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PUBLICATION RATE AS A FUNCTION OF LABORATORY SIZE IN THREE BIOMEDICAL RESEARCH INSTITUTIONS

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In three biomedical research institutions, there is no indication of a single laboratory size at which the number of publications per scientist is maximal or minimal. In a scattergram of the number of publications of a laboratory against laboratory size, the horizontal coordinate measures the number of scientists in a laboratory, the vertical axis measures the number of publications from the laboratory (counting each publication once regardless of the number of authors), and each laboratory is represented by one point. Scattergrams for the Rockefeller University (RU), New York, the National Institute for Medical Research (NIMR), London, and the National Cancer Institute (NCI), Bethesda, are each described well by a straight line through the origin. The slopes of the lines for the three institutions are not significantly different. In these laboratories, ranging in size from 1 to 46 scientists, one additional scientist increases the expected annual number of publications of a laboratory by approximately 1.1, regardless of the size of the laboratory. Although the three institutions have significantly different mean laboratory sizes, the frequency distribution of laboratory size in each institution is described well by a 0-truncated negative binomial distribution, as predicted by a simple model of laboratory population dynamics.

Introduction

What is the relation between the number of scientists in a laboratory and the number of their scientific publications in a year?

The answer to this question is of potential interest to scientists who want to understand what effect, if any, group size may have on their collective and individual productivity. Because scientific publications are an accessible measure of scientific productivity, the relation between the number of publications and the number of scientists in a laboratory may be of practical interest.

A priori, one could imagine at least five possible relationships between the number of scientists and the number of scientific publications in a year. If bigger laboratories benefited from better equipment and more shared expertise, increasing returns to scale would arise. Decreasing returns to scale would arise if each additional member of a laboratory contributed fewer additional publications than the average of the laboratory members already present. If, as laboratory size increased, first increasing returns and then decreasing returns were operative, publications per scientist would be maximal at an intermediate laboratory size. If first decreasing returns, then increasing returns, applied as laboratory size increased, publications per scientist would be minimal at an intermediate laboratory size. Finally, under constant returns to scale, the number of publications per year would be directly proportional to the number of scientists.

For the 60 laboratories at the Rockefeller University (hereafter abbreviated to RU), New York City, a straight line through the origin described well a scatter plot of the number of publications of each laboratory in 1977–78 against the laboratory's number of scientists with academic appointment in 1977–78.[1]

These laboratory sizes ranged from 1 to 27. A larger range of laboratory sizes might have revealed a nonlinear relationship between the number of publications and laboratory size.

To test this possibility, the annual reports of a number of research institutions were examined. Two annual reports that listed individuals and publications by laboratory were found.

In this paper I analyze publication rate as a function of laboratory size at the National Cancer Institute (NCI), Bethesda, Maryland, and at the National Institute for Medical Research (NIMR), London I find that, as at RU, a straight line through the origin describes the number of publications as a function of laboratory size. The slopes of the fitted lines from RU, NIMR, and NCI are statistically indistinguishable.

As at RU, the frequency distributions of laboratory size at NIMR and NCI are described by 0-truncated negative binomial distributions. These distributions are predicted by a simple model of the population dynamics of social groups. The mean laboratory sizes differ among the three institutions.

Materials and Methods

NIMR is the largest establishment of the Medical Research Council (MRC) of England. NIMR is organized into 23 units.[2] In this analysis, I exclude the animal division and the library. For the remaining 21 laboratories, I counted separately the "senior staff", "MRC students", and "attached workers". Technical, secretarial, and administrative staff were not listed under individual laboratories. I defined laboratory size as the sum of the numbers of senior staff, MRC students, and attached workers. This definition is comparable with that used for RU.[1]

For each laboratory, the annual report lists publications and reports in press. To make the figures from NIMR comparable with those from RU and from NCI, I counted only items actually published.

The National Institutes of Health (NIH), Bethesda, Maryland, are the central facilities for biomedical research of the United States government. The *Scientific Directory 1978–Annual Bibliography 1977*[3] gives, by laboratory or other administrative unit, the professional staff of the Institutes and "their scientific and technical publications covering work done at NIH." NCI is the Institute with the largest number of laboratories. On this basis, NCI was chosen for further study.

For comparability with the laboratories of RU and NIMR, I distinguished administrative, co-ordinating, contracting, or service units of NCI (e.g., the Office of the Director) from groups with a mission of intramural research (e.g., the Tumor Pathology Branch). In some cases, the distinction was not obvious. Paul Schaffer, formerly Acting Chief, Management Policy Branch, Office of the Director, NCI, kindly provided a copy of the NCI Organization and Functions Manual (document NCI–1120, parts 1 to 6) and an organization chart of NCI. I selected those 46 units with an assignment to study, investigate or carry out research in a specific scientific area. Five of these 46 units were not called laboratories or branches: the Office of the Director of the Division of Cancer Cause and Prevention, the Office of the Associate Director for the Viral Oncology Program, the Registry of Experimental Cancers, the Office of the Associate Director of the Field Studies and Statistics Program, and the Office of the Associate Director of the Clinical Oncology Program. I shall refer to each of the selected 46 units as a laboratory.

For each laboratory, I recorded the number of personnel in each of four categories: senior staff, including the laboratory chief and, if present, deputy chief and scientists emeriti; associates; visiting scientists; and guest workers. I defined laboratory size as the sum of the numbers of people in these four categories.

The 1978 report lists only papers actually published. I counted all publications listed for each laboratory. Publications with authors from more than one NIH laboratory were listed only under the laboratory of the first NIH author.

Abstracts, but not brief reports or unrefereed contributions to books, were excluded from the publication lists of NIMR and NCI, as well as of RU.

I estimated the increase in number of publications resulting from an additional person in a laboratory in three ways:

(1) by the slope coefficient in the least squares line, assuming the variance in publications to be independent of laboratory size;

(2) by the slope coefficient in the least squares line through the origin, assuming the variance in publications to be proportional to laboratory size;

(3) by the slope coefficient of the least squares line through the origin, assuming the standard deviation of publications to be proportional to laboratory size.

The reason for using all three of these methods is that scattergrams of the data do not reveal unambiguously how the variance in the number of publications, for laboratories of a given size, is related to laboratory size.

For all three methods, I also estimated the variance of the slope coefficient.[4]

Using the regression line fitted by method (1), I tested for non-linearity by comparing the residual variance of the straight line with the residual variance of the best-fitting parabola.[5] I then tested the hypothesis that the regression line obtained by method (1) had a Y-intercept of 0, that is, that the line went through the origin.[6]

I also tested the hypothesis that the slope coefficients of the three lines, one for each institution, were the same, using the corresponding variances, one method at a time. Since the number of laboratories at each institution exceeded 20, I used a large-sample test.[7]

To study the behavior of individuals, I chose two laboratories from each institution. I sought laboratories that were as large as possible, in order to maximize the probability of rejecting null models of individual behavior, subject to the constraint that the laboratories should all be of the same or similar size, so that differences among laboratories or institutions would not arise from sample size alone. Table 6 gives the laboratories sizes.

For each individual listed in each of these 6 laboratories, I computed a *contribution* score and a *title* score. An individual's contribution score counts each published title in which the individual was one of N authors as 1/N. The contribution score is identical to the "fractional productivity" of *Price* and *Beaver.*[8] Thus if an individual is one of three authors of a publication, his contribution score increases by 1/3. An individual's title score is the number of publications on which his or her name appears, regardless of how many authors there were for the publication. Titles in the NIMR report listed as in press were excluded.

To test whether a counted variable is consistent with a *Poisson* distribution, I use the Poisson variance test[9] and an analogous test for the 0-trancated Poisson distribution.[10]

Results

For the benefit of other analysts, Table 1 presents the data for NIMR and Table 2 the data for NCI. Table 3 gives summary statistics for RU, NIMR, NCI, and all three institutions combined.

Laboratory size. The mean laboratory sizes range from 10.30 at RU through 13.48 at NIMR to 19.85 at NCI. These mean laboratory sizes are significantly dif-

Table 1
Raw data for 21 laboratories at the National Institute for Medical Research 1976–77

A	B	C	D	E
5	1	0	4	6
21	7	6	32	34
13	1	3	18	17
5	0	0	1	5
8	0	1	4	9
5	2	2	7	9
7	2	2	1	11
4	1	3	8	8
11	0	0	11	11
8	3	5	15	16
8	3	9	15	20
8	0	3	21	11
4	0	0	2	4
15	3	3	14	21
12	3	6	30	21
6	0	1	3	7
10	2	7	31	19
16	3	4	11	23
5	1	0	14	6
3	0	0	2	3
12	2	8	12	22

(A) Senior staff, (B) MRC students, (C) attached workers, (D) Publications, (E) Laboratory size (A + B + C).

ferent, according to a one-way analysis of variance ($P < 0.005$, where P is the probability of the null hypothesis that the three mean sizes are equal).

If the variation in laboratory size in an institution arose from purely random fluctuations in the number of individuals in a laboratory, the size distribution would be approximately a 0-truncated Poisson distribution. The observed size distributions in each institution are not 0-truncated Poisson ($P < 10^{-4}$).

The frequency distribution of size of laboratories in each institution is not significantly different from a 0-truncated negative binomial distribution. Table 4 repeats the observations of RU[1] for ease of comparison. Parameter estimates were obtained by the method of *Brass.*[11]

Categories of staff. To relate the number of publications to the numbers of people in each staff category at NIMR and NCI, I performed multiple regressions. For NIMR,

Table 2
Raw data for 46 laboratories at the National Cancer Institute 1977–78

A	B	C	D	E	F	A	B	C	D	E	F
20	12	10	4	48	46	14	2	1	2	30	19
23	3	13	2	36	41	7	10	1	3	34	21
15	10	7	4	45	36	2	4	0	0	17	6
7	4	4	2	18	17	3	8	1	0	9	12
14	9	5	8	56	36	11	16	0	4	41	31
10	7	6	5	32	28	10	9	2	0	17	21
13	1	7	4	50	25	12	16	2	0	31	30
8	3	7	0	31	18	7	4	1	0	8	12
12	5	4	2	27	23	9	18	0	6	27	33
12	7	2	3	32	24	6	8	2	0	17	16
37	0	5	1	62	43	10	9	4	1	32	24
7	21	6	2	30	36	6	2	3	3	18	14
17	3	5	1	64	26	1	4	0	1	7	6
12	4	4	1	18	21	12	4	7	0	10	23
13	2	5	2	15	22	9	6	7	1	21	23
5	2	0	0	5	7	7	0	0	0	2	7
2	2	2	0	8	6	2	0	0	0	1	2
10	5	5	0	20	20	11	0	0	0	12	11
13	3	4	0	32	20	19	1	1	0	10	21
4	0	0	0	8	4	4	0	0	0	0	4
10	2	4	0	19	16	3	0	0	1	3	4
39	0	0	0	31	39	3	2	0	0	10	5
7	0	1	0	27	8	4	1	0	1	8	6

(A) Senior staff, (B) Associates, (C) Visiting scientists, (D) Guest workers, (E) Publications, (F) Laboratory size (A + B + C + D)

$$\begin{aligned}\text{publications} = {} & -0.04 + (0.83 \pm 0.49)\ (\text{senior staff}) \\ & +(0.28 \pm 1.51)\ (\text{MRC students}) \\ & +(1.48 \pm 0.72)^{*}\ (\text{attached workers}).\end{aligned}$$

The first of the two numbers in parentheses is the estimated slope coefficient. An interpretation of the slope coefficient, for example, is that an additional member of senior staff increases the average number of publications by 0.83. The second number in parentheses is the standard error of the slope coefficient. A slope coefficient significantly different from 0 at the 0.05 level (by one-tailed t-test) is marked*.

As shown in Table 5, R^2, the square of the multiple correlation coefficient, is 0.580. This figure is approximately the proportion of the variance in the number of publications that can be explained by the regression.[12] If the MRC students are

Table 3
Summary statistics for Rockefeller University (RU), National Institute for Medical Research (NIMR), and National Cancer Institute (NCI)

	RU	NIMR	NCI	Pooled
Year	1977–78	1976–77	1977–78	1976–78
Laboratories	60	21	46	127
Scientists	618	283	913	1814
Scientists per lab.	10.30	13.48	19.85	14.28
Variance	54.35	65.16	138.44	104.20
Range	1 to 27	3 to 34	2 to 46	1 to 46
Publications	631	256	1079	1966
Publications per lab.	10.52	12.19	23.46	15.48
Variance	77.98	96.06	262.88	182.41
Range	0 to 33	1 to 32	0 to 64	0 to 64
Method (1) slope	0.926	0.912	1.101	1.089
Variance	0.00996	0.03385	0.01560	0.00451
Method (2) slope	1.021	0.905	1.182	1.084
Variance	0.00578	0.01114	0.00542	0.00226
Method (3) slope	1.165	0.879	1.207	1.133
Variance	0.01528	0.01468	0.00872	0.00500
Budget	\$ 38 015 000	£ 4 902 000	\$ 90 055 000	
Funds per scientists	\$ 61 500	£ 17 300	\$ 98 600	
Funds per publication	\$ 60 200	£ 19 100	\$ 83 500	

dropped from the regression, R^2 declines to 0.579. If publications are viewed as a linear function of attached workers only, $R^2 = 0.451$, while if publications are viewed as a linear function of senior staff only, $R^2 = 0.432$. All four of these values of R^2 are statistically significantly > 0 ($P < 0.005$ by F test). I conclude that the number of attached workers is most important, and that the number of MRC students is not important, in explaining the number of publications of a laboratory at NIMR. For NCI,

$$\begin{aligned}\text{publications} = {} & 2.55 + (1.03 \pm 0.20)^{**}\ (\text{senior staff}) \\ & + (0.51 \pm 0.32)\ (\text{associates}) \\ & + (1.12 \pm 0.53)^{*}\ (\text{visiting scientists}) \\ & + (3.01 \pm 0.91)^{**}\ (\text{guest workers}).\end{aligned}$$

Here ** marks slope coefficients significantly different from 0 at the 0.005 level (by one-tailed t-test), and $R^2 = 0.681$. If associates are dropped from the regression, $R^2 = 0.662$. If associates and viscting scientists are dropped from the regression, $R^2 = 0.622$. If publications are viewed as a simple linear regression of senior staff only, $R^2 = 0.391$. Again, all four of these values of R^2 are statistically significantly

Table 4

Observed frequency distributions (Obs.) of laboratory size and fitted O-truncated negative binomial distributions (Pred.) at Rockefeller University (RU), National Institute for Medical Research (NIMR) and National Cancer Institute (NCI)

RU			NIMR			NCI		
Size	Frequency		Size	Frequency		Size	Frequency	
	obs.	pred.		obs.	pred.		obs.	pred.
1–4	15	13.8	1–5	3	3.0	1–5	5	2.9
5–8	15	15.9	6–10	6	5.7	6–10	7	7.3
9–12	9	12.1	11–15	3	5.2	11–15	4	8.9
13–16	9	7.8	16–20	4	3.4	16–20	7	8.2
17–20	5	4.7	21–25	4	1.9	21–25	11	6.4
21–24	3	2.7	26–30	0	1.0	26–30	3	4.6
25–	4	3.0	31–	1	0.8	31–35	2	3.0
						36–40	4	1.9
						41–45	2	1.2
						46–	1	1.6

$p = 0.18004$	$p = 0.20681$	$p = 0.14336$
$r = 2.20060$	$r = 3.51369$	$r = 3.32169$
$X^2 = 1.480$	$X^2 = 4.296$	$X^2 = 11.554$
$df^* = 4$	$df^* = 4$	$df^* = 7$
$0.8 < P < 0.9$	$0.25 < P < 0.5$	$0.1 < P < 0.25$
$a/d = 1.804$	$a/d = 2.787$	$a/d = 2.845$
$b/d = 0.820$	$b/d = 0.793$	$b/d = 0.857$

*For each distribution, df = number of cells – 1 (for total) – 2 (for two fitted parameters).

Table 5

Square of the multiple correlation coefficient (R^2) for regression of publications as (1) a multiple linear function of each staff category, as (2) a simple linear function of laboratory size, and as (3) a quadratic function of laboratory size

	Independent variable (s)			
	RU	NIMR	NCI	Pooled
(1) Each staff category	not computed	0.580	0.681	not computed
(2) Laboratory size	0.597	0.564	0.638	0.678
(3) Quadratic in laboratory size	0.597	0.565	0.640	0.678

> 0 ($P < 0.005$ by F test). I conclude that the numbers of senior staff and guest workers are most important, and the number of associates is least important, in explaining the number of publications of a laboratory at NCI.

For comparison with these multiple regressions, I computed the simple linear regression, by method (1), of number of publications on laboratory size, which is the sum of all staff categories. For both NIMR and NCI, R^2 from this simple regression was only slightly less than R^2 from the corresponding multiple regression (Table 5). The value of R^2 at RU, where only a simple regression could be performed with the available data, is intermediate between that at NIMR and that at NCI.

Laboratory size is used as the independent variable in the following analyses.

Publications and laboratory size. Scatter diagrams for the number of publications as a function of laboratory size give no indication of nonlinearity for either NIMR (Fig. 1a) or NCI (Fig. 2a). A more sensitive way of looking for deviations from linearity is to plot the residuals from a straight line fitted by method (1) as a function of the estimated values. The observed number of publications minus the number of publications estimated from the straight line (the residual) is plotted on the vertical coordinate against the estimated number of publications on the horizontal coordinate for NIMR (Fig. 1b) and NCI (Fig. 2b). There is no suggestion of systematic concavity or convexity.

For a more formal test of nonlinearity, the mean square residual from a linear regression $Y = A + BX$ is compared with the mean square residual from a quadratic regression $Y = A + BX + CX^2$. The data from NIMR and NCI give no evidence of nonlinearity significant at the 5 percent level. Neither do the data from RU nor the data from category 3 (medicine and physiology) of the RU laboratories. There was a slight suggestion of nonlinearity in a graph of the data from category 3 at RU. It is now clear that that suggestion of convexity is an insignificant fluctuation. Finally, the pooled data from all 3 institutions also give no evidence of nonlinearity significant at the 5 percent level.

For each institution, R^2 for the quadratic regression $Y = A + BX + CX^2$ of Y = publications on X = laboratory size is at most 0.002 larger than R^2 for the linear regression $Y = A + BX$ (see Table 5). For practical purposes, it seems adequate to conclude that the expected number of publications and laboratory size are linearly related.

Figs 1a and 2a suggest that the linear functions relating publications and laboratory size at NIMR and NCI pass through the origin, as was previously observed for RU[1]. Statistical tests reveal no evidence significant at the 40 percent level that linear regressions by method (1) do not pass through the origin, for each of RU, NIMR, and NCI separately. I conclude that the expected number of publications and laboratory size are related by an equation of the form $Y = BX$.

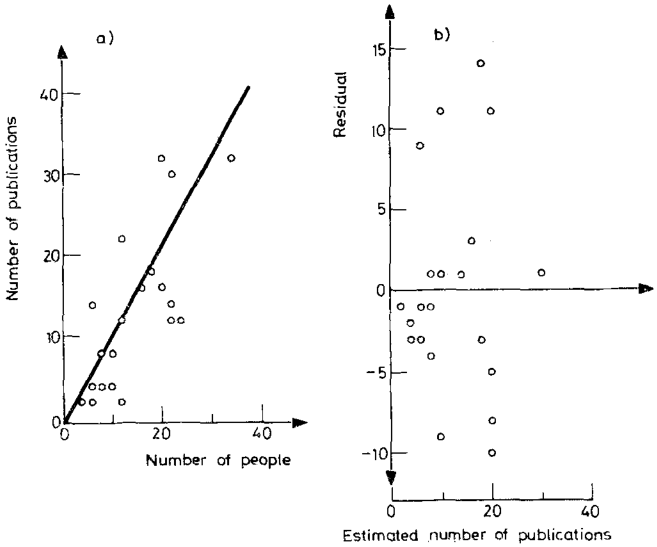

Fig. 1. For laboratories at the National Institute for Medical Research: a) The number of publications as a function of the number of people. The straight line through the origin has slope 1.084, obtained by method (2) from the pooled data of RU, NIMR, and NCI. b) The residual (difference between the observed number of publications and the number of publications estimated from a fitted least squares line) as a function of the number estimated.

Homogeneity of slopes. Comparison of the scattergrams for RU, NIMR, and NCI and of the estimated slopes (Table 3) suggests that the additional numbers of publications per year associated with each additional scientist in a laboratory are similar from one institution to another. Formal tests for the heterogeneity among institutions of the slopes give no evidence of a difference among institutions significant at the 5 percent level. A scattergram of the pooled publications and sizes of all 127 laboratories (Fig. 3) offers no suggestion of differing subpopulations of laboratories. Thus the relationship between the expected number of publications and laboratory size at RU, NIMR and NCI can be described by a single straight line through the origin. Laboratory size accounts for approximately 0.678 of the variation in the number of publications when the data from RU, NIMR and NCI are pooled (Table 5).

Expenditures. I now compare the expenditures per scientist and per publication at RU[1], NIMR, and NCI (Table 3).

The budget of NIMR in 1976–77 was £4 902 000, including salaries, recurrent costs, and scientific equipment (£4 297 000) and capital building works (£605 000).

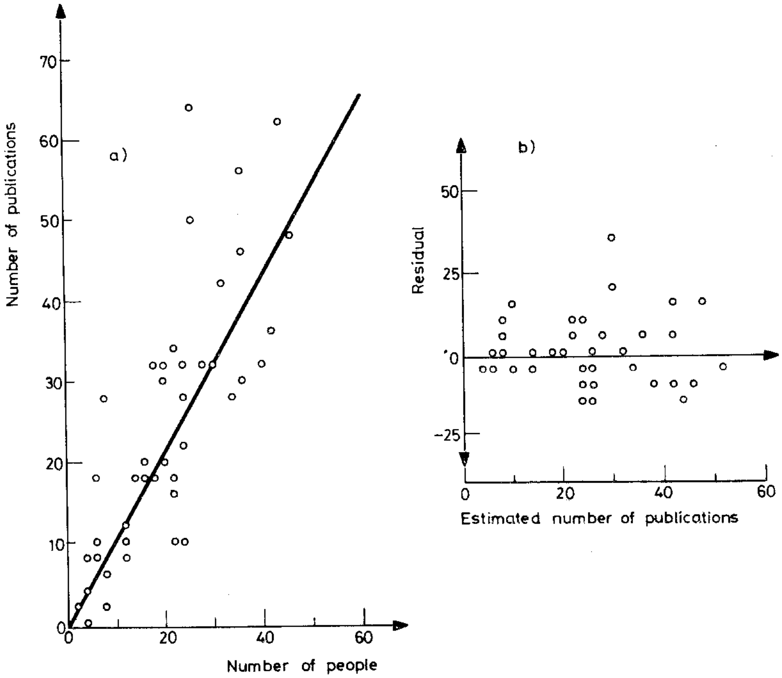

Fig. 2. For laboratories at the National Cancer Institute: a) The number of publications as a function of the number of people. The straight line through the origin has slope 1.084, obtained by method (2) from the pooled data of RU, NIMR, and NCI. b) The residual (difference between the observed number of publications and the number of publications estimated from a fitted least squares line) as a function of the number estimated.

If the budget is divided by the 283 scientists in the 21 laboratories chosen and by the 256 publications of those scientists, the average expenditure per scientist is £17 300 and per publication is £19 100. Taking $2 = £1 for a very rough conversion of pounds to dollars, these figures become approximately $35 000 per scientist and $38 000 per publication.

Because there were several scientists but no publications in the animal division and the library, the actual expenditure per scientist for NIMR may be slightly lower than $35 000. If the capital building works are excluded, the operating expenditures per scientist and per publication are still lower.

Paul Schaffer formerly of NCI made available corresponding figures for NCI. In fiscal year 1977 (October 1976 to September 1977), NCI's budgeted expenditures for intramural research were $67 855 000. In addition, $22 200 000 from the "NIH

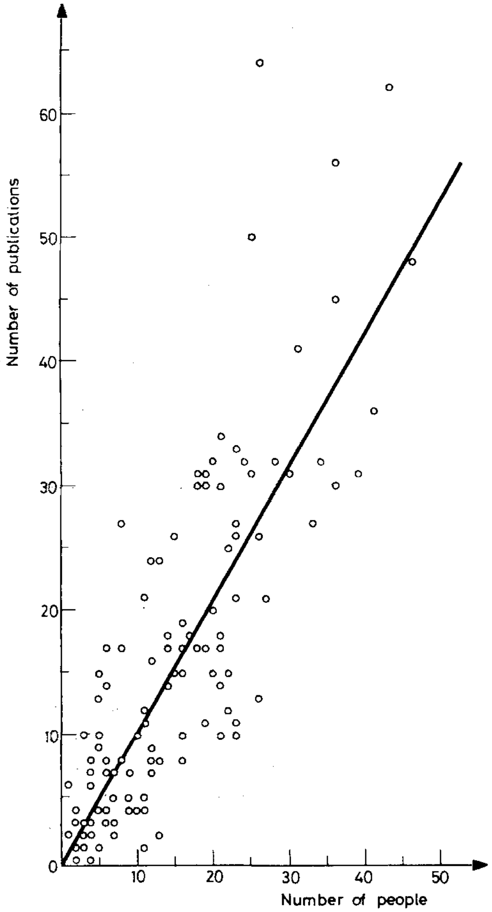

Fig. 3. The number of publications as a function of the number of people in 127 laboratories pooled from the Rockefeller University, the National Institute for Medical Research, and the National Cancer Institute. The straight line through the origin has slope 1.084, obtained by method (2) from the pooled data of RU, NIMR, and NCI.

management fund" were spent in NCI on intramural research, for a total of $90 055 000. If this figure is divided by the 913 scientists and by the 1079 publications of the 46 intramural research laboratories, the average expenditure per scientist is $98 600 and per publication is $83 500. This calculation probably overstates the cost per scientist and per publication, because units other than the 46 that were selected had scientists who published an additional 93 papers. Some of these scientists and some of these publications may have been supported by funds

Table 6

Contribution scores and title scores of individuals in two laboratories from Rockefeller University (RU), National Institute for Medical Research (NIMR) and National Cancer Institute (NCI): means, variances and tests for compatibility with Poisson distributions

	RU				NIMR				NCI			
	Size of lab.	Mean score	Variance of score	P*	Size of lab.	Mean score	Variance of score	P	Size of lab.	Mean score	Variance of score	P
Lab. 1												
Contribution score	23	1.16	3.05		23	0.26	0.22		23	0.58	0.73	
Title score	23	2.13	10.94	$<10^{-4}$	23	0.78	1.63	<0.005	23	1.44	4.89	$<10^{-4}$
Lab. 2												
Contribution score	23	0.99	2.96		22	0.32	0.34		23	0.35	1.30	
Title score	23	4.12	22.95	$<10^{-4}$	22	0.73	1.64	<0.001	23	0.70	4.49	$<10^{-4}$

*P *is the probability that the observed mean and variance could have arisen by random sampling from a Poisson distribution.*

for intramural research. If all 1172 publications of NCI were supported by funds for intramural research, the average cost per publication was $76 800.

Pages per publication. The number of pages in 30 randomly chosen publications from RU had mean 8.57 and variance 21.36. For 30 randomly chosen publications from NCI, the mean and the variance of the number of pages were 7.53 and 27.71. These means do not differ significantly. Though the size of pages in different journals varies, authors from RU and from NCI publish in a similar mix of journals, so no further effort to refine the measurement of article length seemed justified. The NIMR report does not give inclusive pagination of the publications listed.

Individual behavior. The contribution scores (sums of fractional authorships) and title scores (number of publications regardless of co-authors) of individuals at RU, NIMR, and NCI are summarized in Table 6. Within each institution, the mean contribution scores of the two laboratories are not significantly different and the mean title scores of the two laboratories are not significantly different (in all cases, $P > 0.1$ by t-test).

The variance in the title scores is too large, by comparison with the corresponding mean, for the title scores to have been drawn from a Poisson distribution ($P < 0.005$ at most, where P is the probability of the null hypothesis that the scores obeyed a Poisson distribution). In none of these 6 laboratories does every individual in the laboratory have an equal and independent chance of having his name appear on a publication.

In three laboratories, the contribution scores are also highly overdispersed: the ratios of the variances to the mean range from 2.63 to 2.71. (The Poisson variance test cannot be applied here because the contribution scores are not nonnegative integers.) Individuals' contributions, to the extent that they are measured by the contribution scores, appear not to be randomly distributed among individuals in these laboratories. In two of these laboratories, the individuals with the highest contribution scores are the laboratory heads. In the third of these laboratories, the individual with the highest score became co-head of the laboratory in the following year.

In three other laboratories, two at NIMR and one at NCI, the ratios of the variance to the mean of the contribution scores range from 0.85 to 1.26. Here individuals' shares in the laboratory's publications appear closer to randomly distributed. In these three laboratories, at least one individual other than the laboratory head had a higher contribution score than the laboratory head.

It has been suggested that the expected number of publications of a laboratory is so nearly a linear function of laboratory size, with slope near 1, because every scientist feels obliged to have his or her name on a publication a year. The data do not support this suggestion. In the two laboratories at RU, the numbers of individuals with no publications are 10 and 8; at NIMR, 15 and 15; and at NCI, 14 and 18. The fraction of individuals who do not appear as an author is large in each of these 6 laboratories.

Discussion

For three biomedical research institutions, the relation between the expected annual number of publications and the number of scientists in a laboratory is described well by a straight line through the origin. The slope is not significantly different at the Rockefeller University (RU), the National Institute for Medical Research (NIMR), and the National Cancer Institute (NCI). On the average, one additional scientist in a laboratory at any of these institutions increases the laboratory's publications by approximately 1.1.

The finding that the average publication rate per scientist is the same for laboratories of all sizes is not unique to the three institutions studied here. In 172 Swedish academic research units from the fields of natural science and technology, the output per scientist (defined as a unit's output of publications divided by the number of scientists in the unit) is not significantly related to the number of scientists in the group[13]. The sizes of these groups range from 2 to 18. The units belong to a large number of different institutions. The homogeneity of output per scientist across all these institutions suggests that the uniformity of slope observed here for RU, NIMR and NCI may apply to other institutions as well. In particular, homogeneity of average publication rate per scientist for laboratories of different sizes may be found in institutions that are not considered "elite," as some observers consider RU, NIMR, and NCI to be, and that are not engaged in biomedical research.

The study of individual institutions in this paper shows that the homogeneity of output per scientist in Stankiewicz's study may reflect the homogeneity of output per scientist within institutions, rather than being an artefact of pooling across institutions.

Two other studies[14,15] appear to be related.

Data collected by *Wallmark* et al.[14] are consistent with the inference that productivity per scientist neither increases nor decreases as the size of a research group increases. *Wallmark*'s data are based on definitions of productivity and group size that are very different from those used by *Stankiewicz* and me. The references of articles that dealt with the "Gunn effect" were collected from seven journals over a five-year period. A team was defined as an institution where an author of one of the references worked, e.g., Cornell University or IBM Corporation. The size of a team was defined as the number of different individuals from an institution who appeared as authors of one or more references. The number of net references was defined as the number of references to papers written by members of a team after deleting references by a team to its own work. (*Wallmark* et al.[14] do not discuss how valid it is to consider all authors at IBM, or at Cornell, as a single team, nor whether there were collaborative publications by authors from different institutions.) Research efficiency was defined as the ratio of the number of net references to the team size.

Wallmark et al. concluded that their data "show that research efficiency, as defined, increases exponentially with size of the research team."

Unfortunately, *Wallmark* et al. did not describe the statistical procedure they used to conclude that research efficiency increased with team size. Using the counts of net references and team size in their Table 1, I recomputed research efficiency because some of the values they give are not correct to the number of decimal places shown. Then, using method (1) described above, I performed linear regressions of research efficiency on team size and of the natural logarithm of research efficiency on team size. The linear correlation coefficients (0.1581 and 0.1233), based on 18 data points or 16 degrees of freedom, are not close to being significantly different from 0. These data thus do not provide evidence that research efficiency increases, linearly or exponentially, with the size of a research group. The data are consistent with the hypothesis that net references per scientist are independent of the number of publishing scientists in a team.

Wallmark et al.[14] also analyzed a larger sample of references by methods that were not fully explicit. No sampling theory was offered for the larger sample either. Since *Wallmark* et al. did not publish this larger set of data, I cannot confirm the analysis.

Dailey[15] used voluntary questionnaires to study team size, team productivity, and four other socio-psychological variables in 45 research groups in the western United States. These groups worked on pure and applied physics in public and private organizations. *Dailey* measured a team's productivity by summing two subjective ratings, each on a scale from 0 to 100, made by a superviser of the team. *Dailey* did not define team size. The correlation between team size and team productivity was 0.055, not significantly different from 0 at the 0.10 level. The scale of measurement Dailey used for team productivity makes the interpretation of this result unclear.

In summary, even though *Stankiewicz*[13] emphasizes that research groups of size 5 to 7 are optimal for an "Index of scientific recognition"; and even though *Wallmark* et al.[14] claim, without apparent support, that "research efficiency" increases exponentially with the size of a research team, the data presented by Stankiewicz and by Wallmark et al. are consistent with the data and conclusion drawn here:

productivity per scientist (measured by publications or net references) does not vary significantly, on the average, among laboratories or research groups of different sizes.

Other aspects of the results presented also require discussion.

The finding that the publication rate per scientist at RU, NIMR and NCI is approximately 1.1 is consistent with a 1962 publication rate of 1.0 for NIH professionals not belonging to administrative staff.[16] At the Mayo Clinic, from 1950 to 1962, the ratio of the annual total of published papers to the total number of Staff Members averaged 1.6.[16] It is not clear whether Staff Members at the Mayo Clinic correspond to senior staff at NCI and NIMR or to all scientific staff.

At NCI, when one NIH author precedes a second NCI author in the list of authors of a publication, the second author's laboratory is credited with fewer publications than it deserves. Though this undercounting affects laboratories that consult within NCI (such as those in statistics, computing, and pathology), there is no evidence that it affects laboratories differently according to their size.

Multiple regressions of the number of publications on the numbers of people in each staff category show unexpectedly that the numerically largest of the regression coefficients is associated with the "attached workers" at NIMR and the "guest workers" at NCI. All the regression coefficients are positive, but some are not significantly different from 0.

A simple linear regression of number of publications on laboratory size gives a multiple correlation coefficient that is only slightly lower than that obtained from multiple regression on individual staff categories.

A scientist at NCI pointed out that this multiple regression assumes publications result from staff size in the same year. However, the large regression coefficient of guest workers (at NCI) or attached workers (at NIMR) might also arise if disproportionately more workers in these categories are atracted by permanent staff scientists who are unusually productive in earlier years. Since a large fraction of the publications that appear in a given year report research done in earlier years, it would be desirable to study a multivariate time series of numbers of scientific staff by category and numbers of publications.

Why is the expected number of publications directly proportional to laboratory size? Why does the residual increase with laboratory size? I have supposed[1] that associated with each individual is a contribution score or fractional productivity that is independently and identically distributed for every individual in the laboratory. This supposition is consistent with observations of individuals' publications in three laboratories, but is not consistent with observations in three other laboratories, where the head (or head-to-be) of the laboratory had the largest contribution score.

The association in this small sample of 6 laboratories between the overdispersion of individuals' contribution scores and the dominant position of the laboratory head has more than one possible explanation, if the association exists in general. One explanation might be conditions of authorship, another the criteria for selecting a laboratory head.

In laboratories where the head expects to be an author of any publications for which he has raised funds or proposed the problems, the head would have the largest contribution score. In laboratories where the head carries administrative responsibilities and shares authorship only on publications for which he has done a major portion of the bench work, theoretical work, or writing, other individuals in the laboratory might have larger contribution scores.

Selection of the head might also explain the association. In some laboratories outstandingly productive individuals may be selected to be head. Other laboratories might be a confederation of colleagues who pick one to serve as head. During his administrative service, a person might have less time for research.

The available data rule out neither of these explanations.

The observation that the title scores are overdispersed in all 6 laboratories is consistent with studies of the frequency distribution of publications in which the individual scientist, rather than the laboratory, is taken as the unit of analysis.[17]

The observed frequency distributions of laboratory size at NIMR and NCI are statistically indistinguishable from 0-truncated negative binomial distributions. This finding confirms the same result for RU and enhances the interest of a theoretical model proposed as an explanation.[1,18] To review briefly, this model considers a collection of social groups (in this application, the laboratories in a research institution). Individuals may enter a group from outside the institution, may leave a group to go outside the institution, or may migrate from one group to another in the institution. Arrival to a group is assumed to be described by two parameters. A parameter a describes the probability, per unit time per individual outside the institution, of attraction to a given group, regardless of the size of the group. This parameter measures the attractiveness of belonging to a group (at that institution) per se. A parameter b describes the attractiveness of a group per individual in the group. This attractiveness b of individuals is assumed to be the same for all individuals in the institution. The overall attractiveness of a group of size n to an individual outside the institution is the attractiveness of group membership per se plus the attraction of the n individuals in the group: $a + bn$. The probability of leaving a group to go outside the institution, per unit time per individual in the group, is described by a parameter d. Thus for a group of size n the probability per unit time of a departure to outside the institution is dn. For a migration from a group of size n to a group of size m within the institution, the probability per unit time is supposed to be $gnd(a + mb)$, where the constant g describes the intensity of intra-institutional migration.

The equilibrium distribution of group size depends only on two ratios of parameters a/d and b/d which are related to the two parameters p and r of the truncated negative binomial distribution (see Table 4) by $a/d = r(1 - p)$ and $b/d = 1 - p$. (The parameter g does not affect the equilibrium distribution.)

As the mean size of the laboratory increases from RU through NIMR to NCI, the ratio b/d remains near 0.8, while a/d increases monotonically (Table 4). This suggests that the ratio of individual attractiveness to individual departure rates is about the same in all three institutions, but that the ratio of group attractiveness to individual departure rates increases from RU to NCI.

Finding that a frequency distribution is approximately negative binomial is not vacuous. The frequency distribution of group sizes is sensitive to how groups are defined. For example, the frequency distribution of the size of 122 groups of scientific authors related to each other by collaboration[19] cannot be described by a 0-truncated negative binomial distribution. These groups were constructed from the authorships of 533 papers "so as to place together each author with those who had collaborated with him and also with those who had collaborated with his collaborators, etc."[19] By contrast, the groups sizes at RU, NIMR and NCI were defined by a single census.

In constant dollars, the expenditure in 1977 per intramural NIH research publication was almost the same as that in 1958 and less than that in 1961. NIH intramural biomedical research expenditures in 1956 and 1959 were $32 million and $69 million. The numbers of NIH intramural biomedical research publications in 1958 and 1961 were 1 100 and 1 627.[16] The average funds expended two years earlier were $29 100 per publication in 1958 and $42 400 per publication in 1961. If 1956 and 1959 dollars are converted to 1977 dollars by using a price deflator for Federal government purchases of goods and services,[22] the expenditure per 1958 publication was $78 300 and per 1961 publication was $103 724, compared with $83 500 per NCI publication in 1977–78.

RU, NIMR and NCI differ substantially in their expenditures per scientist and per publication. The expenditures at the American institutions are approximately twice those in the British. The exchange rate may not take account of the difference between the two countries in the cost of living and working. RU and NCI do not differ in the mean page length of a publication, approximately 8 pages.

There is still no good quantitative model that explains both the linearity of the regression of the number of publications on laboratory size and the increase in residual variance with laboratory size, and that is consistent with observed individual behavior. Since laboratory size has a negative binomial distribution, it may be possible to adapt bivariate negative binomial models with linear regression[23] to the requirement that the regression pass through the origin.

To explain in substantive terms why laboratories of the same size sometimes produce markedly different numbers of publications may require information about the resources and human characteristics of laboratories.[24]

I emphasized previously[1] the great importance of scientific publications as products of scientific work and the serious weaknesses of number of scientific publications as a measure of the quality, significance and impact of research. To understand better what accounts for numbers of publications seems a useful short term goal. To find better measures of scientific productivity than numbers of publications seems a useful longer-term goal.

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