

\[ \frac{1}{4} \left( \frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4} \right) = 0.25 \]

In contrast, an ACHD center with 4 GPs, which all have only 1 ACHD center within the selected travel time, would face an SCI of

\[ \frac{1}{4} \left( \frac{1}{1} + \frac{1}{1} + \frac{1}{1} + \frac{1}{1} \right) = 1 \]

corresponding to a monopoly situation.

The second metric (SCI distance-weighted) accounts for the fact that although in principle feasible based on the predefined criteria, patients living farther away from the ACHD center may be less likely to attend the particular center, thus quantitatively adjusting access for travel time.

Outcome Measures and Center Volumes

Data on center volumes and mortality rates related to pulmonary valve replacement surgery in adults (defined by Central Cardiac Audit Database as >16 years of age) were obtained from the National Institute for Cardiovascular Outcomes Research. To assess center volume, we used the total number of cardiac operations and catheter procedures performed at each center between 2009 and 2011.

Measures of Research Quality

The PubMed database was searched for original publications related to ACHD using a list of keywords consisting of MeSH terms included
in the PubMed category heart defects and congenital. This list was supplemented with phrases not listed in this category as identified from the tables of content of the current European and American ACHD guidelines. Electronic query using these terms was performed using PubMed E-utility and R-package version 2.13.0. Identified articles underwent electronic filtering and later manual review. In addition, the list was complemented by a manual search focusing on consultants used at the various English ACHD centers. Publications including only pediatric patients were excluded, and only papers in English, published between 2009 and 2011, were included. All articles were manually reviewed subsequently (by 2 of the authors) to exclude non-ACHD publications and ensure adequate linking to individual centers. Articles were linked to centers according to the PubMed affiliation field, and impact factor (IF) data were associated with each publication based on journal and publication year. Journals without IF for a given year were given an IF of zero. IF data for 2011 were assumed to be equal to 2010. The aggregate IF (2IF) was calculated as the sum of all annual IFs for each individual center during the study period as follows:

$$\sum_{y=2009}^{2011} IF$$

where IF is the yearly IF for each center.

Because the Royal Brompton Hospital, London, is a designated National Pulmonary Hypertension Center—including for adults with CHD—and transplantation services are concentrated only at a subset of centers, publications on the topic of pulmonary hypertension and transplantation in CHD were excluded from the analysis to avoid bias in favor of centers specialized in offering such services.

### Statistical Analysis

Beyond conventional descriptive statistics, the correlation between indices of spatial competition and the predefined metrics of clinical quality or research output was assessed. Given the relatively low number of centers (n=10), we preferred a nonparametric Spearman rank correlation to avoid unnecessary assumptions about the distribution of the parameters, but the results of conventional parametric regression analysis (Pearson correlation coefficient) are also presented for completeness. For all analyses, a 2-tailed $P<0.05$ was used as a criterion for statistical significance. R-package version 2.13.0 was used for all analyses (http://cran.r-project.org/). To illustrate the results, maps showing the degree of patient choice/spatial competition were drawn using spatial interpolation methods (using the gstat library for R).

### Results

#### Concentration Indices on a National Level

The included centers performed between 165 and 387 cardiac surgeries (median, 218 surgeries) during the study period (2009–2011). Based on a total of 3133 surgical cases performed at the centers, this is equivalent to a median individual center share of 9.5% (range, 7.2%–16.9%). The resulting HHI based on cardiac surgery was 0.1073. Regarding cardiac catheterizations, individual centers performed between 161 and 486 procedures (median, 294.5 catheterizations) during the study period. The resulting market share of individual centers ranged between 0% and 59% with a median of 9.5%. The HHI based on cardiac procedure numbers was 0.1099. Similar results were obtained when pulmonary valve replacement operations and interventional atrial septal defect closure procedures were assessed as shown in Figure 1 (HHI, 0.133 and 0.105, respectively). Based on the interpretation of the US Federal Trade Commission, HHI values <0.15 are consistent with an unconcentrated (ie, competitive) market situation for invasive procedure and cardiac operations on a national level.

### Patient Choice

The results on patient choice between ACHD centers based on a feasible travel time of 120 minutes are illustrated in Figure 2 (unweighted SCI). It shows that residents of the geographic region broadly framed by the motorways M1, M4, and M5 have the highest levels of choice in the country (of ≤7 centers within 2-hour travel distance), whereas geographic areas exist where patients de facto have only a single provider within a 2-hour drive time available.

### Outcome of Pulmonary Valve Operations and Relationship to Center Volumes or Competition Indices

Based on the results of the Central Cardiac Audit Database, the 30-day mortality postpulmonary valve replacement at the individual centers ranged between 0% and 3.8% (median, 0.5%). Postpulmonary valve replacement mortality was unrelated to the number of pulmonary valve replacements ($p=0.16$; $P=0.65$) or the total number of adult congenital cardiac operations ($p=0.34$; $P=0.33$) performed at the individual centers during the study period. In contrast, pulmonary valve replacement mortality was correlated significantly with the competition faced by individual centers ($p$ between 0.72 and 0.82; $P<0.05$ for all; Table I and Table AII in the Data Supplement Appendix). Figure A1 in the Data Supplement Appendix illustrates the association between indices of competition and clinical or academic results.

### Relationship Between Competition Indices and Research Output

The included centers published original articles fulfilling the inclusion criteria with an aggregate IF between 0 and 132.6 during the study period. The relative share of the individual centers ranged between 0% and 59% with a median of 3.8%; the research IF of individual centers was correlated significantly with measures of spatial competition as shown in Table 2 and Table AIII in the Data Supplement Appendix. In contrast, no correlation was found between center volumes (ie, total cardiac operations, cardiac catheterization procedures, pulmonary valve replacements, or atrial septal defect closures) and research output ($p$ between 0.18 and 0.40; $P>0.28$ for all).

### Discussion

The current article illustrates the existing disparities in patient choice and spatial competition between ACHD centers in England. It also highlights that higher competition may be associated with better clinical results and superior research output. In contrast, no such association was found when assessing center volume, a variable that is conventionally thought to be the major driver of clinical quality and innovation in the field. We do not claim that a causal association between the degree of competition and outcome must necessarily exist but contend that, given the narrow focus traditionally placed on center size, competition and patient choice deserve greater attention in the future. This is not to say that expertise should be diluted by splitting large centers into smaller ones for the sole purpose of increasing competition, but where competition exists without affecting on the volume of work and, thus, quality of care, this should be welcomed as it may benefit care.
On a national level and based on analysis of market shares for adult congenital operations and catheter procedures, our article shows HHI values between 0.107 and 0.133, which is consistent with a competitive market without dominant players according to the interpretation of the US Federal Trade Commission (in fact HHI values <0.15 are generally interpreted as being consistent with a competitive market situation). When accounting for travel distance, a different and more heterogeneous picture is emerging: centers in London, Southern England, and the Midlands face higher levels of competition when considering geography compared with the remainder of the country. This finding is paralleled by disparities in patient choice between ACHD centers based on geography. Overall, the analyses used here suggest that residents of the geographic region broadly framed by the motorways M1, M4, and M5 have the highest levels of choice in the country (of ≤7 centers within a 2-hour drive time), whereas areas exist where patients de facto face a monopoly situation because of geographical factors. In contrast, only a few patients in England have no ACHD center within a 2-hour drive distance as illustrated by Figure 2. This affects mainly patients in sparsely populated areas of Cornwall, the east and far northwest of the country. It is of course inevitable that patients who live in the most populous areas of the country will have a greater choice of providers compared with residents in rural areas. It is also difficult to envision health policy interventions to ensure that all patients with ACHD in the country have an equal choice of providers. However, our analysis illustrates that disparities in patients with ACHD choice exist even in urban areas, and that restriction of competition may have adverse consequences on patient welfare and research in these settings.

Interestingly, the degree of local competition faced by individual centers was correlated significantly with clinical outcomes, measured as the 30-day mortality postpulmonary valve replacement and the quality of research output. Contradicting conventional perception, no association between center volume and outcome could be established in the current article. Pulmonary valve replacement was chosen because it represents 1 of the most common surgical interventions in patients with ACHD with relatively standardized indications and surgical techniques, and there is low but nontrivial mortality. These features distinguish pulmonary valve replacement from other more common operations or interventions that generally have an extremely low mortality but also from more sophisticated operations with considerable mortality that are reserved to specific centers and are related clearly to the relative mix of

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**Figure 1.** Degree of nationwide competition between centers based on the Herfindahl–Hirschman Index (HHI) for overall adult cardiac surgeries and catheter interventions (top row), as well as for pulmonary valve replacement operations and interventional closure of atrial septal defects (ASD, bottom row). The dotted horizontal line represents the expected level if all centers would have the same share of operations/interventions (i.e., perfect competition). The colored bar on the right illustrates the interpretation of the US Federal Trade Commission with regard to the HHI.
diagnoses and severity of disease followed in specific centers. We have shown recently that research output correlates with reported clinical volumes in North American ACHD centers\(^{14}\) and contend that more research active centers are more likely to be more proactive in implementing new scientific evidence into clinical practice, thus providing patients with early access to novel therapies. This is consistent with the view that acting in a more competitive environment fosters innovation in an effort to outperform competitors.

Consolidating ACHD services has been advocated because of the relatively low prevalence of the condition in the community and the special expertise required to provide high-quality care for this heterogeneous and challenging patient group.\(^{15}\) It is commonly recommended that 1 supraregional ACHD center should be available for \(\approx 2\) to 10 million inhabitants to ensure an acceptable trade-off between specialization and feasibility of access for patients.\(^{15,16}\) For England (with a population of \(\approx 53\) million in 2011), this would amount to \(\approx 5\) to 26 centers. Therefore, the status quo with 10 centers is well within this proposed corridor. To the best of our knowledge, the proposed number of ACHD centers per million population is, however, based on expert opinion, and it remains to be tested empirically whether this, indeed, represents the optimum in terms of clinical outcome, responsiveness (especially in terms of access), and cost-efficiency of care. Supraregional ACHD centers offer the benefit of an integrated service delivery with provision of adequate diagnosis, interventional and surgical treatment, electrophysiology services, as well as high-risk obstetric care.\(^{17}\) In addition, this model of care allows to pool expertise to the benefit of patients. There is also little doubt that a fragmented service with many small centers lacking appropriate experience and treating patients as medical curiosities should be avoided.\(^{18}\) On the contrary, an overconcentration of services (with monopolies being an extreme case) may limit patient choice and autonomy, induce inefficiencies because of diseconomies of scale, and provide little incentives to innovate and improve quality. Not surprisingly, therefore, Propper et al\(^{19}\) have suggested that “[m]onopoly power is directly harmful to patients, in the worst way possible … [and] policies directed at increasing

Table 1. Correlation Between Level of Spatial Competition and PVR Mortality

<table>
<thead>
<tr>
<th>Competition index</th>
<th>Correlation coefficient</th>
<th>(P) value</th>
<th>Correlation coefficient</th>
<th>(P) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>120-min travel radius</td>
<td>0.73*</td>
<td>0.02</td>
<td>0.75*</td>
<td>0.01</td>
</tr>
<tr>
<td>Competition index (distance weighted)</td>
<td>0.82*</td>
<td>0.004</td>
<td>0.86*</td>
<td>0.001</td>
</tr>
</tbody>
</table>

PVR indicates pulmonary valve replacement. \(^*\)Significant parameters.

Table 2. Correlation Between Level of Spatial Competition and Research Output Measured as the Sum of Research Impact Factors

<table>
<thead>
<tr>
<th>Competition index</th>
<th>Correlation coefficient</th>
<th>(P) value</th>
<th>Log (Impact Factors)</th>
<th>Impact Factors</th>
<th>Pearson ((r))</th>
</tr>
</thead>
<tbody>
<tr>
<td>120-min travel radius</td>
<td>−0.56</td>
<td>0.09</td>
<td>−0.82</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Competition-index (distance weighted)</td>
<td>−0.67*</td>
<td>0.03</td>
<td>−0.89</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>

\(^*\)Significant parameters.
or maintaining competition such as antitrust enforcement, appear to have an important role to play in the functioning of the health sector and assuring patients’ well-being. As a consequence, the challenge remains to establish the optimum size, avoiding extremes in terms of both overconcentration and fragmentation of service provision.

Microeconomic theory is unequivocal on the beneficial effects of free competition under (near) perfect market conditions. However, the healthcare market lies far from this ideal scenario. Despite this shortcoming, however, several empirical studies outside the field of ACHD have highlighted a positive association between competition and clinical results. The available evidence is derived mostly from the US and the UK healthcare markets. It includes the seminal study by Kessler and McClellan demonstrating that higher competition is associated with lower acute myocardial infarction mortality rates in elderly US patients. This correlation between degree of competition and outcome, under a fixed price regimen, is corroborated by other US studies. For a comprehensive review of the US evidence, see Propper and Gaynor. Recently, 2 large, methodologically robust econometric studies examined the effect of intensified competition on mortality rates in the United Kingdom. Both studies represent quasi-experiments, taking advantage of countrywide patient-level panel data, capitalizing on the introduction of choice and increased competition after 2006 in the NHS, and using extensive robustness checks and sensitivity analyses. These studies show that more intense competition is linked to lower postacute myocardial infarction mortality. In addition, Gaynor et al suggest improvements in efficiency and net monetary benefits from procompetition policies. The results of the current study are consistent with these 2 recent UK studies, suggesting a beneficial effect of competition on clinical and academic quality in the setting of ACHD.

The results of these studies are particularly timely given the ongoing process of ACHD service reorganization in the United Kingdom. Although we cannot comment specifically on whether the care for patients with ACHD would improve or worsen as a consequence of service consolidation, the current study highlights the potential beneficial effects of competition, directly opposing the view that services ought necessarily to be highly concentrated. Although currently speculative because of the lack of robust data, it could be argued that rather than attempting to improve quality by simply increasing center volumes, policies fostering a competitive environment may be equally promising and should be explored further. This should be supported by continuing to provide regular national outcome measures but also assessing research output and, in the future, potentially metrics of process quality.

Our findings also have potential implications outside the UK healthcare market. Increasingly, efforts are made to accredit ACHD centers. This process does not, in itself, limit choice and competition; however, healthcare insurers should resist the temptation to regard all accredited centers as equal and limit patient choice (eg, by reimbursing treatment only at the closest center).

**Limitations**

This was a cross-sectional study investigating the unadjusted association between measures of spatial competition and clinical outcome or academic output. The results of this study are, therefore, potentially subject to unobservable variable bias because of intrinsic differences between the centers included, and residual confounding cannot be excluded. For example, we accept that the patient case mix may be different between centers, and this factor was not accounted for because of lack of patient-level data. Unfortunately, because the number of centers and, thus, the degree of spatial competition assessed did not change during the study period, panel data analyses could not be performed.

In addition, 3 centers are located in the capital, and a London effect cannot be excluded. It could be argued that these centers are subject naturally to a greater degree of competition because of their geographic proximity but also benefit from the dynamic economic microclimate and general affluence of the capital. Although we cannot methodologically disentangle the effects of competition from this assumed London effect, we can exclude the possibility that the performance of the London centers is merely because of higher clinical volumes. In addition to the potential reason for a link between degree of competition and research output provided above, it should be acknowledged that increased competition might favor the establishment of larger ACHD programs (ie, economies of scale), which may, in turn, lead to larger patient volumes and more resources available for research. However, the fact that degree of competition was not correlated with clinical volume suggests that this is not a likely explanation. All studied centers are large established institutions, and this may explain the lack of an association between center volume and outcome. We accept that different results may have been obtained when studying centers with smaller volume loads. In fact, one may argue that competition between centers becomes relevant only once a sufficient number of supraregional centers has been established. Therefore, we do not question the necessity of supraregional ACHD centers per se.

In summary, the results of the current study illustrate that not all patients with ACHD benefit from the same degree of choice between ACHD centers based on geography, and some patients may have hardly any choice at all. Competition between ACHD centers is related to clinical and academic results of individual centers. Although our findings merit further validation, it should be recognized that restriction of competition may have adverse consequences on patient welfare and research productivity.

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We thank the Karla Völlm Foundation for providing a research grant to assess the health economic implications of regulation and competition in the field of adult congenital heart disease. Dr Kempny was supported by the Deutsche Herzstiftung.

**Disclosures**

None.

**References**


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### Table A1 - Online Appendix. Data sources.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source / Reference</th>
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</thead>
</table>
Table A2. Correlation between level of spatial competition and pulmonary valve replacement (PVR) mortality. The Table illustrates that the statistically significant associations between measures of competition and PVR mortality are robust to the choice of the correlation analysis (Spearman rank or parametric Pearson correlation), choice of travel time (90 and 180 minutes) and weighting for travel distance.

<table>
<thead>
<tr>
<th>Competition-index</th>
<th>30-day post PVR Mortality</th>
<th>30-day post PVR Mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spearman rank ($\rho$)</td>
<td>Pearson ($r$)</td>
</tr>
<tr>
<td>90 minute travel-radius</td>
<td>Correlation Coefficient $p$-value</td>
<td>0.78</td>
</tr>
<tr>
<td>180 minute travel-radius</td>
<td>Correlation Coefficient $p$-value</td>
<td>0.78</td>
</tr>
<tr>
<td>90 minute travel-radius (distance weighted)</td>
<td>Correlation Coefficient $p$-value</td>
<td>0.81</td>
</tr>
<tr>
<td>180 minute travel-radius (distance weighted)</td>
<td>Correlation Coefficient $p$-value</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Significant parameters printed in bold.
**Table A3.** Correlation between level of spatial competition and research output measured as the sum of research impact factors. The Table illustrates that the statistically significant associations between measures of competition and research output are robust to the choice of the correlation analysis (Spearman rank or parametric Pearson correlation), choice of travel time (90 and 180 minutes) and weighting for travel distance.

<table>
<thead>
<tr>
<th>Competition-index</th>
<th>Correlation Coefficient</th>
<th>Impact factors Spearman rank ((\rho))</th>
<th>Log(Impact factors) Pearson (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 minute travel-radius</td>
<td>-0.67 (\rho) 0.03</td>
<td>-0.77 (r) 0.01</td>
<td></td>
</tr>
<tr>
<td>180 minute travel-radius</td>
<td>-0.82 (\rho) 0.004</td>
<td>-0.86 (r) 0.003</td>
<td></td>
</tr>
<tr>
<td>90 minute travel-radius (distance weighted)</td>
<td>-0.69 (\rho) 0.03</td>
<td>-0.81 (r) 0.008</td>
<td></td>
</tr>
<tr>
<td>180 minute travel-radius (distance weighted)</td>
<td>-0.70 (\rho) 0.03</td>
<td>-0.68 (r) 0.045</td>
<td></td>
</tr>
</tbody>
</table>

Significant parameters printed in bold.
Figure A1. Scatterplots illustrating the association between indices of competition and post pulmonary valve replacement (PVR) mortality or research output (measured as the aggregate impact factor $\Sigma IF$). For details on the analysis and the data sources see text and Table A1. * log-transformed parameter.