Does Private Equity Investment Spur Innovation? Evidence from Europe*

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Abstract

While recent studies have looked at the effect of private equity investment on innovation, the premise of this effect across countries hasn't been studied empirically. We provide the first cross-country evidence of the effect of private equity on innovation, focusing on a sample of European countries and using Kortum and Lerner's (2000) empirical methodology. Using an 18-country panel covering the period 1991-2004, we study how the volume of private equity finance affects patent applications and patent grants. We address concerns about causality in several ways, including exploiting variation in laws regulating the investment behavior of pension funds and insurance companies across countries and over time. We also control for the standard determinants of innovation like R&D, human capital, and patent protection. Our estimates imply that while private equity investment accounts for 8% of aggregate (private equity plus R&D) industrial spending, PE accounts for as much as 18% of industrial innovation. We also present similar evidence from the biotech industry to alleviate concerns that our results are biased by aggregation.

JEL classification: C23, G15, O16

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1 Introduction

The US productivity boom of the 1990s produced a lasting fascination among economists with the ability of risk capital markets to boost innovation by allocating finance to the best ideas available. A growing body of empirical literature has provided ample evidence that this "new" type of finance represents an important engine of new business creation and job growth, and that it has been a major force in commercialising scientific results. This latter effect, it has been argued, has come both through the impact of risk capital finance on existing industries and through its role in creating and developing entirely new industries.[1]

While evidence to the ability of private equity and venture capital finance to stimulate innovation remained anecdotic for quite some time, Kortum and Lerner (2000) provided the first rigorous estimation of the magnitude of this effect. They explored the experience of twenty industries covering the U.S. manufacturing sector between 1965 and 1992. In essence, they used reduced-form regressions to explore whether, controlling for industrial R&D spending, venture capital has an impact on the number of patented innovations. They found that VC is associated with a substantial increase in innovation. Even after employing different functional forms and addressing possible omitted variable bias, their results still suggested a strong effect of VC on innovation. Specifically, they measured an elasticity of up to 0.09 of ultimately successful patent applications to venture capital disbursements, and found that while the ratio of venture capital to industrial R&D averaged less than 3% between 1983 and 1992, VC has accounted for 8% of industrial innovation over that period.

A host of subsequent papers have tested the main results of Kortum and Lerner in a variety of different environments, with ambiguous results. In those, researchers

[1] See, for example, Gilson (2003).

looked not only at the effect of VC on innovation, but at the channels of this effect. Hellman and Puri (2000) presented an analysis of cross-sectional, hand-collected data on 149 Silicon Valley firms in the computer, telecommunications, medical and semi-conductor industries with information about the founding strategy of the firm, i.e. whether the firm follows an innovator strategy or an imitator strategy. They found that firms that pursue an innovation strategy are more likely to obtain venture funding than imitating firms, and that innovators obtain venture capital more quickly. Their results thus suggest that venture capital may not stimulate innovation via incentives and monitoring, but via screening of firms. And Engel and Keilbach (2007) reached similar conclusions. They analysed innovative activity by German VC-backed and non-VC backed firms and found that VC seems to be more focused on bringing existing innovations to the markets rather than on fostering new ones.

However, Lerner et al. (2008) suggested that the effect of VC on innovation goes beyond "cherry-picking". In a US firm-level sample they found that receiving venture capital funding is associated with a significant reduction in the time to bring a product to the market. Their evidence suggests that, controlling for the characteristics of the firm at the time of the venture capitalist's involvement, firms pursue more influential innovations – as measured by the number of patent citations – in the years after venture capital investment took place.

To our knowledge, the current study is the first to apply the Kortum and Lerner (2000) empirical framework to a cross-country environment. We first estimate reduced form regressions of patent applications and patent grants on industrial R&D and private equity investment in a panel of 21 countries followed between 1991 and 2004. The knowledge production associated with an increase in research input has been shown to affect growth via the process of innovation both theoretically (for example, Romer [1990]) and empirically (for example, Griliches [1979] and Ulku [2004]).

We then extend the empirical framework to estimate different specifications of the production function entailing private equity finance and R&D, to account for the fact that reduced-form regressions may be overstating the effect of risk capital finance.

We also address the main problem identified by Kortum and Lerner, namely that both VC funding and patenting are positively related to the arrival of technological opportunities. We do that in two different ways. First, we explore Kortum and Lerner's insight that the 1979 clarification by the U.S. Department of Labor of the Employee Retirement Income Security Act (ERISA) was a policy shift that allowed pension funds to invest in venture capital. This policy can thus be used as a supply shifter for venture capital as it is unlikely to be correlated with the arrival of technological opportunities. We collect information on the national rules guiding the extent to which of institutional investors (pension funds and insurance companies) can invest in risk capital, and use changes in these rules in an instrumental variable regression framework to extract the endogenous element of private equity finance. We also use Kortum and Lerner's (2000) insight that the causality problem disappears once the effect of private equity finance is measured on the patent-R&D ratio rather than on patents *per se*.

Finally, the cross-country environment allows us to eliminate the variation in innovative activity that is explained by the other determinants of innovation (apart from finance and industrial R&D) suggested by the literature, like government financed R&D, human capital, GDP, and patent protection[2], by directly controlling for those.

Even after addressing the causality concerns and controlling for other characteristics of the regulatory and business environment, we find a significant effect of risk capital finance on innovative activity. Specifically, a 1% increase in private equity investment increases the number of USPTO patents by between 0.04% and 0.05%.

[2] See, for example, Furman et al. (2000) and Kanwar and Evenson (2003).

In addition, while private equity investment accounts for 8% of aggregate (private equity plus R&D) industrial spending, PE accounts for as much as 12% of industrial innovation. However, three caveats are in place. First, while the effect of risk capital finance on innovation is both economically and statistically significant when we measure innovation by the number of USPTO patents (i.e., patents granted by the U.S. Patent and Trademark Office to establishments from foreign countries), it is practically nonexistent if we proxy innovative activity by EPO patent applications. Second, while the preferred measure of risk capital finance in the empirical literature on innovation has been venture capital finance (i.e., investment in seed, start-up, and expansion stages), our data doesn't allow us to isolate venture capital and for this reason we use private equity investment (roughly, venture capital plus buy-out finance) as a proxy for risk capital. Finally, the industrial classification used by our two main data sources - on private equity investment (European Private Equity and Venture Capital Association) and on patent application and grants (Eurostat) - doesn't allow us to match our data for the multitude of industry classes, hence we focus on economic aggregates in our empirical analysis.

The first caveat implies that risk capital increases innovative output only in terms of ultimately successful applications rather than increasing application activity, and so points to real effects. The second one suggests that we may be picking up certain private equity capitalists' "cherry-picking" effect in our estimations, but at the same time the exclusion of private equity may bias the true effect of risk capital on innovation by eliminating the effect of innovation which was undertaken to attract future private equity funds. It is reasonable to assume that the net of these two latter effects could be close to zero, but the overall results still need to be taken with a degree of caution. Finally, with regards to the third caveat, we can still match data on private equity investment and patent application and grants in the biotech industry. Hence, in the final section of our paper we also report in this paper similar estimates on the effect of private equity investment on biotech patents, implying that the estimates hold even when we account for variation in the industrial composition of national economies.

The paper proceeds as follows. Section 2 provides an overview of the European private equity industry. Section 3 describes the data. Section 4 presents the empirical methodology and the set of initial reduced-form regressions. In Section 5, we address the causality problem by repeating Kortum and Lerner's (2000) extension of the model of the relationship between private equity, R&D, and innovation, and report the refined estimates. Section 6 reports the robustness tests and the estimates from the biotech industry, and Section 7 concludes.

2 Risk Capital and the Financing of Young Innovative Companies

Private equity (PE) in general and venture capital (VC) in particular is a form of finance usually provided by professional investors to young innovative companies, to which they also act as advisors or even managers, with the main goal of taking them to an Initial Public Offering (IPO) or a trade sale. While the profit motive of private equity capitalists has been discussed to great lengths in the media over the past years, recent empirical literature has suggested that this "new" type of finance also has real effects. Namely, it has been argued that VC represents an important engine for the Schumpeterian process of "creative destruction", and that it is a major force in transforming scientific knowledge into commercial output. This effect has come both through the impact of VC on existing industries and through its role in creating and developing entirely new industries.

As Kortum and Lerner (1998, 1999) report, the venture capital industry dates back to the formation of American Research in Development in 1946 and the Small Business Investment Company Act in 1953, designed to increase the availability of funds to new ventures. However, the flow of money into venture funds really only picked up in the late 1970s and the early 1980s after the 1979 clarification of the "prudent man" rule governing pension funds investment. Prior to that, the ERISA severely limited the ability of pension funds to invest in risk capital markets, but in 1979 the U.S. Department of Labor issued a clarification of the rule stating that diversification is an inalienable part of prudential investment behavior. As a result, in the eight years following this decision the amount invested in new venture funds soared from $481 million to nearly $5 billion, with pension fund accounting for nearly half of all contributions (Gompers and Lerner [1999]). This surge of funds into the venture capital industries is often credited with the high-tech revolution in the US in the 1990s (Gilson [2003]).

The PE industry in Europe has been slow to reproduce this development. In fact, only recently did the European Commission undertook explicit regulatory intervention to prohibit national legislation from preventing insurance companies and pension funds from investing in risk capital markets[3], and as of the end 2006, some EU countries hadn't adopted these directives yet.[4] Prior to that period, the extend of recommended prudential behavior by institutional investors was left to the discretion of national governments, and as a result, there were large differences across countries and over time in the degree of regulation of these activities before the current harmonization drive. As a result, only in 2006 did pension funds become the largest source of PE funds raised by investors, with this role asserted by banks prior

[3]Directives 2002/13/EC and 2002/83/EC concerns the investment behavior of insurance companies, and directive 2003/41/EC the investment behavior of EU pension funds.

[4]See the December 2006 "Benchmarking European Tax and Legal Environments" report of the EVCA for details.

to that. Nevertheless, recent years have seen a dramatic increase in the level of PE and VC fund-raising and investment, with risk capital investment as a share of GDP approaching US levels in European countries like Denmark, Finland and Sweden.

3 Data

This paper uses data from two main sources: on patent applications and grants from the EPO and USPTO[5], and on private equity investment from the EVCA yearbooks. The EVCA yearbooks compile annual data on private equity funds raised, funds allotted to venture capital, and the actual allocation of private equity investment. It is reported annually starting in 1991. Three caveats are in place. First, while the EVCA yearbooks try to be exhaustive in terms of the European countries they cover, in some cases they discontinue their reporting (Iceland after 2001). In others - notably, the new EU members from Central Europe (Czech Republic, Hungary, Poland and Slovakia) - EVCA only started reporting PE activity in 1998. Understandably, in cases when there were too few years included, or when it was judged impossible to disaggregate reliably the information on private equity, the data was not used. Apart from current EU members, the EVCA yearbooks also include information on Iceland, Norway, and Switzerland.

The second caveat deals with the reporting of investment by US private equity houses. If a deal has been backed by both a US and a European private equity house, the deal is then split into two parts. The part of the investment coming from the European PE firm is allocated to the respective European country, and the part of the investment coming from the US PE firm is allocated to the US. However, if the US PE firm has no office in Europe, then its investment is not included in the EVCA figures. In addition, concerning US PE houses investing in Europe, only investments made by

[5] European Patent Office and US Patent and Trademark Office, respectively.

those having offices in Europe are taken into consideration. This would imply that if a US PE firm, which has no office in Europe, invests in a European company, the investment would not be included in the EVCA figures. While the vast majority of US PE houses operate through their European offices, it is still the case that the EVCA data is by construction incomplete. Thus, while the EVCA yearbooks represent the most comprehensive collection of information on venture capital in Europe, our results should be taken with caution.

Finally, while EVCA offers disaggregated data on the staging of PE investment (seed, start-up, expansion, replacement, and buy-out), it only disaggregates investment by country of management. Popov and Roosenboom (2008) suggest an algorithm for projecting the stage distribution by country of destination, which in theory would allow us to perform the identical analysis as in Kortum and Lerner (2000) on the effect of VC on innovation. However, they explicitly state that when matching to data on real economic behavior, from a measurement error point of view only using the data on private equity investment makes sense. Hence, we run the analysis using data on the aggregate of PE investment only, which includes buy-outs, and so our results may be overstated by some "cherry-picking" effects.

Table 1 summarizes the information on total actual private equity investment, as well as for industrial R&D (from Eurostat) and the ratio of the two, for the countries used in the study, aggregated for the 1991-1995, 1996-2000, and 2001-2004 period. It gives a clear idea of the rapid growth and accompanying volatility of private equity investment. For example, from the 1991-1995 to the 2001-2004 period, in millions of 1991 euros, total private equity has less than doubled in Greece and Portugal (from 22.93 to 42.51 and from 47.95 to 89.01, respectively), increased by a magnitude of 5 in France and Germany (from 842.22 to 4,240.03 and from 632.68 to 3,042.50, respectively), and by a magnitude of 10 in Denmark (from 37.77 to 372.48). At the same time, while it has doubled from the 1996-2000 to the 2001-2004 period in Belgium and Sweden (from 286.33 to 525.30 and from 649.76 to 1,337.75, respectively) it has decreased slightly over the same period in the Czech Republic and Poland (from 25.71 to 15. 13 and from 18.16 to 14.40, respectively). Industrial R&D oscillates much less around the trend, and with the exception of Hungary, Poland and Slovakia, it has increased steadily in all countries by an average of about 50% between 1991 and 2004. This results in large variations in the PE/R&D ratio: for example, during the 2001-2004 period it is as low as 4% in Austria and as high as 25% in the Netherlands.

The data on patent applications comes from the EPO and USPTO offices and is reported by Eurostat. The data on patent applications to the EPO runs from 1977 to 2005 and the data on patent applications granted by the USPTO runs from 1977 to 2002. Table 2 summarizes the data on innovation by 5-year periods. The data is aggregated across industries. In both data series, the last year is reported as an estimate, and so we drop it in the empirical analysis. We also discard the data for the years before 1991 as there is no private equity data before that. Unfortunately, the inability to disaggregate the data on investment by industry classes (although we can do the same with the patent data) forces us to perform the empirical tests on aggregate country data. Still, in the last section of the paper, we present some results on the effect of private equity investment on innovation in the biotech industry, for which we are able to match the two types of data. It needs to be emphasized though that the focus on an aggregate analysis is not as problematic as it initially seems: as pointed out by Kortum and Lerner (2000), the USPTO does not compile patent statistics by industry and many firms have multiple lines of businesses, so the primary technological classification of a patent application/grant can only be indirectly inferred.

The final sample consists of 21 countries observed over a period of 14 years in the case of patent applications to the EPO (1991-2004) and 11 years in the case of ultimately successful patent applications to the USPTO (1991-2001). See Appendix 1 for all data sources.

4 Empirical methodology and initial estimates

4.1 Patent production function

We estimate the same Constant Elasticity of Substitution (CES) patent production function as in Kortum and Lerner (2000), which is of the form

$$P_{it} = (RD_{it}^{\rho} + bPE_{it}^{\rho})^{\frac{\alpha}{\rho}} u_{it} \tag{1}$$

Patenting (P) is a function of privately funded industrial R&D (RD) and private equity disbursements (PE), while the error term (u) captures shifts in the propensity to patent or technological opportunities, all indexed by country (i) and year (t). Our focus is on the parameter b which captures the role of private equity in the patent production function. $b > 0$ would imply that private equity matters for innovation, while $b = 0$ would imply that the patent production function includes industrial R&D as its only input and thus reduces to $P_{it} = RD_{it}^{\alpha} u_{it}$. The parameter α measures the return to scale, that is, the percentage change in patenting brought about by a 1% change in both RD and PE. The parameter ρ measures the degree of substitutability between RD and PE as inputs in the production function. If $\rho = 1$, the patent production function reduces to

$$P_{it} = (RD_{it} + bPE_{it})^{\alpha} u_{it}, \tag{2}$$

and if $\rho = 0$, the patent production function reduces to a Cobb-Douglas functional form

$$P_{it} = RD_{it}^{\frac{\alpha}{1+b}} PE_{it}^{\frac{\alpha b}{1+b}} u_{it} \quad (3)$$

Finally, it is worth noting that while we treat industrial R&D as a variable independent from PE disbursements, undoubtedly some of it includes research directly financed by venture capitalists. Similarly, while most of the venture capital disbursements directly finances innovative activities in high-tech firms, some of it is devoted to low-tech and marketing activities. Both practices work to weaken the direct impact of VC disbursements on innovation, and so the estimated effects are likely to be understated.

4.2 Initial estimates

4.2.1 Estimating the Cobb-Douglas production function

In the first two columns of Table 3 we present our estimates from the initial estimation of the Cobb-Douglas production function (the $\rho = 0$ case). We regress the logarithm of patent applications and patent grants (i.e., ultimately successful patent applications) in each country and year on the logarithm of private equity disbursements and the logarithm of industrial R&D in that country and year. We also include government-funded R&D, as well as country and year dummies (to control for natural propensity to patent and for policy changes affecting patenting activity) as controls. The first important observation is that neither private equity disbursements nor industrial R&D have an effect on patent applications, but both exhibit an effect on patent grants. We next address the concern that these results may be distorted by the inclusion of numerous countries which invest too little in R&D (columns (iii) and (iv)). We repeat the analysis with only the top half of the countries in terms of R&D investment as a share of total industrial output. This time we find an effect of both privately funded R&D and PE investment on patenting which is both economically and statistically meaningful. A doubling of PE disbursements leads to an increase of patent applications by 3% and of patent grants by 5%. Finally, we account for the possibility that our results are distorted by the inclusion of countries which invest too little in PE or for which too many data points are missing. The natural candidate are the transition economies (the Czech Republic, Hungary, Poland and Slovakia), so in columns (v) and (vi) we drop those. We get similar results.

We notice then that by dropping the transition economies (17 observations in the case of patent applications and 8 in the case of patent grants), we get results which are much more in line with the prediction of the model, as well as with prior empirical analysis on the effect of industrial R&D on patent activity. This is partially because the four transition economies are left-tail outliers in terms of both PE investment and industrial R&D: they have average annual PE investment equal to 1.4% of the European average (14.4 mln. vs. 1.001 bln. euros) and average R&D investment equal 2.1% of the European average (189.9 mln. euros vs. 8,949.4 mln. euros).[6] In addition, EVCA data on PE investment in these only becomes available in 1998. This anomalous nature of the transition economies gives us confidence to continue the analysis with the 17 non-transition countries only.

4.2.2 Estimating a non-linear specification

We next proceed to estimate equation 1, or the non-linear specification of the patent production function, and report the estimates in Table 4. We use the same controls as in the previous exercise, namely government-funded R&D and country and year dummies. Again, the results suggest that private equity matters for innovation: in

[6] The difference is smaller but still substantial in terms of investment as share of GDP: average annual PE investment for the 4 transition economies is 21.5% of the 17 non-transition economies (0.028% vs. 0.131%) and average industrial R&D investment in the new EU-member states is 22.8% of the analogous investment in the rest of Europe (0.37%% vs. 1.62%).

the unconstrained case the estimate of the coefficient b is positive, significant at the 1% for both patent applications and patent grants, and its magnitude, while larger than in the Cobb-Douglas case, is not implausible. Together, industrial R&D and private equity investment explain between 34% and 44% of the variation in patenting activity not captured by country and time effects and government-funded R&D. A likelihood test applied to the estimation in columns (ii) and (v) strongly rejects the hypothesis that $b = 0$.

We also find that private equity investment and industrial R&D are very substitutable, with the point estimate of ρ close to 0.5. A likelihood ratio test strongly rejects the restriction $\rho = 0$ (columns (iii) and (vi)), with a p-value less than 0.01. Hence, in the following estimations we proceed with estimating equation 2, namely, the $\rho \rightarrow 0$ case. In addition, while the estimate of the parameter α in the case of patent applications is implausibly high (1.204), it is close to what Kortum and Lerner (2000) report in the case of patent grants (0.304 relative to their estimate of 0.22).

4.2.3 Estimating a linear specification

As noted by Kortum and Lerner (2000), in the case when PE funding is small relative to R&D (a sample average of 0.128 for the most PE-intensive period, 2001-2004), it is reasonable to estimate b through a linear approximation of the patent production function. Also, in case we are concerned about inflated estimates in the previous estimation procedures, such a linear approximation has the virtue of providing a conservative estimate of the effect of PE investment on patenting, that is, an estimate of this effect when the ratio PE/R&D approaches zero. This is only logical in light of the fact that we are evaluating the null hypothesis that the effect of PE on patenting is zero.

We next proceed to manipulate equation (2) by multiplying and dividing by RD_{it}

in the right hand side to obtain

$$P_{it} = RD_{it}^{\alpha}(1 + b\frac{PE_{it}}{RD_{it}})^{\alpha}u_{it}$$

and linearizing around $\frac{PE}{RD} = 0$ gives us

$$\ln P_{it} = \alpha \ln RD_{it} + \alpha b\frac{PE_{it}}{RD_{it}} + \ln u_{it} \tag{4}$$

This linear approximation was suggested by Griliches (1986), who argued that a Taylor expansion of the logarithm of the function is reasonable when one is trying to evaluate the impact on output of a variable whose values are relatively small to the other input in the production function.[7]

The results of this estimation are reported in Table 5. The basic equation are in columns (i) and (ii), and the estimates suggest that private equity matters for both the propensity to submit patent applications and the overall quality of these submissions. It is important to note that we have reported the estimates for α and for αb in the table, so in order to obtain the estimated impact of private equity investment b, one needs to divide the two estimates reported. Hence, for instance column (ii) implies that $b = 1.21$, suggesting that a euro of private equity is slightly more effective in promoting ultimately successful innovation than a euro in industrial R&D. A quick comparison to the findings of Kortum and Lerner (2000) suggests that European private equity is far less efficient than US one.[8]

4.2.4 Differences analysis

Next we address concerns about autocorrelation of the residuals. The error term is affected by shocks to the propensity to innovate, which may be affected by policy

[7]Griliches used basic research at the firm level instead of private equity investment.

[8]Kortum and Lerner (2000) find that a dollar of VC is about 7 times more productive in terms of the number of ultimately successful patent applications than a dollar of industrial R&D.

changes, and those effects are likely to persist over time. For example, a decrease in the difference between the personal income tax and the capital gains tax will induce more people to leave their job and become entrepreneurs (Da Rin et al. [2006]), and such an increase is likely to persist, at least due to lengthy electoral cycles. Analogically, the propensity to patent may be correlated with the size of the pool of talent, thus with the size of the population, so it may be affected by a persistent demographic change. Hence, our standard errors may be artificially low and our t-statistics artificially high.

A natural solution to this problem is a first-difference analysis, which will eliminate the autocorrelation element if the original errors follow a random walk. However, a first-difference approach is likely to amplify the errors-in-variables problem, if such is present (Griliches and Hausman [1986]). Given that private equity disbursements fluctuate a lot from year to year due to the fact that venture funds are provided to firms at stages rather than at a steady stream[9] - implying that a disbursement recorded in 1997 may all be spent in 1997 or in portions over the, say, 1997-1999 period - it is likely to be the case. Therefore, instead of a simple first-difference approach, we first compute averages of all the variables over 3-4 year intervals, and then take the difference measured at 6-8 year intervals. Given the length of our time series - 14 years in the case of patent applications and 11 years in the case of patent grants, this leaves us with two differences only.[10] For example, we take the difference of the average value of log private equity disbursements over the 1995-1997 period from the average value of log private equity disbursements over the 2001-2004 period, and the difference of the average log values of the same variable over the 1991-1994 from its average log value over the 1998-2000 period.

[9]See, for example, Gompers and Lerner (1999).

[10]In the case of patent applications, we use two 3-year period and two 4-year periods, and in the case of patent grants we use one 2-year period and 3 3-year periods. The results we report are robust to the allocation of the period lengths along the time series.

Table 6 presents the results from this empirical exercise. We employ two empirical specifications, for the $\rho = 0$ and the $\rho = 1$ case. In the first case, we only record an economically and statistically meaningful effect of private equity finance on patent grants, while in the second case it has effect on both patent grants and patent applications. While both the impact of R&D and of the ratio of private equity to R&D are diminished by about half relative to the estimates in Table 5, the value of b - the effect of private equity - is essentially unchanged at a little over 1 in the case of ultimately successful patent applications, confirming that a euro of private equity disbursements is somewhat more effective in generating innovation than a euro spent on industrial R&D.

5 Addressing the causality problem

So far our estimates have given us reason to believe that there is a strong association between private equity and innovation. However, our reduced form equations do not enable us to make causality claims, and we haven't addressed the possibility that our estimates may be affected by unobservable factors. We address these concerns in the following section.

5.1 A simple model

The starting point is a simple model of private equity, corporate research, and innovation borrowed from Kortum and Lerner (2000). The basic idea is to incorporate technological opportunities in the model so that testable predictions could be developed. Assume that the economy as a whole is a single industry in which inventions can be pursued either via corporate R&D investment or via private equity finance. Four assumptions are made about this relationship.

1. The previously employed innovation production function holds in this economy, namely,

$$I_{it} = (RD_{it} + bPE_{it})^{\alpha} N_{it},$$

where I_{it} is innovative activity in country i at time t, and N_{it} is a shock to the patent production function, which is interpreted as the arrival of new technological opportunities.

2. Innovation translates into patents in a proportionate manner. Let ϵ_{it} be an independent shock affecting the propensity to patent innovation. Then, if P_{it} is the number of patent applications in country i at time t, we can write

$$P_{it} = I_{it}\epsilon_{it} = (RD_{it} + bPE_{it})^{\alpha} N_{it}\epsilon_{it}$$

3. Assume that individual innovative firms are small enough and so they take the expected value of new innovation and given. Let this expectation be Π_{it}. While innovation is pursued actively, the innovative output will or will not be worth patenting, and it is Π_{it} what will determine which innovation is actually patented.

4. In order to derive testable implications, an assumption about the marginal cost of innovation is necessary. We assume that in addition to direct R&D and PE expenditures, there also is the cost of screening, managing and advice, recruiting, etc. Assume that a project has a combination of characteristics which make it either more suitable for funding in an industrial lab or through a venture capital investment in a private entrepreneur setting. Corporate researchers are free to pursue those projects that are closest to their comparative advantage, while investing in one more project takes the venture capitalist farther from his own comparative advantage.

Formally, we model the venture capitalist's cost of managing the marginal project as $v_t f_{PE}\left[\frac{PE_{it}}{\lambda_{it}(RD_{it}+bPE_{it})}\right]$ and the corporation's cost of managing the marginal corporate-backed project is $f_{RD}\left[\frac{PE_{it}}{\lambda_{it}(RD_{it}+bPE_{it})}\right]$. Following from the discussion in the previous paragraph, we assume that $\frac{\partial f_{PE}}{\partial \frac{PE_{it}}{\lambda_{it}(RD_{it}+bPE_{it})}} > 0$ while $\frac{\partial f_{RD}}{\partial \frac{PE_{it}}{\lambda_{it}(RD_{it}+bPE_{it})}} < 0$. A rise in λ is interpreted as the determinant of technological opportunities that are conducive to private equity finance, and so a rise in λ implies that science has generated technological opportunities with a higher chance of success if PE-financed in an entrepreneurial setting. Finally, the term v_t has been included to account for the cost of raising PE funds.

As shown by Kortum and Lerner (2000), the optimization problem yields two equilibrium conditions, namely

$$\Pi_{it}\frac{\partial I_{it}}{\partial PE_{it}} = \alpha\Pi_{it}N_{it}b(RD_{it}+bPE_{it})^{\alpha-1} = v_t f_{PE}\left[\frac{PE_{it}}{\lambda_{it}(RD_{it}+bPE_{it})}\right]$$

$$\Pi_{it}\frac{\partial I_{it}}{\partial RD_{it}} = \alpha\Pi_{it}N_{it}(RD_{it}+bPE_{it})^{\alpha-1} = f_{RD}\left[\frac{RD_{it}}{\lambda_{it}(RD_{it}+bPE_{it})}\right],$$

which can be rewritten as

$$(RD_{it}+bPE_{it}) = \left[\frac{\alpha\Pi_{it}N_{it}}{g_1(v_t)}\right]^{\frac{1}{1-\alpha}} \tag{5}$$

$$\frac{PE_{it}}{RD_{it}} = \lambda_{it}\left[\frac{g_2(v_t)}{1-b\lambda_{it}g_2(v_t)}\right], \tag{6}$$

where g_1 and g_2 are such that $\frac{\partial g_1}{\partial v_t} > 0$ and $\frac{\partial g_2}{\partial v_t} < 0$. Therefore, total innovative effort is decreasing in the cost of venture funds, but increasing as a result from positive shocks to the value of invention or from the arrival of technological opportunities. PE investment relative to corporate R&D is increasing in the extent to which technological opportunities are conducive to VC-type innovation and decreasing in the cost of venture funds.

Obviously then, technological opportunities are not orthogonal to the ratio of private equity investment to R&D. Worse even, if the two shocks are positively correlated - which is logical - a burst of innovative opportunities will be accompanied by a radical shift in technology which VC-financed entrepreneurs will be better able to explore than large corporations specializing in industrial R&D. Therefore, the potential correlation between a shock to the patent equation and a shock that favours VC finance implies that our reduced-form equations are unable to capture the full dynamics of the true impact of PE on patenting.

As noted by Kortum and Lerner (2000), one way to identify the linear form of the patent production function

$$\ln P_{it} = \alpha \ln RD_{it} + \alpha b \left(\frac{PE_{it}}{RD_{it}} \right) + \ln N_{it} + \ln \epsilon_{it} \tag{7}$$

would be to account for variation in the value of innovation Π_{it} which would identify α by causing a variation in RD (courtesy of equation (5)) and a variation in the cost of venture funds v_t which would identify b by causing variation in $\frac{PE}{RD}$ (courtesy of equation (6)). However, as the more plausible scenario is that we will only be able to partially capture technological opportunities, then variations in RD and in $\frac{PE}{RD}$ will also be correlated with the disturbances, and so an OLS regression on (7) will produce biased estimates.

The solution suggested is to find a good instrument for the cost of funds. In our case, regulatory changes concerning the investment behavior of institutional investors with respect to risk capital will likely be correlated with the cost of raising private equity funds, and so an instrument based on the interaction of such changes with historical differences across countries in venture funding relative to corporate R&D

would help identify v_t. Second, akin to Olley and Pakes (1996), it is suggested to use R&D to control for the unobservable N_{it}. Namely, plugging $P_{it} = (RD_{it} + bPE_{it})^{\alpha} N_{it} \epsilon_{it}$ in (5) gives a closed solution of the patent-R&D ratio

$$\frac{P_{it}}{R_{it}} = \left[\frac{g_1(v_t)}{\alpha \Pi_{it}} \right] \left(1 + b \frac{PE_{it}}{RD_{it}} \right) \epsilon_{it}, \tag{8}$$

which implies that normalizing patents by R&D eliminates N_{it} from the equation. Although α is no longer identified, b can be identified without the contamination brought about by the correlation between $\frac{PE}{RD}$ and the error.

5.2 Instrumental variable estimation

Based on the above discussion, Kortum and Lerner (2000) use the Department of Labor's clarification of the "Prudent man" rule to instrument for the ratio of venture capital to industrial R&D.[11] The idea is that the influx of funds into venture capital companies after the easing of the restrictions decreased the cost of funds and allow for the identification of b in equation (7). They also quote Gompers and Lerner (1999) who found that in the eight years following this decision, the amount invested in new venture funds soared from $481 million to nearly $5 billion, with pension fund accounting for nearly half of all contributions.

We hand collected data on changes at the national level in regulations concerning the investment behavior of institutional investors - pension funds and insurance companies - and created dummies equal to 1 in the year in which regulations were lifted

[11] This principle was expressly declared by Section 404 of the Employee Retirement Income Security Act (ERISA) act from 1974, and it mrefers not to an investment outcome, but a course of conduct. After a long-lasting restrictive interpretation, a legislative modification in 1979 made its application more flexible, encouraging pension funds to increase the range of their possible investments also to venture capital by advising them that "[...] a fiduciary shall discharge his duties with respect to a plan solely in the interest of the participants and beneficiaries [by] diversifying the investments of the plan so as to minimize the risk of large losses, unless under the circumstances it is clearly prudent not to do so".

and on.[12] And while EU-wide directives 2002/13/EC and 2002/83/EC eased restrictions to the investment behavior of insurance companies, and directive 2003/41/EC the investment behavior pension funds in this regard (subject to quantitative limits), they were not adopted at the national level immediately, and in some countries not even by the end of 2006[13], hence we still rely on our data on EU-member regulations at the country level until the end of the 2004 period. The increase in the role of institutional investors in the volume of private equity funds raised in the years after lifting investment restrictions has been apparent, and as of end 2006, pension funds have overtaken banks as the single largest provider of funds to private equity houses in Europe as a whole (see EVCA 2007 yearbook for details). And in an unreported empirical exercise we find that a first-stage regression of the ratio of private equity investment over R&D on the remaining right-hand side variables of equation plus our institutional investors dummies yields an R-squared of 0.76 and an F-value of 19.18, fulfilling the relevance condition of a good instrument (see, for example, Angrist and Krueger [2001] for a discussion).

In addition, it is inconceivable that a policy shift will have the same effect in each country; it is far more likely to have a higher effect in countries with a high level of private equity investment prior to the policy shift. Thus, as advised by Kortum and Lerner (2000), the level of private equity funding before the policy shift can be interacted with our institutional investors dummies, and so the instrument proposed takes on the value of 0 before the policy shift, and after the policy shift its value is the average value of the $\frac{PE}{RD}$ ratio during the years before the shift.

The results from the IV regressions are reported in Table 7. In the first two columns, we have only instrumented for the $\frac{PE_{it}}{RD_{it}}$ ratio in the linearized specification (the $\rho = 1$ case). We obtain a positive estimate of the impact of private equity funding

[12]See Appendix 2 for details.
[13]See EVCA (2006) for details.

on innovative activity on ultimately successful patent applications to the USPTO, but it is not statistically significant. This leads us to address the second concern expressed in the above quoted US study namely, that industrial R&D may also be related to the shift in technological opportunities, biasing our estimates. Therefore, in columns (iii) and (iv), we instrument for R&D by employing the value of total output as an instrument. While we can only be reasonably rather than perfectly sure that the exclusion restriction is satisfied (in that technological opportunities do not affect the size of the market), it is more than certain that relevance condition is satisfied in that the amount of R&D investment will certainly be affected by the size of the market. This time, both the ratio $\frac{PE_{it}}{RD_{it}}$ and R&D have an economically and statistically meaningful impact on both patent applications and patent grants.

However, even after this refinement, the problem still remains that industrial gross output is not a good instrument because it is correlated with technological opportunities, and so our estimates are biased. This prompts the use the second technique of dealing with endogeneity described in equation (8).

5.3 Accounting for technological opportunities

The basic second approach suggested by Kortum and Lerner to deal with the endogeneity problem is to use the fact that conditional on the ratio of private equity to industrial R&D and the expected value of the innovation, the patent-R&D ratio does not depend on technological opportunities (as N_{it} is not present in equation (8)). Using our original linearization procedure around $\frac{PE}{RD} = 0$, we obtain

$$\ln P_{it} - \ln R_{it} = b\frac{PE_{it}}{RD_{it}} - \ln \Pi_{it} + \ln \epsilon_{it}, \tag{9}$$

with the rest of the terms subsumed by the year dummies. The assumption made here is that the ratio of venture funding to industrial R&D is uncorrelated with shocks to the expected value of invention. While in the original US study, which used industry variation, this is more problematic, as different industries have natural characteristics which affects the extent to which innovation is pursued in a VC-backed entrepreneur setting or an industrial R&D setting, we use aggregates which will tend to diminish this problem via industrial diversification.

In Table 8, we report the estimates of this model, as well as the differenced model in the spirit of Table 6. This time, the evidence points strongly to the fact that while private equity finance has an effect on innovation as measured by ultimately successful patent applications to the USPTO, there is no effect to speak of in the case of patent applications to the EPO. There are two ways to interpret this fact. The first is that different classes of inventions are submitted for commercial recognition to the EPO and to the USPTO. The second is that private equity has no effect on the volume of innovative activity, but it has an effect on the quality of this activity. There is nothing we can do about the first concern, absent matching the same patents across patent offices. And if he second explanation is true, it will eliminate any concern about cherry-picking by private equity firms and it would rather imply that either venture capitalists are better in detecting commercially successful innovation. This is consistent with Hellman and Puri's (2000) finding in a sample of 149 firms in the computer, telecommunications, medical and semiconductor industries that firms which pursue an innovation strategy are more likely to obtain venture funding than firms which pursue an imitation strategy.

6 Robustness tests

6.1 Accounting for the country-level determinants of innovation

The first contribution of our paper is to use two types of data on patent activity in order to distinguish between innovation and successful innovation. The second is to use a cross-country setting which enables us to explicitly account for other dynamic characteristics of the country's business environment, apart from the different types of finance, that affect innovative activity. Recent empirical studies like Furman et al. (2002) and Kanwar and Evenson (2003) have highlighted human capital, GDP, and patent protection as empirically important country-level determinants of innovation. Human capital can be thought of as the pool of initial ideas which innovative effort draws from, and so it will be complementary to both types of innovation finance. GDP per capita can be thought to capture other unobservables like demand which will affect the value of innovation Π_{it} as the same new commercial product will bring a higher return in a richer country. Finally, patent protection will also affect the return Π_{it}: we could think that intellectual piracy acts as a tax $\tau > 0$ on the value of the final product, and so the true value of innovation is $(1-\tau)\Pi_{it}$. Patent protection will work to decrease the value of τ.

As we have established that the effect of private equity investment is reliably strong only in the case of ultimately successful patent applications to the USPTO, we focus on patent grants only. Table 9 presents the empirical estimates of our various models previously estimated in Tables 5(ii), 6(iv) and 7(iv), where we have added the logarithm of GDP per capita, the share of the population with tertiary education, and the index of patent protection in the respective country and year (see Appendix 1 for data sources)[14]. In all three cases, we still record economically and statistically meaningful effect of private equity finance on innovation, albeit the magnitude is somewhat diminished relative to the previous estimations. All controls have the expected positive sign, and the estimates of the effects of GDP per capita and patent protection are also statistically meaningful.

6.2 Evidence from the European biotech industry

The biotech sector is generally taken to be the representative example of a dynamic fast growing research-intensive high-tech industry which lives off innovation and of the commercialization of applied sciences. For example, 55% of biotech companies in Europe are less than 5 years old, the rate of new business incorporation is 14% on average, 44% of biotech employees in Europe are actively involved in R&D, and the industry spent 7.5 bln euros on R&D in 2004, or around 80,000 euros per employee, making it one of the most R&D intensive sectors in Europe (see "Biotechnology in Europe" 2006 Comparative Study: Critical I Comparative Study for Europe Bio). This industry presents an opportunity to investigate whether the measured effects in the aggregated regressions haven't been contaminated by the inclusion of too many industries with low innovative potential.

The reason we choose to focus on the biotech industry, besides its obvious relevance as a classic example of an industry thriving on the commercialization of scientific output, is that this is the only industry for which data from EVCA can be matched to data from the EPO and USPTO without measurement error. SIC codes in general fall under at least two of the other 16 industrial classes used by EVCA which precludes us from matching classes completely. In the case of biotechnology, the classification match is automatic, that is, the class called by EVCA "biotechnology" is

[14] The data on patent protection is only available until 2001.

matched uniquely to a single IPC class used by the EPO and the USPTO and called "Biochemistry; beer; spirits; wine; vinegar; microbiology; enzymology; mutation or genetic engineering". However, data on R&D by industrial classes is not that easily matched to the EVCA class. We use R&D data on food and beverages, chemicals, other business activities, and R&D, which comprises between 70% and 90% of the total R&D activity of biotech firms.[15] Of course, this match is not perfect and therefore our results should be taken with a grain of salt. Finally, similar to Popov and Roosenboom (2008), we recalculate private equity investment in biotech from country of management to country of destination by assuming that the gap between the two is proportionate to the gap that exists between the two measures at the total PE level.

We report the estimates in Table 10. In the OLS and IV case (repeating our previous estimations from table 5(ii) and 7(ii), we get very large and statistically meaningful estimates for the impact of private equity investment on patents granted. In fact, the implied average b from the two regressions equals 9.05, implying that private equity is 9 times more effective than in-house R&D effort, which is in the neighbourhood of the effect measured by Kortum and Lerner. We do a robustness check in the spirit of Table 8 to account for the effect of unobservable technological opportunities, and we still find a large and statistically meaningful result of biotech private equity investment on ultimately successful biotech patent applications.

[15] See, for example, Bloch (2004).

7 Conclusion

This paper examines the impact of private equity investment on technological innovation. To our knowledge, it represents the first study to use both country and industry data to this end. The pattern of ultimately successful patterns over a period of 15 years suggests that there is a both economically and statistically significant effect. The results are robust to different specifications of the patent production functions, as well as to different sub-samples of countries and to controlling for the range of standard determinants of patenting activity suggested by prior literature.

Our estimates of b (the impact of an euro of private equity finance relative to a euro of industrial R&D) are generally positive and significant, but they tend to vary depending on the specification used. Averaging across different estimations, we come up with an average estimate of b of 2.6. The mean ratio of private equity disbursements to total disbursements (private equity plus industrial R&D) between 1991 and 2004 was 8%. Using these two averages, we calculate that private equity accounts for as little as 8% and much as 18% of industrial innovation since the early 1990s.[16] Our estimates thus imply that European risk capital markets are somewhat less efficient than their US counterparts in spurring innovation: for comparison, Kortum and Lerner (2000) find that venture capital accounted for 8% of industrial innovation between 1965 and 1992, while accounting for less than 3% of industrial R&D. However, this may not necessarily be due to a less effective private equity market, but rather to more stringent employment practices, less developed exit markets, stricter regulatory policies, and Europe's still rudimentary knowledge networks. While the European private equity and venture capital industry has developed rapidly in recent

[16] As in Kortum and Lerner (2000), we average the values of b implied by the coefficients from the linearized regressions with $\rho = 1$ in the robustness tests (Table 9 (i)-(iii)). The ratio of private equity to R&D (V/R) is an average over the years 1991-2004. Our calculation of the share of innovation due to private equity is $b(V/R)/(1 + b(V/R))$. The lower bound is obtained by not including the largest estimate (the one from column (ii)).

years, with some countries surpassing the US in terms of share of the industry's share of GDP, labor market reforms have been slow and the deregulation of investment activity by large institutional investors like pension funds and insurance companies has only recently been enacted. Such reforms can most probably greatly boost Europe's innovative potential.

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Table 1. Aggregate Private Equity Disbursements and Industrial R&D Expenditures for 21 European Countries, by 5-year periods

Country	Private equity investment			Industrial R&D			PE investment/Industrial R&D		
	1991-1995	1996-2000	2001-2004	1991-1995	1996-2000	2001-2004	1991-1995	1996-2000	2001-2004
Austria	1.35	108.20	135.73	2,285.68	2,990.96	3,684.96	0.00	0.03	0.04
Belgium	147.44	286.33	525.30	2,982.19	3,774.50	4,239.49	0.05	0.07	0.12
Czech Republic		25.71	15.13	280.45	297.50	408.12		0.08	0.04
Denmark	37.77	192.73	382.48	2,036.57	2,806.88	3,658.97	0.02	0.07	0.10
Finland	30.94	251.01	369.47	1,842.64	3,074.57	4,094.45	0.02	0.08	0.09
France	842.22	2,034.16	4,240.03	24,612.35	25,654.19	28,594.53	0.03	0.08	0.15
Germany	632.68	1,862.16	3,042.50	35,839.71	38,166.88	42,299.31	0.02	0.05	0.07
Greece	22.93	42.51	45.96	274.18	350.66	426.07	0.08	0.13	0.11
Hungary		9.37	12.52	165.38	80.39	121.21		0.12	0.11
Iceland	0.95	25.02	8.19	67.14	133.40	179.54	0.01	0.14	0.04
Ireland	49.51	189.79	202.97	478.42	834.87	1,117.40	0.11	0.22	0.18
Italy	285.08	1,002.76	1,856.43	9,154.30	8,567.31	10,020.21	0.03	0.11	0.18
Netherlands	252.51	766.09	1,536.90	5,127.27	5,978.39	6,222.43	0.05	0.13	0.25
Norway	56.36	199.14	246.02	1,658.41	2,054.08	2,559.26	0.03	0.09	0.10
Poland		18.16	17.40	257.24	194.85	175.44		0.09	0.10
Portugal	47.95	82.16	89.01	380.77	506.99	654.63	0.13	0.15	0.14
Slovakia		5.23	12.55	108.28	76.51	54.77		0.08	0.23
Spain	112.28	440.02	1,024.70	3,382.16	3,560.85	5,085.65	0.03	0.12	0.20
Sweden	68.35	649.76	1,337.75	5,386.19	7,202.32	8,731.04	0.01	0.09	0.15
Switzerland	64.47	204.40	346.55	5,065.59	5,882.19	6,808.01	0.01	0.03	0.05
UK	1,053.61	4,829.29	5,581.18	16,104.32	19,635.73	23,763.00	0.07	0.23	0.24

Notes: All euro figures are in millions of 1991 euros. The ratio of PE disbursements to industrial R&D is computed using all venture capital and buyout disbursements. Data for the Czech Republic, Hungary, Poland, and Slovakia is available starting in 1998, and data on Iceland is available up to 2002.

Table 2. Patent Applications to the EPO and Patents Granted by the USPTO for 21 European Countries, by 5-year periods

Country	Patent applications			Patents granted	
	1991-1995	1996-2000	2001-2004	1991-1995	1996-2001
Austria	658.40	986.64	1,286.27	397.96	580.79
Belgium	731.96	1,158.03	1,291.09	562.27	749.97
Czech Republic	16.71	53.83	94.45	22.43	36.05
Denmark	431.28	755.77	943.47	332.27	503.30
Finland	585.93	1,164.06	1,291.13	532.99	892.11
France	4,899.94	6,607.79	7,589.38	3,374.27	4,256.48
Germany	12,055.21	19,152.81	21,732.90	8,171.09	11,883.20
Greece	26.73	51.17	73.37	14.42	24.87
Hungary	50.44	86.21	121.66	44.31	59.31
Iceland	8.25	24.61	27.73	5.28	22.04
Ireland	78.13	170.71	231.96	75.87	153.91
Italy	2,317.04	3,419.69	4,209.35	1,372.04	1,835.15
Netherlands	1,530.07	2,686.01	3,535.62	1,023.72	1,467.83
Norway	192.60	334.34	355.76	177.82	277.81
Poland	16.69	32.19	90.02	16.42	27.19
Portugal	13.44	29.42	47.96	6.64	12.63
Slovakia	5.97	11.93	21.38	5.61	6.26
Spain	351.25	631.70	961.50	199.33	319.78
Sweden	1,195.03	2,076.17	2,029.02	1,053.21	1,714.83
Switzerland	1,687.39	2,317.91	2,734.44	1,221.15	1,463.02
UK	3,570.44	5,104.59	5,335.73	3,024.66	4,018.45

Notes: Patent applications refer to applications by host countries to the European Patent Office. Patent granted refers to ultimately successful patent applications by host countries to the United States Patent and Trademark Office.

Table 3

Ordinary least squares regression analysis of the patent production function ($\rho \rightarrow 0$ case). The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable is the logarithm of the number of patent applications filed/granted in the respective country and year. The independent variables are in each case the logarithm of government and industrial R&D investment in the respective year and country (in millions of 1991 euros), as well as the logarithm of private equity finance in the respective year and country (in millions of 1991 euros). All regressions include dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	PE investment		High R&D countries only		Excluding transitional economies	
	(i)	(ii)	(iii)	(iv)	(v)	(vi)
	Patent applications	Patent grants	Patent applications	Patent grants	Patent applications	Patent grants
Private equity finance	0.002	0.035	0.028	0.049	0.018	0.053
	(0.016)	(0.020)*	(0.015)*	(0.023)**	(0.012)*	(0.021)***
Industrial R&D	0.093	0.370	0.255	0.644	0.220	0.366
	(0.123)	(0.166)*	(0.120)**	(0.201)***	(0.099)**	(0.159)***
Government-funded R&D	0.375	0.533	0.441	0.403	0.434	0.522
	(0.102)***	(0.146)***	(0.107)***	(0.164)***	(0.081)***	(0.138)***
Number of observations	250	192	151	151	233	184

Table 4

Non-linear least squares regression analysis of the patent production function. The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable is the logarithm of the number of patent applications filed/granted in the respective country and year. The specification we estimate in columns (i) and (iv) is $\ln(P_{it}) = \frac{\alpha}{\rho}\ln(RD^{\rho}{}_{it} + bPE^{\rho}{}_{it}) + controls + \varepsilon_{it}$, where R_{it} denotes industrial R&D investment in country *i* and year *t* (in millions of 1991 euros), and PE_{it} denotes private equity finance in country *i* and year *t* (in millions of 1991 euros). The control variables in each case is the logarithm of government funded R&D. In the regressions in columns (ii) and (v) we use the same specification, but constrain the PE parameter to be zero. In the regressions in columns (iii) and (vi) we use the same specification, but constrain the substitution parameter to be zero, and so we estimate the model $\ln(P_{it}) = \frac{\alpha}{(1+b)}\ln(RD_{it}) + \frac{\alpha b}{(1+b)}\ln(PE_{it}) + controls + \varepsilon_{it}$.

All regressions include dummy variables for each country and year (coefficients not reported). Standard errors are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	PE investment					
	Patent applications			Patent grants		
	(i) Unconstrained	(ii) $b=0$	(iii) $\rho \to 0$	(iv) Unconstrained	(v) $b=0$	(vi) $\rho \to 0$
Returns to scale parameter (α)	1.204	0.339	0.199	0.304	0.244	0.960
	(0.082)***	(0.006)	(0.066)***	(0.016)***	(0.004)***	(0.067)***
Private equity finance (b)	0.068	0.000	7.321	0.132	0.000	0.045
	(0.019)***	---	(20.498)	(0.049)***	---	(0.020)**
Substitution parameter (ρ)	0.408	0.276	0.000	0.401	0.289	0.000
	(0.120)***	(3.781)	---	(0.264)	(0.326)	---
Government-funded R&D	-0.012	0.508	0.262	-0.028	-0.196	-0.115
	(0.002)***	(0.220)**	(0.101)	(0.002)***	(0.016)***	(0.010)***
Number of observations	233	249	233	184	198	184
R	0.98	0.98	0.98	0.98	0.98	0.98
R relative to dummy variable only test	0.54			0.64		

Table 5

Ordinary least squares regression analysis of the patent production function (linear approximation to $\rho = 1$ case). The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable is the logarithm of the number of patent applications filed/granted in the respective country and year. The independent variables are in each case the logarithm of government and industrial R&D investment in the respective year and country (in millions of 1991 euros), as well as the logarithm of the ratio of private equity finance in the respective year and country to industrial R&D investment (both in millions of 1991 euros). All regressions include dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	PE investment		High R&D countries only	
	(i)	(ii)	(iii)	(iv)
	Patent applications	Patent grants	Patent applications	Patent grants
Private equity finance /	0.234	0.589	0.260	0.409
Industrial R&D (αb)	(0.138)*	(0.257)**	(0.262)	(0.464)
Industrial R&D (α)	0.272	0.488	0.418	0.721
	(0.094)**	(0.151)***	(0.126)***	(0.222)***
Government-funded R&D	0.397	0.422	0.376	0.386
	(0.078)***	(0.135)***	(0.114)***	(0.183)**
Number of observations	233	184	123	98

Table 6

Difference regression analysis of the patent production function ($\rho \to 0$ and linear approximation to $\rho = 1$ case). The sample consists of differenced observations at four intervals covering 1991 and 2004 (1991-1994, 1995-1998, 1999-2001, and 2002-2004). The dependant variable the difference between the 2002-2004 and 1995-1998 and between the 1995-1998 and the 1991-1994 averages of the logarithm of the number of patent applications filed/granted in the respective country and the respective period average. The independent variables are in each case the differences between the above interval averages of the logarithm of government and industrial R&D investment in the respective country (in millions of 1991 euros), as well as the logarithm of private equity finance in the respective country (columns (i) and (ii)) and the ratio of the logarithm of private equity finance and the logarithm of industrial R&D inevstment (column (iii) and (iv)), in millions of 1991 euros. In the first and second column, we employ the specification used in table 3 **(** $\rho \to 0$**)**; in the third and fourth column we employ the linear approximation to the non-linear regression estimated in Table 5 (the $\rho = 1$ approximation). All regressions include dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	$\rho \to 0$ case		Approximation to $\rho = 1$ case	
	(i) Patent applications	(ii) Patent grants	(iii) Patent applications	(iv) Patent grants
Private equity finance	-0.018 (0.042)	0.065 (0.037)*		
Private equity finance / Industrial R&D (αb)			0.062 (0.029)*	0.252 (0.056)***
Industrial R&D (α)	0.607 (0.287)**	0.303 (0.508)	0.195 (0.112)*	0.245 (0.143)*
Government-funded R&D	0.396 (0.181)**	0.272 (0.406)	0.069 (0.149)	0.309 (0.201)*
Number of observations	34	34	34	34

Table 7

Instrumental variables (IV) regression analysis of the patent production function (linear approximation to $\rho = 1$ case). The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable is the logarithm of the number of patent applications filed/granted in the respective country and year. The independent variables are in each case the logarithm of government and industrial R&D investment in the respective year and country (in millions of 1991 euros), as well as the logarithm of the ratio of private equity finance in the respective year and country to industrial R&D investment (both in millions of 1991 euros). For the ratio PE/R&D, we employ as an instrument a variable that equals zero if the observation is before the year in which pension funds or insurance companies were encouraged to invest in PE (or a formal ban on their investing in PE was lifted), and otherwise equals the average value in the pre-ban period of the ratio of PE investment divided by industrial R&D spending in the biotech industry. We also use gross output (in millions of 1991 euros) as an instrumental variable for industrial R&D. All regressions include dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	Instrumenting for PE		Instrumenting for PE and R&D	
	(i) Patent applications	(ii) Patent grants	(iii) Patent applications	(iv) Patent grants
Private equity finance/	1.293	2.611	3.739	4.419
Industrial R&D (αb)	(3.427)	(2.465)	(1.918)**	(1.909)**
Industrial R&D (α)	0.109	0.480	0.451	0.422
	(0.262)	(0.226)**	(0.231)**	(0.244)*
Government-funded R&D	0.328	0.412	0.281	0.226
	(0.099)***	(0.184)**	(0.151)*	(0.207)
Number of observations	233	184	233	184

Table 8

Ordinary least squares regression analysis of the patent-R&D ratio. The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable in regressions (i), (ii), (vii) and (viii) is the logarithm of the number of patent applications filed/granted minus industrial R&D investment (in millions of 1991 euros) in the respective year and country. The dependant variable in regressions (iii) and (iv) is the logarithm of the number of patent applications filed/granted minus the difference between industrial R&D investment (in millions of 1991 euros) and gross output (in millions of 1991 euros) in the respective year and country. The dependant variable in regressions (v) and (vi) is the differences between the 5-year averages of the logarithm of the number of patent applications filed/granted minus industrial R&D investment in biotechnology (in millions of 1991 euros), where the differences are taken over the same period as in Table 6. The independent variables is in each case the logarithm of private equity finance (in millions of 1991 euros) minus the logarithm of industrial R&D spending in the biotech industry (in millions of 1991 euros) in the respective country and year (columns (i), (ii), (v) and (vi)) or averaged time period (columns (iii) and (iv)). Regressions (i), (ii), (v) and (vi) employ dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	Levels regressions, Dep. Var. $\ln P_{it} - \ln RD_{it}$		Levels regressions, Dep. Var. $\ln P_{it} - (\ln RD_{it} - Y_{it})$		Difference regressions		High-R&D countries only	
	(i) Patent applications	(ii) Patent grants	(iii) Patent applications	(iv) Patent grants	(v) Patent applications	(vi) Patent grants	(vii) Patent applications	(viii) Patent grants
Private equity finance /	-0.002	0.047	-0.037	0.036	-0.039	0.056	0.002	0.033
Industrial R&D (b)	(0.014)	(0.019)**	(0.018)*	(0.022)*	(0.029)	(0.032)*	(0.017)	(0.020)*
Number of observations	234	184	234	184	34	32	124	99

Table 9

Robustness tests (linear approximation to $\rho = 1$ case). The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable is the logarithm of the number of patent applications filed/granted in the respective country and year (columns (i) and (iii)) and the difference between the 2002-2004 and 1995-1998 and between the 1995-1998 and the 1991-1994 averages of the logarithm of the number of patent applications filed/granted in the respective country and the respective period average (column (ii)). The independent variables are in each case the logarithm of government and industrial R&D investment in the respective year and country (in millions of 1991 euros), the logarithm of gdp per capita in the respective country and year, the logarithm of the average years of schooling in the respective country and year , and the logarithm of the Park-Ginarte index of patent protection in the respective country and year, as well as the logarithm of the ratio of private equity finance in the respective year and country to industrial R&D investment (both in millions of 1991 euros). All regressions include dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	PE investment		
	OLS	Difference regression	IV
	(i) Patent grants	(ii) Patent grants	(iii) Patent grants
Private equity finance /	0.500	0.253	5.303
Industrial R&D (αb)	(0.257)**	(0.049)***	(2.629)**
Industrial R&D (α)	0.490	0.251	0.886
	(0.156)***	(0.285)	(0.941)
Government-funded R&D	0.289	0.397	0.580
	(0.157)*	(0.249)*	(0.272)**
Log GDP per capita	0.473	0.572	0.562
	(0.187)**	(0.560)	(0.238)**
Years of schooling	0.084	0.795	0.178
	(0.457)	(0.719)	(0.589)
Patent protection	0.005	3.615	1.466
	(0.476)	(1.086)***	(0.879)*
Number of observations	184	34	184

Table 10

Robustness tests (linear approximation to $\rho = 1$ case): evidence from the biotech industry. The sample consists of annual observations between 1991 and 2004 of the aggregated economy. The dependant variable is the logarithm of the number of patent applications filed/granted in the respective country and year (columns (i) and (iii)) and the logarithm of the number of patent applications filed/granted minus industrial R&D investment (in millions of 1991 euros) in the respective year and country (column (ii)). The independent variables are in each case the logarithm of government and industrial R&D investment in the respective year and country (in millions of 1991 euros), the logarithm of gdp per capita in the respective country and year, the logarithm of the average years of schooling in the respective country and year , and the logarithm of the Park-Ginarte index of patent protection in the respective country and year, as well as the logarithm of the ratio of private equity finance in the respective year and country to industrial R&D investment (both in millions of 1991 euros). All regressions include dummy variables for each country and year (coefficients not reported). Standard errors adjusted for heteroskedasticity are reported in brackets. *** denotes significance at the 1%, ** at the 5%, and * at the 10% level.

	PE investment		
	OLS	Levels regressions, Dep. Var. $\ln P_{it} - \ln RD_{it}$	IV
	(i) Patent grants	(ii) Patent grants	(iii) Patent grants
Private equity finance /	6.798	14.596	6.969
Industrial R&D (αb)	(3.255)**	(4.860)***	(1.667)***
Industrial R&D (α)	0.454	---	1.998
	(0.216)**		(0.582)***
Number of observations	158	158	158

Appendix 1. Data sources

Patent applications:	European Patent Office (EPO). From 1991 to 2004
Patent grants:	United States Patent and Trademark Office (OSPTO). From 1991-2001
Industrial R&D:	Eurostat. From 1991 to 2004
Government R&D:	Eurostat. From 1991 to 2004
Private equity investment:	European Private Equity and Venture Capital Association (EVCA) yearbooks. From 1991 to 2004
Gross output:	STAN industrial database. From 1991 to 2004
GDP:	Eurostat. From 1991 to 2004
Years of teritary schooling:	World Bank Development Indicators. From 1991 to 2004
Patent protection:	Park and Wagh (2002). From 1991 to 2001.

Appendix 12. Changes in prudential rules concerning the investment behavior of institutional investors.

Country	Pension funds	Insurance companies
Austria		
Belgium		
Czech Republic		
Denmark	2005	
Finland	1995	
France		1998
Germany		
Greece		
Hungary	1998	
Iceland		
Ireland	1993	
Italy	1993	
Netherlands	1993	1993
Norway		
Poland	2001	2001
Portugal		
Slovakia	2004	
Spain	2004	2007
Sweden		
Switzerland	2000	
UK	pre-1991	pre-1991