Determinants of R&D and Its Productivity: Identifying Demand and Supply Channels (First revision)

Sadao Nagaoka

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Institute of Innovation Research
Hitotsubashi University

Tokyo, Japan
http://www.iir.hit-u.ac.jp

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Summary

Identifying whether an exogenous factor affects R&D from a demand side or from a supply side is an important issue. This paper, first, theoretically shows that a favorable change in either side can reduce the R&D productivity in equilibrium, so that the reduced form estimation cannot provide a clear identification. Secondly, it estimates both structural and reduced form patent production functions, based on instrumental variables approach, using a large database on Japanese firms. According to the estimation, while the initial firm size, market concentration or export orientation increases R&D, none of them significantly shifts the structural patent production function.

Key words: R&D productivity; patent; firm size; competition
JEL classification: O31, O34, L11

*) Sadao Nagaoka, Institute of Innovation Research, Hitotsubashi University, 2-1 Naka Kunitachi Tokyo 186 Japan. Fax 81-425-77-2495, Email nagaoka@iir.hit-u.ac.jp

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I Introduction

There exist supply and demand side channels through which an exogenous factor affects research and development (R&D) of a firm. We define the channel in which the marginal revenue from a given technology is affected as a demand side channel[i] and that in which the marginal cost of technology production is affected as a supply side channel. A large firm may do more R&D since its ability to appropriate the benefit of R&D is high. It may also do more R&D due to the availability of a larger firm-specific knowledge stock[ii]. Similarly, export opportunities enhance appropriability of R&D for a firm, but it may also enhance R&D by facilitating international technology spillover[iii].A similar point may also apply to the effects of market structure. Competitive market structure may affect the demand by a firm for R&D by strengthening its strategic motivation, by reducing the replacement effect or by reducing the appropriability of R&D[iv]. It may also affect R&D from a supply-side by influencing R&D efficiency (see Nelson and Winter (1982)).

This paper aims at identifying the channels by which such factors as firm size affect R&D and its productivity. While firm size, market structure as well as export orientation of a firm are partially endogenous variables with respect to R&D, we attempt to control these endogeneity by using an instrumental variable (the age of a firm as an instrument for the initial firm size) and by introducing three-digit industry dummies. In addition we focus here on the effects of the levels of these causal variables in the beginning of the period on the flow R&D expenditure and its output in that period, as much of existing empirical literature does[v]. The identification of demand and supply channels is important both for public policy and for management strategy. As pointed out by Cohen and Klepper (1996), lower (average) R&D productivity of a large firm does not necessarily imply that it is less efficient in R&D than a small firm. It may only reflect the combination of an appropriability advantage of such firm, i.e. its stronger capability of making profit by commercializing a given technology, and a deceasing return of R&D investment. With respect to a policy choice, if export opportunities affect R&D primarily through a demand side channel, export subsidy will be hard to be justified globally, since it will become a zero-sum game from a global perspective.

A standard productivity analysis may suggest the following identification approach, assuming that a R&D performing firm recovers the cost of R&D primarily through internal manufacturing. If an exogenous R&D determinant is found to increase the R&D output but to reduce the R&D productivity, we may identify that with a positive demand side change. On the other hand, if it is found to increase both the R&D output and the R&D productivity, we may identify that with a positive supply side change. However, such approach is based on a wrong theoretical basis, since improved technological opportunities for R&D can actually cause the equilibrium R&D productivity to decline, as shown in this paper. Consequently, a reduced form estimation of R&D productivity equation, which is used in most existing empirical studies, cannot provide a definitive conclusion on the identification.

Given this theoretical result, we directly estimate a structural patent equation, using an instrumental variable approach. The comparison with the results of reduced form estimation would enable us to distinguish the direct effects of, for an example, market structure on patent production from its indirect effect through its effect on the level of R&D. We use corporate debt (relative to the total asset size) and the advertising expenditure (relative to the total sales) as instruments for R&D investment in the structural patent equation, since they do not directly affect technological opportunities faced by a firm. Thus, if market structure does not shift the structural patent production function, we can rule out the supply side channel in its effect. In addition, if market structure is found to affect patent production in its reduced form, we may conclude that it affects R&D only from the demand side.

The rest of the paper is organized as follows. Section two reviews briefly the existing work. Section three presents an analytical framework and theoretical results. Section four describes the empirical framework and the data used in the estimation. Section five presents estimation results. Section six concludes.

II Existing literature

There exists a large volume of empirical work on the determinants of R&D, especially focusing on the relationship between R&D on the one hand and firm size and market structure on the other, substantially stimulated by the writings of Schumpeter (1942)[vi]. According to Cohen (1995), there are three stylized empirical facts established from these works[vii].

(1) Among R&D performing firms, R&D tends to increase, often proportionately, with firm size in most industries[viii].

(2) R&D average productivity tends to decline with firm size among R&D performing firms.

(3) While R&D intensity tends to be high in industries with higher concentration, inter-industry differences in technological opportunities and demand growth account for most of the variations in R&D intensity.

Recently, theoretical literature has attempted to systematically analyze how a structural model of R&D can contribute to explaining these empirical findings consistently. Cohen and Klepper (1996) have presented a theoretical model emphasizing a demand side or appropriability of R&D, which may consistently explain the above two empirical propositions. In their model a large firm conducts more R&D since it can apply the R&D output for a larger sale, and its R&D productivity is lower due to a declining schedule of average R&D productivity. Klette and Griliches (2000) present a quality ladder model explaining both of the first two propositions as well as the Gibrat's law. In their model, the initial production cost of a firm and interest rate affects its R&D from the demand side, and its efficiency in conducting R&D affects its R&D from the supply side. The level of R&D of a firm has a proportional relationship with its size in their analysis, if the following opposing forces cancel each other out. On the one hand a large firm has a stronger incentive to do R&D since it can gain more from the same amount of R&D due to its larger output size. On the other it faces higher cost of doing R&D due to increasing difficulty in achieving technical progress in the technology frontier.

In the empirical front, however, most studies have relied on reduced form estimation in evaluating the effects of firm size and market structure on R&D and innovations. Acs and Audretsch (1990) provide some evidence for a positive effect of competitive market structure on R&D productivity based on cross-section data of US industries in reduced form estimation. However, they do not control industry fixed effects, so that the causality between innovation and market structure is not clear. Geroski (1990) controls such industry effects in his reduced form estimation of innovation equations, and finds that competitive market structure enhances innovations, based on the panel data of UK industries. Neither of these two studies addresses the question of whether such effect works through demand or supply side.

Cohen and Klepper (1996) in their empirical part have presented evidence showing that the overall firm size has little effect on a firm's R&D once business unit size is controlled for. They interpret this evidence as well as the above first two stylized facts as supporting the cost spreading model or the view that a large firm size provides an appropriability advantage. Although such evidence is useful in rejecting some hypotheses on R&D determinants such as the financial capability of a firm, a firm-wide scope economy or its risk pooling capability, it is not sufficient to determine whether the size of a firm in each business line affects its R&D through appropriability channel or through supply side channel such as the availability of firm specific knowledge. More recently, Blundell et al (1999) shows that a larger market share positively affects innovation, while higher concentration has a negative effect, based on the panel data of the British firms. Again, they depend on a reduced form estimation of innovations equation. Besides, in their analysis the market share variable may have picked up the effect of firm size on R&D, since the capital stock variable introduced as a control variable for firm size is not found to be statistically significant. The study by Henderson and Cockburn (1996) show the existence of economy of scope in R&D, based on the project level data in pharmaceutical industry. While their study is based on the structural patent production function, it does not control the endogeneity of R&D and the other explanatory variables.

III Theoretical analysis

In this section, we analyze how R&D productivity responds to the changes in the exogenous variables on demand and supply sides. We define those factors that affect the marginal revenue from a given technology as demand side factors and those that affect the marginal cost of technology production as supply side factors. We use a standard theoretical model of R&D, based on the assumption that each firm sells a differentiated product and appropriates the return from R&D only through internal manufacturing. We denote the amount of new technology generated by Z which is assumed to be proportional to the number of patents and the R&D investment by rd. Thus, the structural patent production function is given by

$$Z = Z(rd, b) \qquad (1)$$

with b being an efficiency parameter of the patent production function or a supply side factor for R&D ($\partial Z(rd,b)/\partial b>0$). The marginal cost of patent production and the marginal productivity of R&D are given respectively by $MC(Z,b)=\partial(rd)/\partial Z$ and $MZ=\partial Z/\partial(rd)$. We assume that $\partial MC/\partial b<0$.

The value of R&D investment is given by

$$V(Z,q,a,b)=R(Z,q,a)-rd(Z,b) \tag{2}$$

, where $R(Z,q,a)$ represents a gross profit, q is the output of a firm and *a* represents a demand side factor of R&D ($\partial R(Z,q,a)/\partial a>0$). We assume that $\partial^2 R(Z,q,a)/\partial Z\partial a>0$. The profit maximizing Z or a reduced form patent function is given from (2) by

$$Z_R=Z_R(a,b) \tag{3}$$

and the reduced form R&D function is given by

$$rd_R=rd(Z_R(a,b),b)=rd_R(a,b) \tag{4}$$

The total derivative of the marginal (average) productivity of R&D is given from (1) by

$$d(MZ)=\partial^2 Z(rd,b)/\partial(rd)\partial bdb+\partial^2 Z(rd,b)/\partial(rd)^2 d(rd). \tag{5}$$

$$d(AZ)=(\partial AZ/\partial b)db+(MZ-AZ)(d(rd)/(rd)). \tag{6}$$

The first term of both equations is equal to zero for a change in a demand side factor. For a shock increasing the demand for R&D output (and therefore R&D investment *rd*), the second term is negative in the case of declining marginal (average) productivity of R&D[ix]. Thus, we have the following proposition.

Proposition 1

If a patent production function exhibits declining marginal (average) productivity with respect to R&D investment, any positive change increasing the demand for R&D reduces marginal (average) productivity of R&D investment.

Let us turn to a supply side factor for R&D. A favorable supply side change such as an improved technological opportunity increases the marginal productivity of R&D investment for a given level of R&D investment, and it may also increases the level of R&D. Since the latter effect reduces the marginal R&D productivity, the net effect on productivity depends on which of the two effects is stronger. As shown below, the marginal productivity in equilibrium can decline, due to the dominance of the investment effect (see Appendix 1 for a formal proof).

Let us consider the case of cost-reducing innovation. We postulate that R&D investment reduces the (constant) marginal cost of production of the firm by the amount of Z (or the number of patents), that is, there is no diminishing return in the technical effect of a patent, although there is a diminishing return in patent production. A firm chooses Z and the output level q to maximize its profit. Let us consider the effects of the downward shift of the MC curve of a patent production (from *b’* to *b”* in Figure 1). The marginal revenue (MR) of Z is constant for a given q, as illustrated by the flat MR(Z,q) curve in Figure 1. As a result, the downward shift of the MC curve does not reduce the marginal cost of patent production in the equilibrium, for a given output q (compare the point A and the point B). In addition, larger Z causes the expansion of q (from q’ to q”), since it reduces the marginal cost of production and the profit-maximizing level of output. Consequently, the MR curve shifts up, as shown in Figure 1. Thus, a favorable supply side change increases the equilibrium MC of a patent production (compare the point A and the point C in Figure1).

(Figure 1)

Higher efficiency of product innovation can also reduce the marginal productivity of R&D in the equilibrium, when a firm can introduce a new product complementary to the existing products. In this case the MR curve can be upward-sloping, since introduction of a new product enhances the demand for the other products and expands the scope of complementarity, as shown in Figure 2. In addition, the expansion of the portfolio of products causes the expansion of the supply of existing products ($q''>q$), which in turn can enhance the marginal revenue from innovations. Thus, a favorable supply side change increases the equilibrium MC of a patent production in the case of product innovation too. Thus, we have the following proposition.

(Figure 2)

Proposition 2

A favorable supply side change shifting up the marginal productivity schedule of R&D can reduce the marginal productivity of R&D in equilibrium.

(See Appendix 1 for a formal proof)

If we assume that marginal and average productivities move in the same direction[x], the proposition 2 holds for the average productivity of R&D as well. If R&D output and its marginal productivity move in the same direction, it does indicate that a supply side factor is involved. However, the fact that they move in the opposite direction does not indicate that the source of variation is on the demand side. As a result, the sign of the coefficient of a particular exogenous variable in a reduced form R&D productivity equation cannot provide sufficient information with respect to the channel by which such variable works through.

Let us consider the logarithmic linearization of the reduced form patent and R&D equations (3) and (4):

$$dZ_R / Z_R = \alpha da / a + \beta db / b \quad (7)$$

$$d(rd)_R /(rd)_R = \gamma dZ_R / Z_R - \delta db / b = \gamma\alpha da / a + (\gamma\beta - \delta) db / b \quad (8)$$

Here the inverse of the parameter γ indicates the economy of scale in patent production with respect to R&D investment. The comparison of equations (7) and (8) suggests the following proposition, which would help interpreting the econometric results and identification.

Proposition 3

Assume that a logarithmic linearization gives a good approximation of reduced form R&D and patent equations. If there is a slight diseconomy of scale ($\gamma = 1 + \rho, 0 < \rho << 1$), the demand side factor has a larger coefficient in R&D equation and the supply side factor has a larger coefficient in patent equation.

IV Framework for empirical analysis

IV (i). Statistical Specification

We estimate reduced-form R&D and patent functions (equations (3) and (4)) as well as the structural patent production function (equation (1)). The comparison of the structural and reduced form equations helps us identify the channel by which a specific determinant of R&D works through. The supply side factors affect the patent equation (1) directly, while the demand side factors affect the patent production only through their effects on R&D investment. Thus, if a factor is found to be significant only in equations (3) and (4) but not in equation (1), we can infer that it works only from the demand side[xi]. We use instrumental variables approach to control the endogeneity of independent variables such as the initial firm size and R&D investment. While we control industry fixed effects, we will not directly control firm-level fixed effects due to our data constraint, in particular, with respect to the available time period of data (see Appendix 2 for the explanations of data sources).

The R&D and patent reduced form equations are specified for firm j in industry J as follows:

$$(\log R\&D_j) or (\log Z_j) = d + \delta a_j + \varphi\, b_j + d_{IND} + \mu_j\,. \qquad (9)$$

The independent variable a_j stands for a set of demand side factors of firm j. The variable b_j stands for a set of supply side factors. We use the initial firm size as represented by its sales ($s0$) , the HHI index, export sales ratio ($exp0$) , advertising sales ratio ($advs0$) and debt asset ratio ($da0$) as firm-level variables (a_j or b_j) (The list of all variables are given in Table 1). We do not know a priori whether the initial firm size, for an example, belongs to a_j , b_j or both. It may have a positive effect on R&D by enhancing the appropriability of its R&D investment, to the extent that it represents the size of assets complementary to R&D or the initial production cost level. It may also promote R&D from a supply side, to the extent that it represents the size of larger knowledge stock specific to a firm.

(Table 1)

We specify the HHI index of a multi-product firm as a weighted average index of its HHI in each industry, with its sales in each industry as a weight. Since many firms operate in more than one industry, a firm in the same industry faces a different overall market structure[xii]. Such variation allows us to identify the effect of market structure, even if we use only cross-section data and use industry dummies at three digit level (77 or 78 industry dummies). The set of d_{ind} represents industry dummies, controlling both technological opportunities, demand growth rates, patenting propensities and the other industry-level factors. Finally μ_j is a firm specific error term (either demand or supply side) , such as management or R&D capability, which are unaccounted for by an initial firm size and the other firm level explanatory variables .

It is very likely that there a positive correlation between a firm specific error term μ_j and the initial firm size. Such correlation can cause a spurious positive correlation between the initial firm size and the production of patents or R&D. In order to address this, we use the age of a firm (*age*) as an instrument for the initial firm size. It is well-known that firm age has a systematic correlation with the size of a firm. On the other hand, age is likely to be far less correlated with a firm specific error term than the initial firm size. Although there may exist experience effects in management and R&D, the stylized fact that an older firm statistically performs worse than the average suggests that they may not be very strong. We assume that the instrument and the rest of the explanatory variables are independent of μ_j.

We specify the structural patent production function for firm j in industry J as follows for a given period:

$$\log Z_j = c + \phi \log(rd)_j + \theta \log(rdgr)_j + \beta b_j + c_{IND} + \varepsilon_j . \qquad (10)$$

In this equation, ϕ is the elasticity of patent production with respect to the scale of a firm (not with respect to R&D (*rd*), since we use an intensity form for the explanatory variable of the initial size of a firm). We introduce the growth of R&D investment (*rdgr*) as a variable to control the tendency of underestimating the patent production of a firm with fast growing R&D investment due to the lag between R&D and patent grants. The variable b_j stands for a set of firm-level supply side factors: the logarithm of the ratio between the initial size of a firm (sales or asset level) and R&D investment (*s0rd* or *asset0rd*), its export orientation at the beginning of the period (*exp0*), and the HHI index at a firm level (*hhi0*). The elasticity of patent production with respect to R&D is given by $\phi - \beta_{\ln s0rd}$. The variable c_J stands for a set of industry dummies, controlling the differences in technological opportunities and in patenting propensities across industries. ε_j is a firm specific productivity term on the supply side.

Although ε_j is clearly correlated with rd_j, most existing studies have not controlled it, as pointed out by Griliches (1995)[xiii]. We use advertising intensity (*advs0*) and debt asset ratio (*da0*) as instruments for R&D and its growth. Advertising helps a firm to establish its brand, which will in turn help a firm recover the cost of R&D. That is, advertising enhances the appropriability of R&D investment. Similarly, high debt of a firm would increase the opportunity cost of capital for the firm, so that it would negatively affect R&D. On the other hand, both of them would not directly affect the patent production function. We will also use the log of firm age as an instrument for the initial firm size. We will not instrument export ratio, due to the absence of proper instruments. We assume that the rest of b_j as well as the instruments are independent of ε_j.

IV (ii). Sample and data

Our sample is extracted from the compulsory survey on the Japanese firms (the Basic Survey of Business Structure and Activity), based on the conditions that the firm reports positive R&D in all survey years and it has a positive number of registered patents and utility models in 1991 FY and 1999FY. It covers 2069 firms (see Appendix 2 for details). They predominantly belong to manufacturing firms[xiv].

As a measure of R&D output, we use the estimated number of the patents and utility models that each Japanese firm had internally developed and registered with the domestic and foreign patent offices during a eight-year period from the beginning of 1992 FY to the end of 1999 FY. Since the statistical survey from which our data is extracted asks a firm to report only the number of patents and utility models (hereafter, patents) maintained by each firm at the end of the fiscal year, we estimate the number of patents registered during this period, based on the survival data of patents (see the Appendix 2 for a method). Since the patent data covers both domestic and foreign patents, the same invention is counted more than twice[xv] when registered in more than two countries. Since a firm tends to seek foreign patents for an invention with higher quality, given additional costs of foreign patent applications, adding both domestic and foreign patents together is very likely to increase the value of patent counting as an indicator of the research output. In addition, the export ratio of a firm (*exp0*), which we will introduce as one of the explanatory variables in equations (9) and (10), will control the duplicative aspect of foreign patents, if it is important. Thus, the coefficient of the export ratio may reflect both technology spillover from exports and the duplicative effects of foreign patents.

As for R&D input, we use the R&D expenditure used internally within the firm for its own sake, so that our measure of R&D expenditure excludes the R&D expenditure commissioned out by a firm. Such measure of R&D input is consistent with the R&D output defined above. Given a significant time lag between R&D expenditure and patent registration[xvi], we use the average R&D expenditure of a firm for the period from 1991FY to 1997FY (*rd*) and its growth rate in this period (*rdgr*), as the input measures of R&D. The firm with a rapidly growing R&D expenditure would have smaller patent output for a given level of recent R&D expenditures, given the lag between R&D and patents grants as well as due to a lower level of past R&D expenditure. The growth rate of R&D controls this effect. Table 1 provides brief explanations and summary statistics of all variables.

V Estimation results and discussions

We estimated the above equations, using both OLS and instrumental variables method. We used heteroskedasticity-consistent standard errors, specifying a cluster for each of three -digit industries.

V.1 Estimation of reduced form R&D and patent equations

Table 2 shows the results of estimating equation (9). The firm size (*lnsl0*) has a highly positive coefficient both in the R&D and patent equations. The estimated coefficients based on instrumental variables regression (estimation I and III) are very close to one (1.01 for R&D and 1.06 for patent). Thus, there is no sign that the average R&D productivity declines significantly with firm size, unlike the past findings, including Doi (1993) and by Wakasugi et al (1996) on Japanese firms. The difference is due to our use of an instrumental variable for firm size, since the OLS estimation results in a significantly lower coefficient for firm size in the patent production function (1.07 for R&D and 0.93 for patent). Thus, the stylized fact of declining R&D average productivity with firm size can be significantly due to a regression bias.

(Table 2)

One explanation for the above findings is the bias due to the positive correlation between the initial firm size and a supply-side component of a firm specific error term. A firm with higher R&D efficiency is likely to have a large initial firm size (lns0), since such capability is likely to be a long-lasting asset. The bias due to such correlation is larger in the patent equation than in the R&D equation if the return to scale in patent production is close to one.

This is because a supply-side component of an error term has two offsetting effects on R&D (compare equations (7) and (8)). That is, higher R&D capability of a firm reduces R&D investment for a given level of patents, but it also enhances patent production itself.

With respect to the estimation of the coefficients of the other independent variables, we focus on instrumental variables estimation (estimation I and III). HHI index has a significant and positive coefficient for R&D equation, implying that the R&D investment of a firm is high relative to its sales when it operates in more concentrated industries on the average, even controlling for the effects of its size and industries. However, it is not significant in patent equation. Export ratio has a significant and positive coefficient in both R&D and patent equations. We cannot definitely tell whether market concentration and export ratio affect R&D and/or patent production from the demand side or supply side without directing estimating a structural patent equation. However both having a significantly larger elasticity in R&D equation than in patent equation suggests that they work more from the demand side (see Proposition 3)[xvii].

Two instruments for R&D investment in the structural patent equation have expected signs in both estimations I and III. Debt asset ratio is highly significant in both equations. It reduces both R&D and patent production, given the initial firm size and the other explanatory variables, consistent with a theoretical prediction that higher opportunity cost of capital reduces demand for R&D. Advertising sales ratio (advs0) has a significant coefficient only in R&D equation. Its positive sign is consistent with a theoretical prediction that advertising encourages R&D through enhancing the latter's appropriability.

V.2. Estimation of structural patent production function

Table 3 shows the results of the estimation of the structural patent equation (10). We use two measures of the initial firm size: sales and asset. We use age, debt asset ratio, and advertising sales ratio as instruments for R&D, its growth and the initial firm size. The OLS regressions (Estimation I and III) suggest that the initial size of a firm and its export ratio are significant in enhancing patent production (but not market concentration). They also suggest that there is a very strong diminishing return to R&D in patent production. In particular, according to estimation I, the elasticity with respect to the sales over R&D ratio is 0.43 and export sales ratio has the coefficient of 0.97, implying that 10% point increase of export sales ratio results in 10 % point increase of patent productivity. On the other hand, the elasticity of patent production with respect to scale is only 0.47 so that the elasticity with respect to R&D is only 0.04 (=0.47-0.43).

(Table 3)

Instrumental variables regressions (estimation II and IV), however, show a significantly different picture. Neither the initial firm size nor its export orientation enhances its R&D productivity of a firm, while the return to scale in patent production is less than but close to one. In both estimations, we cannot reject the hypothesis that the return to scale is one. In addition, the elasticity with respect to R&D is estimated to be 0.88 (estimation II) and 0.85 (estimation IV), so that the diminishing return with respect to R&D is not very strong, although it is less precisely estimated. On the other hand, we cannot reject the hypothesis that the initial firm size, the HHI index and the initial export orientation have individually zero coefficients. The estimation bias due to the correlation between a firm specific error and the initial firm size would explain the difference between the OLS and instrumental variables estimations.

Since a firm size as represented by its sales is significant only in reduced form equations, we can infer that it affects R&D only from the demand side at its margin. That is, a firm size as represented by its sales or its asset affects positively its R&D only from the demand side by improving its appropriability, but it does not represent a supply side factor such as the firm specific knowledge stock. Similarly, while market concentration and export ratio are significant in the reduced form R&D equation, it is not significant in the structural patent production function. These results indicate that they do not represent the supply side factor, such as the level of technology spillover, but the demand side factor affecting the appropriability from R&D investment.

VI Conclusions

This paper has attempted to identify the channels by which such factors as an initial firm size and market competition affect R&D and its productivity. Main findings are the following. First, it has theoretically shown that, while a favorable demand side change shifting up the marginal revenue curve of R&D reduces the marginal R&D productivity in equilibrium, a favorable supply side change shifting up the marginal productivity curve of R&D can also reduce the marginal R&D productivity in equilibrium in both process and product innovations. This can happen if the induced expansion of R&D investment is large and the diminishing return to R&D exists. This finding implies that the information based on the reduced form estimation of R&D productivity does not provide definitive information on whether an exogenous factor affects a demand or supply side of R&D (more predominantly).

Second, the paper estimated both structural and reduced form patent production function, using instrumental variables approach, based on a large scale database on Japanese firms. Major empirical findings are the following:

(1) None of the initial firm size as represented by sales or assets, market concentration, or export orientation significantly shifts the structural patent production function.

(2) Initial firm size, export orientation and, less significantly, market concentration significantly enhances R&D in a reduced form. Thus, they look to affect R&D mainly from a demand side.

(3) The stylized fact of declining R&D average productivity with firm size can be significantly due to a regression bias (the endogeneity of firm size).

One major constraint of this paper is that it does not fully control firm level fixed effects. This might have caused an estimation bias, especially, in the effects of export orientation. While the limitation of the available data and difficulty of identifying lag structure between R&D and patent grants prevented us from using fixed effect estimation in this exercise, we plan to extend the work in the near future.

Appendix 1. A negative response of R&D productivity to an improved R&D efficiency

The profit of a firm is given by

$$V(Z,q,a,b) = R(Z,q,a) - rd(Z,b) \qquad \text{(a.1)},$$

, and the profit maximizing level of Z and q are given by

$$MR = \partial R / \partial Z(Z,q,a) = MC = \partial rd(Z,b) / \partial Z\,. \qquad \text{(a.2)}$$

, and

$$\partial R / \partial q(Z,q,a) = 0\,. \qquad \text{(a.3)}$$

The responses of the optimal Z and q to b are given by differentiating equations (a.2) and (a.3):

$$\begin{bmatrix} A & B \\ B & C \end{bmatrix} \begin{bmatrix} dZ \\ dq \end{bmatrix} = \begin{bmatrix} Edb \\ 0 \end{bmatrix} \qquad \text{(a.4)}$$

, where

$A = \partial MR / \partial Z - \partial MC / \partial Z$,

$B = \partial MR / \partial q$,

$C = \partial^2 R(Z,q,a,b) / \partial q^2$,

$E = \partial MC(Z,b) / \partial b < 0$.

If we denote the determinant of the above matrix by $D=AC-B^2$, we have the following second order conditions for a profit maximization choice:

$$D>0 \text{ and } A,\ C<0 \qquad \text{(a.5)}$$

The response of MC (or the inverse of marginal R&D productivity) to a supply side change can be assessed by using its equality to MR in the equilibrium:

$$dMR = \partial MR(Z,q,a) / \partial Z dZ + \partial MR(Z,q,a) / \partial q dq \qquad \text{(a.6)}.$$

First, we discuss a case of process innovation. A firm sells its product for price $p(q, u)$, where u represents the factors exogenous to the firm, such as income and market structure. Let us consider a two-period model where a firm invests in R&D in the first period and its output can be commercialized in the second period. The unit cost of production c depends on the number of patents Z, which the firm will be granted for its inventions. Thus, we have

$$R(Z,q,u,r) = [p(q,u) - c(Z)]q/(1+r) \qquad \text{(a.7)},$$

where r is interest rate. The firm chooses Z and q, so as to maximize V. Given the envelope theorem, the marginal revenue of Z is given by $MR(q,r) = (-\partial c/\partial Z)q/(1+r)$, and the optimal level of patent production is given by

$$MR = (-\partial c/\partial Z)q/(1+r) = \partial rd(Z,b)/\partial Z\,. \qquad \text{(a.8)}$$

We assume that a firm can reduce its constant marginal cost of production by Z, according to $c = c_0 - Z$, with c_0 being the initial level of constant marginal cost of production. In this case, marginal revenue of patent production is constant for a given q:

$$MR = (-\partial c/\partial Z)q/(1+r) = q/(1+r)\,. \qquad \text{(a.9)}$$

,as shown in Figure 1 in the main text. MR increases with q, since the firm can apply more widely the knowledge produced by R&D.

The optimal level of q is given by

$$[p(q,u) - (c_0 - Z)] + \{\partial p(q,u)/\partial q\}q = 0\,. \qquad \text{(a.10)}$$

q increases with Z and decreases with c_0, since larger price cost margin encourages a firm to expand supply. The responses of the optimal Z and q to db are given by the solutions of the equation (a.4):

$$dZ=ECdb/D>0 \qquad \text{(a.11)}$$

and

$$dq=-BEdb/D>0, \qquad \text{(a.12)}$$

, since we have $B=\partial MR/\partial q=1/(1+r)$ >0.

From (a.6), the change of MR in response to db is given by

$$dMR=dq/(1+r)>0 \qquad \text{(a.13)}$$

, since we have $\partial MR/\partial Z=0$ from (a.9). Thus, a positive supply side change shifting down the marginal cost schedule of patent production results in the increase of the marginal cost (or the decrease of marginal productivity of R&D) in equilibrium in this case of process innovation. The reason for this result is easily seen from equation (a.9). A larger b invites the increase of q, which in turn enhances the marginal revenue of R&D investment. This leads to the expansion of rd to such an extent that the marginal cost of R&D investment increases.

Second, let us consider the following case of product innovation, where a firm chooses an introduction of a new product complementary to the existing products. The number of products sold by a firm is given by Z, which is equal to the number of patents, and the price of each product ($p(q,Z;u)$) depends on how many products a firm sells in the market, in addition to the amount of the sales of each product (q) and the other exogenous factors as represented by u. We assume that

$$\partial p/\partial Z>0, \qquad \text{(a.14)}$$

due to the complementarity of consumption of the products sold by a firm.

The value of R&D investment is given by

$$V(Z,q)=\{p(q,Z;u)-c\}Zq/(1+r)-k(Z,b) \quad , \qquad \text{(a.15)}$$

, where c is a constant marginal cost of production and r is interest rate. The marginal revenue of inventions is given by

$$MR(Z,q;u,c,r)=\{(\partial p/\partial Z)Z+(p-c)\}q/(1+r)\,, \tag{a.16}$$

MR curve is up-ward sloping with Z, unless p is strongly concave to the origin with respect to Z. That is, we assume that

$$\partial MR(Z,q;u,r)/\partial Z=\{(\partial^2 p/\partial Z^2)Z+2\partial p/\partial Z\}q/(1+r)>0\,. \tag{a.17}$$

The profit-maximizing level of patent production is given by the intersection of the MR and MC curves:

$$MR(Z,q;u,c,r)=MC(Z,b)\,. \tag{a.18}$$

The optimal q is given by a standard profit maximization condition:

$$(\partial p/\partial q)q+(p-c)=0\,. \tag{a.19}$$

With respect to the conditions associated with matrix (a.4), using the condition (a.19), we have

$$B=\partial MR/\partial q=\{\partial p/\partial Z+(\partial^2 p/\partial Z\partial q)q\}Z/(1+r)>0\,, \tag{a.20}$$

, unless $\partial^2 p/\partial Z\partial q$ is significantly negative. We assume that such is the case. Then, we have $\partial Z/\partial b>0$ and $\partial q/\partial b>0$, as in equations (a.11) and (a.12). Consequently, the derivative of MR with respect to db is also positive:

$$dMR=\partial MR(Z,q;u,r)/\partial ZdZ+\partial MR/\partial qdq>0 \qquad \text{(a.21),}$$

from equations (a.17) and (a.20). Given the equality of MC and MR in the equilibrium, a positive supply side change shifting down the marginal cost schedule of patent production causes an increase of the marginal cost in the equilibrium.

Appendix 2. Statistical data

(1) Data source

We use the firm level data from the Basic Survey of Business Structure and Activity (Kigyoukatudou-kihonnchousa) by the Ministry of Economy, Trade and Industry. The Survey has been made for business activities in 1991FY, 1994FY and every year thereafter. It covers all firms with more than 50 engaged workers and with capital more than 30 million Yen in manufacturing, mining, retail and wholesale distribution, and restaurant and drinking places. It is a compulsory survey. Our data is extracted from the database of the Basic Survey, based on the conditions that the firm reports positive R&D investments for all five years (1991FY, 1994FY, 1995FY, 1996FY and 1997FY) and it has a positive number of registered patents and utility models in 1991FY and 1999FY.

(2) Estimates of registered number of patents and utility models

We estimate the number of patents and utility models registered during the period between 1992FY and 1999FY from the data on the stock number of patent and utility models that a firm maintained at the end of the 1991FY and 1999FY. The Japanese Patent Office annually publishes the survival rates of patents and utility models registered domestically for each year in the past. Thus, we can estimate the aggregate age distribution of patents and utility models effective at the end of 1991CY. According to this calculation, for an example, 49% of the effective patents and 57% of effective utility models effective in 1991CY were registered within the preceding 5 years. This profile can be used to estimate how many of the utility and patent models effective at the beginning of 1992FY would have remained effective at the end of 1999FY, or in 8 years later. According to the calculation, 23.9 % of patents had remained effective and 8.3% of utility models had remained effective. Since the number of effective patents was 506 thousands and that of effective utility models was 384 thousands at the end of 1991CY, the average survival rate is estimated to be 17.2%. Thus, the number of patents and utility models registered for the eight year period can be estimated by subtracting 17.2% of the stock number of the patent and utility model at the end of 1991FY from that at the end of 1999 FY. We omitted the data of 65 firms, for which the above procedure resulted in zero or negative counts, since they are more likely to be outliers in patenting behaviors. They are only a small part of the total sample.

(3)Market structure (concentration) at a firm level(*hhi0*)

The market is defined at three-digit industry level and the market share is defined based on the sales (domestic and export sales) of each firm in 1991FY and does not take into account import competition. When a firm operates in more than one industry, we use a weighted average index of HHI, with its sales in each industry as a weight.

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[i] It is important to distinguish the demand for R&D from the demand for goods. The entry of a new firm will reduce the demand for the goods produced by existing firms, but may increase their demand for R&D.

[ii] Schumpeter (1942) pointed out that a large firm had advantages over a small firm both in demand and supply sides of R&D.

[iii] Grossman and Helpman (1991) built a model of endogenous growth based on technological spillover through international trade.

[iv] Competition may weaken appropriability of R&D investment by reducing the size of output of each firm and by increasing the chances for the outputs of R&D being copied. Thus, the net demand side effect of competition on R&D is ambiguous theoretically. The net effect of competition on the efficiency of motivating managers is also generally ambiguous (see Nickell (1996)).

[v] See Cohen (1995) for a survey of such literature.

[vi] As pointed out by Fisher and Temin (1973), however, the relationship between firm size and R&D input has little direct implications on economy of scales in R&D.

[vii] While the following propositions mainly refer to the empirical evidence based on the U.S. or U.K. industry, Wakasugi et al (1996) and Doi (1993) provides evidence consistent with the following first and second propositions for the Japanese industry.

[viii] They also show that that R&D size relationship is weaker in the industries where licensing is important.

[ix] The declining average productivity implies the following: $AZ = Z / k > MZ = \partial Z / \partial k$.

[x] Such is the case for a geometric patent production function ($Z = bk^{\alpha}$).

[xi] Since we do not estimate a marginal revenue curve of technologies (or a demand function for technologies), we can tell at best whether a particular determinant of R&D works through the supply side or not, but not whether they work only through the supply side.

[xii] For an example, the HHI in the pharmaceutical industry ranges from 0.0141 to 0.0527, with the mean 0.0192 and the standard deviation of 0.0060 for 71 firms.

[xiii] One of his proposals is to use factor prices as instruments. The debt asset ratio of a firm used in this paper can be regarded to be an application of this proposal.

[xiv] There exist 1843 manufacturing firms, 176 wholesale firms and 34 construction firms and the other 16 firms..

[xv] The Japanese firms applied 340,861 domestic patens and 190,895 foreign patents in 1996 (JPO(2000)). The number of the patent applications to the USA was 43,156.

[xvi] In Japan patent application is examined only after the patent applicant requests that. It used to be the case that a patent applicant can defer examination up to seven years after the submission of patent applications (this period was reduced to three years in 2000).

[xvii] This is particularly the case for export ratio, since its coefficient in the patent equation may be inflated by our use of the patents granted both domestically and abroad, to the extent that foreign patents may have a duplicative aspect.

(Figures and Tables)

Determinants of R&D and Its Productivity: Identifying Demand and Supply Channels

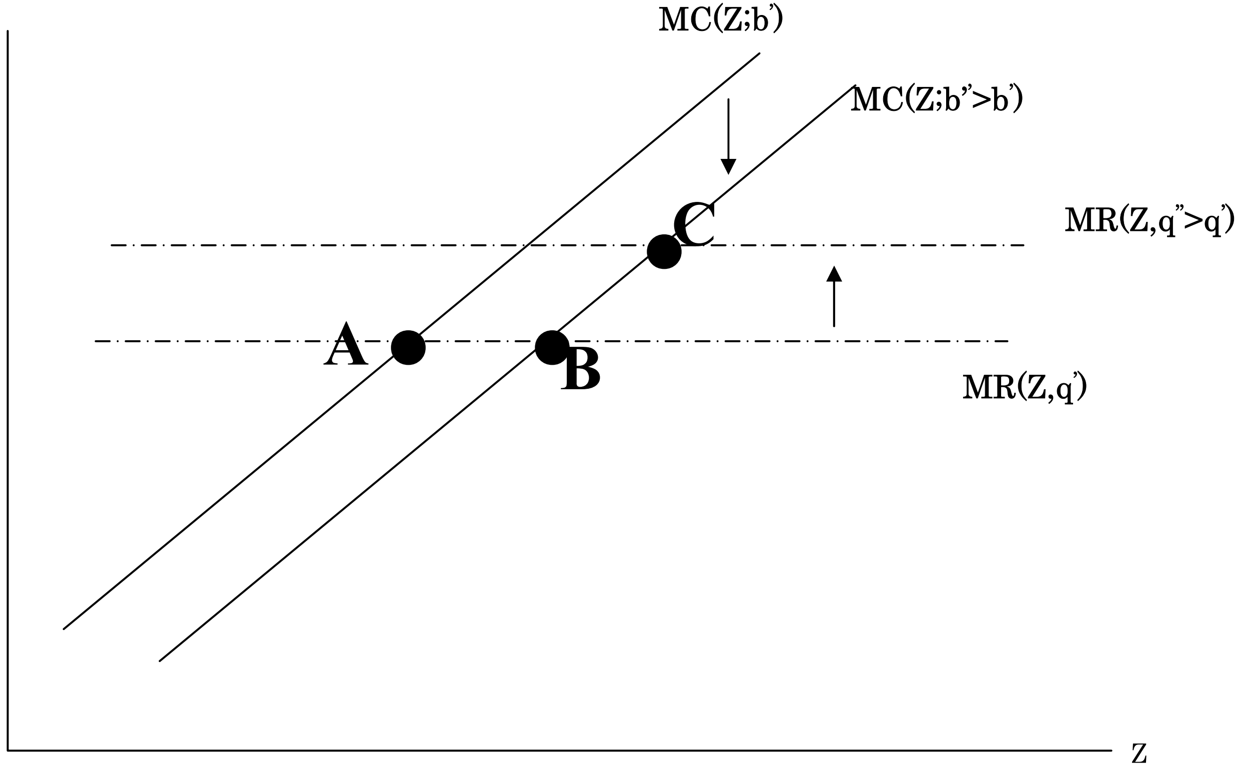

Figure 1 Marginal cost and marginal revenue of patent production for a process innovation

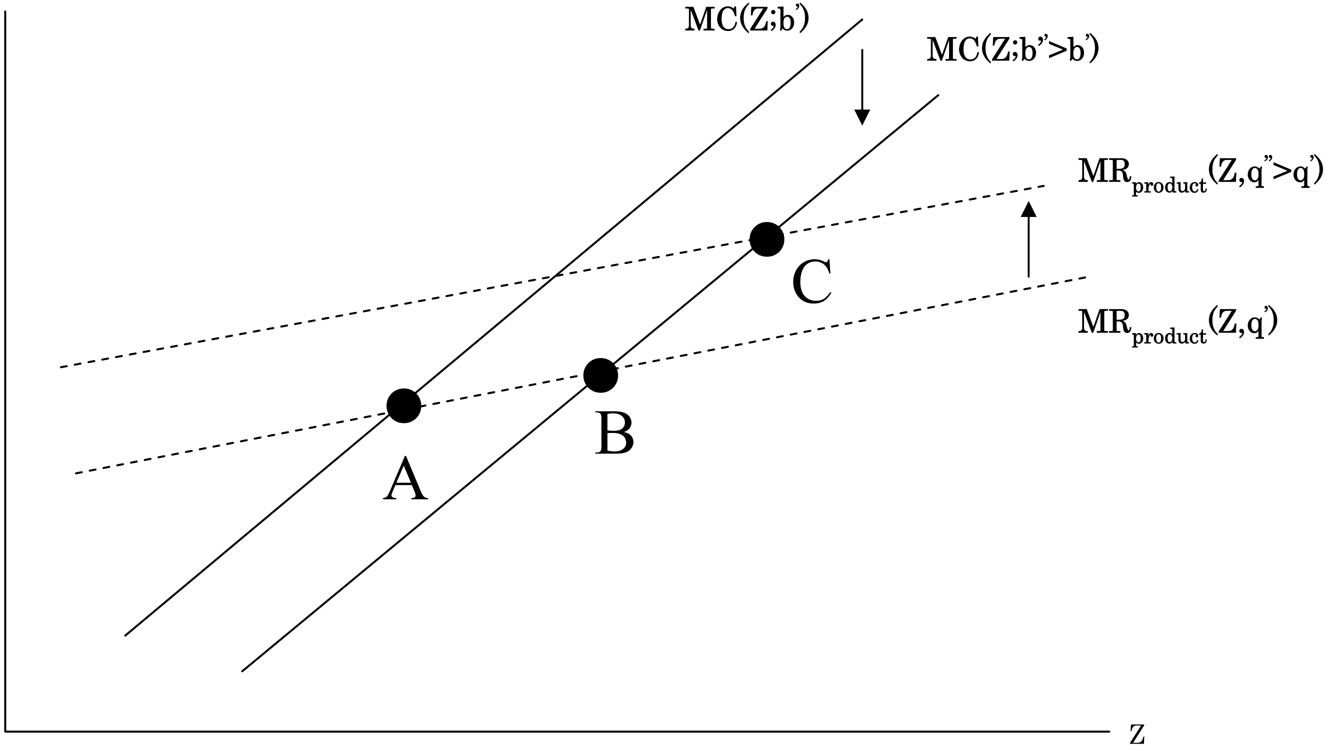

Figure 2 Marginal cost and marginal revenue of patent production for complementary product innovation

Table 1 Summary statistics

Variable	Meaning	Explanation	Obs	Mean	Std. Dev.
z	No. of patents and utility models granted for internally generated inventions	Estimated number of the patents and utility models granted globally from the beginning of 1992 FY to the end of 1999 FY	2069	292	1999
rd	R&D expenditure internally used	the average R&D expenditure of a firm for the period from 1991FY to 1997FY	2069	2633	16960
rdgr	growth rate of rd	from 1991FY to 1997FY	2069	0.032	0.185
s0	sales	the level of sales of each firm in 1991 FY	2069	73173	281258
asset0	asset size	the asset size (a book value) in 1991FY	2069	19095	72021
s0rd	sales relative to R&D	s0/rd; lns0rd=ln(s0/rd)	2069	183	468
asset0rd	asst relative to R&D	asset0/rd; lnasset0rd=ln(asset0/rd)	2069	43	122
hhi0	Herfindhal–Hirshman index	a weighted average index of HHI, with its sales in each industry as a weight, based on markets shares of the firms in 1991FY	2069	0.0335	0.0264
exp0	export sales ratio in 1991FY	ln1exp0=ln(1+exp0)	2069	0.073	0.123
age	age as of 1997	the difference between 1997 and the year of establishment	2069	46	15
advs0	advertising sales ratio in FY 1991	ln1advs0=ln(1+advs0)	2069	0.009	0.020
da0	debt asset ratio in 1994 FY	ln1da0=ln(1+da0)	2069	0.646	0.215

Table 2. Estimation of reduced form R&D and patent equations with three-digit industry dummies (number of obs= 2069, 58 industry dummies)

	I Reduced form R&D equation (lnrd)			II Reduced form R&D equation (lnrd)			III Reduced form patent equation (lnZ)			IV Reduced form patent equation (lnZ)		
	Coef.	Robust Std. Err.		Coef.	Robust Std. Err.		Coef.	Robust Std. Err.		Coef.	Robust Std. Err.	
lns0	1.014	0.048	***	1.069	0.019	***	1.063	0.083	***	0.930	0.028	***
lnhhi0	0.147	0.069	**	0.131	0.067	*	0.075	0.078		0.116	0.068	*
ln1exp0	2.492	0.357	***	2.264	0.354	***	1.408	0.601	**	1.963	0.571	***
ln1advs0	3.833	2.130	*	3.695	2.187	*	3.593	2.819		3.928	2.673	
ln1da0	−1.302	0.218	***	−1.248	0.218	***	−0.827	0.250	***	−0.959	0.239	***
R−squared	0.783			0.784			0.590			0.598		
Root MSE	0.963			0.961			1.287			1.275		
Estimation	IV（lnage for lns0)			OLS			IV（lnage for lns0)			OLS		

77 industry dummies and constant are used. Values for industry dummies and for constants are not reported.

Heteroskedasticity-consistent standard errors are reported, with 77 clusters corresponding to three-digit industries.
***Significant at 1 % level. **Significant at 5% level.*Significant at 10% level.

Table 3. Estimation of structural patent production function with three-digit industry dummies (number of obs=2069, 78 industry dummies)

	I. Structural patent equation (lnZ)			II. Structural patent equation (lnZ)			III. Structural patent equation (lnZ)			IV. Structural patent equation (lnZ)		
	Coef.	Robust Std. Err.		Coef.	Robust Std. Err.		Coef.	Robust Std. Err.		Coef.	Robust Std. Err.	
lnrd	0.473	0.032	***	0.948	0.230	***	0.838	0.023	***	0.938	0.130	***
rdgr	−0.067	0.168		−3.860	7.777		−0.085	0.175		−3.954	6.854	
lns0rd	0.429	0.049	***	0.069	0.726							
lnasset0rd							0.283	0.041	***	0.090	0.935	
lnhhi0	0.057	0.072		−0.021	0.092		0.070	0.072		−0.011	0.149	
ln1exp0	0.973	0.474	**	−0.758	1.256		0.863	0.468	*	−0.683	1.973	
R-squared	0.645			0.488			0.636			0.486		
Root MSE	1.198			1.439			1.214			1.442		
Estimation	OLS			IV (Instruments: lnage ln1advs0 ln1da0 for lnrd, rdgr & lns0rd)			OLS			IV (Instruments: lnage ln1advs0 ln1da0 for lnrd, rdgr & lns0		

78 industry dummies and constant are used. Values for industry dummies and for constants are not reported.
Heteroskedasticity-consistent standard errors are reported, with 78 clusters corresponding to three-digit industries.
***Significant at 1 % level. **Significant at 5% level.*Significant at 10% level.