J Technol Transfer
DOI 10.1007/s10961-006-9020-0

Commercializing biomedical science in a rapidly changing "triple-helix" nexus: The experience of the National University of Singapore

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Abstract Since the late 1990s, the Singapore government had embarked on a significant push to develop the city-state into a major life-science R&D and industrial cluster in Asia. Although a major focus of this new thrust involves attracting leading life science companies overseas to establish operations in Singapore and developing new public life science research institutions to attract overseas life science research talents (Finegold, Wong, and Cheah (2004)), the local universities are expected to play an important role as well. In particular, the National University of Singapore (NUS), the leading university in Singapore, has also started to pursue major strategic change to become more "entrepreneurial", and identified life science as a major focus for technology commercialization as well. Adapting the "Triple-Helix" framework of Etzkowitz, Webster, Gebhardt, & Terra (2000), this paper examines the significant changes in the university-government-industry "Triple-Helix" nexus for life science in Singapore, and their consequent impact on life science commercialization at NUS. Implications for universities in other late-comer countries seeking to catch up in the global biotech race are discussed.

Keywords University technology commercialization · Innovation policy · Life science · Singapore

JEL Classifications O31 · O32 · O53

1 Introduction

There is by now a vast literature on the genesis and growth of biotechnology clusters in the world (see e.g. Cooke 2003, 2004). Notwithstanding some regional variations, the general consensus appears to be the critical new knowledge generation role of

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universities and public research institutes in the emergence and sustained growth of every major biotechnology cluster in the world. For example, Feldman and Francis (2003) showed how public funding of NIH in the Capitol region helped cement the region as the leading biomedical hub in the US, while Casper (2003) similarly argued for the crucial role of Cambridge University in the growth of the Cambridge area as a leading life science hub in Europe. As pointed out by Owens-Smith, Riccaboni, Pammolli, and Powell (2005) and Prevezer (2001), however, significant differences exist in terms of university organization and governance between the US and Europe, resulting in distinctive differences in the role of universities in the commercialization of life sciences in the US and Europe. Although no comprehensive studies have been conducted in the Asian context, preliminary evidence emerging in the literature (see e.g. Allen and Wong (2003)) suggests that Asian university technology commercialization practices appear to differ from the US model as well.

This paper examines the changing role of university in the national strategy to accelerate the development of Singapore as a regional hub for commercialization of life sciences. The paper focuses in particular on the National University of Singapore, the leading and largest comprehensive public university in Singapore. The government of Singapore is of course not exceptional in terms of its strategic targeting of the life science industry as a major economic development engine; the government of many other countries, not only relatively advanced ones but also newly industrialized economies and developing ones, have espoused a vision to build up indigenous biomedical industry capabilities. What probably makes the Singapore case of particular interest is the scale and intensity of the government effort. Moreover, this strategic move is taken from an initial position that is arguably further away from the biomedical technology frontier than were many other advanced OECD countries pursuing similar goals. The experience of Singapore is thus of relevant interest to study how the mission and governance of local universities in late-comer economies can be reformed to enable such economies to achieve a faster ‘‘catch-up’’ in the global biotech race.

2 Theoretical framework: adaptation of the nexus of Triple-Helix in a small open economy

As argued by Etzkowitz et al. (2000), universities around the world increasingly operate within a Triple-Helix nexus involving interaction with government institutions and private industries. In the context of life science, the nexus is characterized by a number of special characteristics, as summarized in Table 1. Notwithstanding some

Table 1 Key actors in the Triple-Helix nexus of life science

Private Industry	
	• Large global pharmaceutical MNCs • Dedicated biotech firms (DBFs) • Venture capital firms
Government	
	• Public Research Institute • Public Hospitals • Regulatory Institutions (Drug approval (equivalence of FDA), healthcare policy setting agencies, etc.)
Universities	
	• Teaching faculty/Research Labs • Technology licensing/commercialization arms

regional variations (Cooke, 2003, 2004), literature on the emergence and growth of leading life science industrial clusters in advanced countries suggest that they all share the core elements identified in Table 1: (a) the presence of cutting edge basic biomedical research by universities and public research institutes; (b) the emergence of entrepreneurial dedicated biotechnology firms (DBFs) seeking to commercialize certain promising results from the basic research; (c) the availability of seed funding by specialized venture capital that facilitates the formation of such DBFs; and (d) the provision of more sizable follow-on funding by large pharmaceutical firms to the DBFs in exchange for licensing deals that provide them with the downstream marketing and distribution rights. In most clusters, the presence of advanced hospitals (often in close proximity or related to the universities or research institutes) also provided significant lead-user feedbacks and testbeds of new medical technologies.

As argued by Cooke (2003), the science-driven nature of the biomedical industry suggests a higher degree of governmental role in the Triple-Helix nexus compared to other industries where ‘‘Porterian’’ market competitive forces may exert greater influence. However, in the context of small, open economies, especially late-industrializing economies like Singapore, the potential for greater governmental role is offset by the significantly higher degree of linkages to *foreign* actors. Although even advanced life science clusters in the world have a significant amount of extra regional and international linkages due to the global nature of life science knowledge production (Cooke, 2004), the degree of external linkages are expected to be significantly higher for any life science clusters to be established in small open economies like Singapore. In particular, from a public policy perspective, a strategic issue is how much a small open economy can afford to develop and nurture her own indigenous capabilities versus ‘‘borrowing’’ or ‘‘importing’’ the relevant capabilities from outside. To the extent that public policy puts greater weight on leveraging foreign linkages, it may entail significant changes to the structure of the traditional Triple-Helix nexus. This in turn puts greater pressure on the capabilities of the local universities to adapt their traditional governance and organization to assimilate or otherwise accommodate an increasingly greater degree of foreign elements in their own organization as well as in their nexus of external relationships.

Using the above framework, and building upon my earlier work on life-science cluster development in Singapore (Finegold et al., 2004) and national innovation system development more generally (Wong 2001, 2005), I first examine the key changes in the two key external sectors in the Triple-Helix nexus to which the National University of Singapore (NUS) is linked, before analyzing how the university responds to these external changes through instituting internal changes. I will then examine the impact such external and internal changes have on the performance of NUS’ life science commercialization.

3 Changes to the external industry and public policy contexts for life science commercialization

3.1 Overview of Singapore’s economic development strategies

Having achieved remarkable economic growth in the four decades after political independence in 1965, the city-state of Singapore entered the 21st century with a relatively high level of income/capita, but growing recognition of the need to sustain future growth through innovation. As highlighted by Wong (2001, 2005), for much of its history of rapid economic growth, Singapore had relied on a strategy of attracting DFI from global MNCs and leveraging them to exploit technologies and know-how developed elsewhere. However, as the city state's costs increasingly approach those of leading cities in the advanced economies, and as global competition for DFI continues to intensify particularly with the opening up of major economies in Asia like China and India with large domestic markets and abundant supply of skills, its only recourse to stay competitive is to become more innovative, i.e. not just by being efficient in ''using'' technologies and knowledge produced elsewhere, but by ''creating'' (commercializing) its own intellectual capital as well.

The global MNC-leveraging strategy has served Singapore well in the past, by making Singapore a leading information technology and electronics manufacturing and services hub in the world (Wong, 2002). Although on a smaller scale and started later, the same leveraging strategy appears to have worked as well in terms of developing Singapore into a major pharmaceutical manufacturing hub. As can be seen from Annex Table 1A, pharmaceutical manufacturing output in Singapore grew rapidly between 1990 and 2004, with average growth per annum exceeding 20%, reaching S$415.2 billion in 2004. In terms of value add contribution, the pharmaceutical sector in 2004 contributed 19% of total manufacturing output, up from less than 5% in 1990 (see Annex Table 1B). Reflecting the high capital intensity and scale of operations of such manufacturing activities, the average capital per worker for the industry amounted to S$0.9 million per worker in 2003, while the average output per firm was S$255 million, both significantly above the average of all manufacturing. Virtually all of the 40 pharmaceutical manufacturing firms in operation in Singapore in 2004 are foreign majority owned. Annex Table 2 provides summary profile of some of the leading global pharmaceutical companies with significant manufacturing operations in Singapore.

Table 2a R&D expenditure & manpower in the biomedical sector[1] (S$ million), 1993–2004

Year	Private sector	Higher education sector	Government sector	PRIC sector	Total	Total RSEs[2]
1993	3.6	32.1	7.4	0.0	43.1	447
1994	5.0	39.5	14.8	0.0	59.4	386
1995	29.1	37.0	15.3	0.0	81.8	570
1996	7.8	42.4	18.2	0.1	68.5	507
1997	15.0	47.5	25.2	3.5	91.2	556
1998	24.8	52.1	35.6	5.9	118.3	625
1999	37.1	53.1	29.1	3.6	122.9	654
2000	47.0	62.5	32.5	15.6	157.6	1333
2001	88.4	87.3	57.9	77.1	310.7	2055
2002	147.4	106.8	87.5	121.5	463.1	2150
2003	149.3	87.6	91.8	46.7	375.4	2504
2004	238.1	124.9	116.7	280.7	760.4	2238

[1] Includes biomedical sciences and biomedical engineering. From 2002 biomedical & related sciences and biomedical engineering

[2] RSE: No. of full-time equivalent Research Scientists and Engineers

Source: *National Survey of R&D in Singapore* (various years), Agency for Science, Technology and Research (previously National Science & Technology Board)

Table 2b Biomedical share of total Singapore R&D expenditure & manpower by sector (%), 1993–2004

Year	Private sector	Higher education sector	Government sector	PRIC sector	Total	Total RSE
		% of total Singapore R&D expenditure				% of Singapore RSEs
1993	0.6	20.4	6.9	0.0	4.3	6.7
1994	0.7	22.0	10.4	0.0	5.1	5.4
1995	3.3	19.2	13.9	0.0	6.0	6.8
1996	0.7	17.8	10.9	0.0	3.8	5.0
1997	1.1	17.1	11.6	1.2	4.3	4.9
1998	1.6	17.0	11.9	1.7	4.7	4.9
1999	2.2	17.1	9.5	1.0	4.6	4.7
2000	2.5	18.5	7.7	4.1	5.2	7.3
2001	4.3	23.8	13.6	19.5	9.6	11.1
2002	7.0	23.8	20.3	28.0	13.6	11.1
2003	7.2	19.1	21.1	10.4	11.0	11.8
2004	9.2	29.4	26.4	46.4	18.7	14.6

Source: Same as Table 2a

As part of her strategic shift towards a knowledge-based, innovation-driven economy, the government of Singapore began fine-tuning the global MNC leveraging strategies since the mid-1990s by putting increasing emphasis on attracting global MNCs to conduct R&D activities in Singapore, either as an extension of existing manufacturing operations, or as de novo standalone R&D operations. The expansion of R&D activities by foreign firms in Singapore contributed significantly to the rapid growth in recent years of the aggregate R&D/GDP ratio in Singapore, which increased steadily from only 0.3% in 1981 to 0.9% in 1990 and 1.9% in 2000, reaching 2.3% by 2004, a level that exceeds those of many OECD countries (Wong, 2005). Foreign firms accounted for more than one-third of total national R&D expenditure and 60% of total private sector R&D in the more recent years.

3.2 Life science strategies

As part of the overall intensification of investment in R&D and innovation, the Singapore government announced in 2000 a strategic shift towards the promotion of biomedical science and technology as a leading sector in the economy for the 21st century, and as a means to diversify from its previous high dependence on IT/electronics manufacturing. The vision is to turn Singapore into Asia's premier hub for biomedical sciences, with world-class capabilities across the entire value chain, from basic research to clinical trials, product/process development, full-scale manufacturing and healthcare delivery (Biomed-Singapore, 2003). To achieve this vision, a US$1 billion fund was initially allocated to boost public investment in several new life science research institutes, to co-fund new R&D projects by global pharmaceutical firms, as well as to initiate the building of a new life science complex called Biopolis. Additional public funding was further announced to sustain the growth of the life science cluster beyond 2006.

Since the announcement of the new initiative, the government has moved decisively in terms of implementation (see Finegold et al., 2004 and Tsui-Auch, 2004 for more details). A new Biomedical Research Council (BMRC) was established in the

Table 3 Share of life science patents in Singapore, 1977–2004

Note: Singapore assigned patents and patents with at least one Singapore inventor

Source: Calculated from USPTO database

Year	Life science patents	Total patents	Life science patents/total patents (%)
1977–1991	5	187	2.7
1992–1999	26	969	2.7
2000–2004	55	2486	2.2
Total	86	3642	2.4

revamped public agency responsible for public R&D funding (A*STAR, formerly known as NSTB) to allocate R&D funding to strategic biomedical research areas. Four new public research institutes (PRIs) in bioinformatics, genomics, bioprocessing and nanobiotechnology were established over the period 2000–2002, while the existing Institute of Molecular & Cell Biology (IMCB) was expanded (see Annex Table 3). Public fund amounting to $200 million has been committed to three bioscience venture capital funds to fund start-up of DBFs in Singapore as well as to attract DFI by overseas DBFs in Singapore. A further $100 million has also been earmarked for attracting up to five globally leading corporate research centres.

The four new life science-related public research institutions have all been located in Biopolis, a new physical hub for life sciences costing S$500 million when completed that is intended to make Singapore a world-class life science R&D hub for the Asian region. Dedicated to biomedical R&D activities and designed to foster a collaborative culture among the institutions present and with the nearby National University of Singapore, the National University Hospital and Singapore's Science Parks, the Biopolis also provides integrated housing and recreation facilities for the many foreign scientists to be attracted to work in the research facilities.

Because of the ambitious scale and speed of development, the attraction of foreign talents has become an integral part of the government's life science strategy. Not only would it have taken much too long for the local university to train and develop the large number of scientists needed to staff these major new research institutes, there was also a dearth of local star researchers with sufficient international reputation and stature who can serve as the initial magnet to attract other younger researchers (Zucker & Darby, 1996). Consequently, the government focused much attention initially on attracting several internationally renown scientists, including Sidney Brenner, a Nobel laureate; Alan Colman, the leading transgenic animal cloning scientist from Scotland's Roslin Institute; Edison Liu, the former head of the US National Cancer Institute; Sir David Lane, the former director of Cancer Research UK's Cell Transformation Research Group; and Yoshaki Ito, a leading Japanese cancer researcher who recently retired from a leading Japanese university. The directorship of the new Nano-Biotechnology Institute also went to a young rising star researcher from MIT, Jackie Ying. Other star researchers talent-spotted include Axel Ullrich, a well-known molecular biologist from Max Planck Institute for Biochemistry, and Markus Wenk, a noted biophysicist and lipid researcher from Yale (Traufetter, 2005).

Although most of these new PRIs maintain some affiliation with the National University of Singapore, they have been funded separately by the BMRC and are largely autonomously operated with their own management and advisory board that report directly to the BMRC.

The government has also intervened significantly in the development of a specialized life-science venture capital industry. Although a relatively sizable venture capital industry had emerged in Singapore (driven partly by initial government's injection of funds as LPs) by the end of 2000, there was hardly any local expertise on life science related VC investing, due to the lack of a critical mass of life science DBFs in Singapore. Consequently, the government took a lead role in directly running a number of life-science related funds, which were subsequently centralized under one fund management umbrella called Bio*One Capital. To-date, Bio*One Capital reported investment in 36 portfolio companies in the area of drug discovery/development, cellular therapy, medical technology, and protein therapeutics/monoclonal antibody. Bio*One also invested funds in five other life-science VC funds, perhaps as an inducement for these fund to operate in Singapore. Although many of the portfolio companies of Bio*One were originally founded outside Singapore, the fund had been instrumental in getting some of them to move some operations into Singapore. For example, Bay Area-headquartered Fluidigm had chosen Singapore to locate her first Asian manufacturing operation.

Through support activities such as Bio*One, a fledgling DBF sector comprising over twenty firms has emerged in Singapore (see Annex Table 4). Although still relatively small when compared to the leading biotech clusters in the world, the record is actually creditable, given that there were virtually no such DBFs 7–8 years ago. Complementing these DBFs, about a dozen global pharmaceutical companies as well as a number of independent contract research organizations (CROs) have also been attracted to establish some R&D operations in Singapore (see Annex Table 2).

Reflecting the growing emphasis on life science research, the share of total R&D expenditure in biomedical fields rose sharply from less than 5% in the 1990s to over 18% by 2004 (see Table 2). However, symptomatic of the long gestation nature of much of biomedical research, the share of biomedical-related patenting in total output of patenting by Singapore-based inventors continued to lag behind its share of R&D spending. As can be seen from Table 3, while the cumulative number of biomedical patents granted by USPTO to Singapore-based inventors and Singapore-based organizations more than doubled in the five years 2000–2004 compared to

Table 4 Profile of National University of Singapore (NUS) (FY 2004/5)

Indicator	FY 2004/5
Faculty members (end June 2005)	1,765
Research staff (end June 2005)	1,087
Undergraduate students enrolled	21,761
Graduate students enrolled	6,461
Total research funding	S$157.6 mil
Journal publications in SCI/SSCI (CY 2004)	2,930
Patents filed	124
Patents granted	51
Cumulative US patents granted (CY1990–2004)	162
Cumulative journal publications (Jan 1995–June 2005)[1]	21,760

[1] Thomson ISI-indexed journal articles only

Source: NUS Annual Research Report 2003–2004, National University of Singapore; NUS Annual Report 2005, National University of Singapore; Database of the USPTO before 2000, the share of biomedical patents in total patents granted actually declined slightly (from 2.7% before 2000 to 2.2% for the five years 2000–2004).

Consistent with the larger role of public sector (including universities) in life science research, two-thirds of biomedical R&D expenditure in Singapore in the 2000–2004 period were conducted by public organizations, versus about one third for non-biomedical R&D. Taking into account the financial incentives given to some private sector pharmaceutical firms to conduct R&D in Singapore, the share of public funding in R&D spending in Singapore is likely to be larger than two-thirds. It is also interesting to note that, while biomedical R&D accounted for only 15% of total research scientists and engineers (RSEs), it accounted for close to one-quarter of all PhD holders in R&D.

Notwithstanding this recent rapid growth in importance of life science R&D in Singapore, it is important to recognize that, compared with the advanced countries that are the world leaders in biomedical science and technology, the scale and intensity of Singapore's biomedical R&D remains modest. For example, Singapore's total annual biomedical R&D spending of about US$450 mil. is about 1% of US federal annual funding for biomedical R&D (estimated at US$38 billion in 2002). Even in terms of intensity, Singapore's biomedical share of around 12% of total national R&D is still substantially lower than that of UK and US (over 25%). Finally, biomedical technology output from Singapore in 2004 amounted to about S$2 billion, only 13% of the total pharmaceutical manufacturing output in Singapore in the same year (BMS, 2006).

In addition to direct commitment of public funding, the government also significantly changed the regulatory and promotional landscape for life science industry development in Singapore. Exploiting the ban on new stem cell lines in the US, the Singapore government allowed, and indeed strongly promoted, the establishment of stem-cell research in Singapore, enabling the island state to gain a beachhead for stem-cell based work (Chang, 2001). The government also established various promotional initiatives designed to make Singapore a regional hub for life science-related conferences, publishing and networking, as well as putting in place a tighter bioethics policy framework governing life science research, after a controversial case involving alleged breach by a noted researcher recruited from Cambridge University (see Annex Table 5 for a summary of major milestones of life science industry development in Singapore). Last, but not least, the government also hastened the move towards increasing competition in the national healthcare system, including greater liberalization and transparency of pricing of healthcare services, and greater

Table 5 Ranking of NUS in the World University rankings by the Times Higher Education Supplement, 2004–2005

	2004 ranking	2005 ranking
Overall	18	22
Biomedicine	25	15
Science	35	34
Technology	9	9
Social Sciences	10	13
Arts and Humanities	17	56

Source: Knowledge Enterprise Online, various issues, downloaded from http://www.news-hub.nus.edu.sg/; The Times Higher Education Supplement (various years) autonomy among the public hospitals in introducing innovations to gain competitive advantage. In addition, the government is promoting Singapore as a regional healthcare hub by inviting foreign healthcare players to invest in Singapore, further exerting competitive pressure on the public hospitals to improve their operational efficiencies.

4 Changes to internal university policy contexts for life science commercialization

4.1 Overview of National University of Singapore (NUS)

Established in 1905, National University of Singapore (NUS) has been the oldest and largest public university in Singapore, with a total student enrolment of over 34,000 (two-third of which are undergrads). Although there are two other public universities in Singapore, both were newer and not as comprehensive in scope (NTU was established in 1965 and until recently primarily focused on engineering, applied science, accounting and business, while SMU was only established in 2000 and focuses on management and economics education). Besides enjoying higher reputation and a much stronger overall track record in terms of internationally refereed research publications, NUS has also established a strong lead in terms of patenting records than NTU. In addition, with the only medical school and faculty of science, NUS had a practical monopoly on biomedical research and education. Although this is likely to change in the future with the establishment of a new medical school and a new school of life sciences in NTU in 2004, for the purpose of this study, I confine my analysis on NUS.

Table 4 provides a summary profile of NUS. With an annual R&D budget of about S$158 million in 2004, NUS alone constitutes almost 5% of total R&D spending in Singapore. With 162 US patents, NUS is also the third largest patent holder in Singapore, after Chartered Semiconductor (a local firm) and HP (a foreign MNC subsidiary). Despite being a relatively late comer, NUS has begun to attract international recognition of her research capabilities and educational standards, as reflected by her surprisingly high ranking in the recent Times Higher Education Supplement's annual rankings of top 200 universities in the world (see Table 5), both overall as well as for individual faculties. In particular, NUS was ranked 15th in the field of Biomedicine in 2005, up from 25 in 2004.

4.2 Recent shift towards entrepreneurial university model

Like most other public universities developed under the British Commonwealth tradition, NUS has in the past been following the traditional model of having teaching as her primary mission, with research as a secondary function. While the 1980s and 1990s saw increasing emphasis on research, it was only in the mid-1990s that NUS established a technology licensing office.

The major impetus for change came only at the end of the 1990s, when a new vice-chancellor was appointed who enjoyed the strong support of the deputy prime minister who oversaw tertiary education. Harvard-trained and having prior background in US industry (General Electric) and research administration experience at an Ivy-League university in the US, the new vice chancellor not only significantly accelerated the pace of change of several initiatives that were already in motion earlier, but more importantly, he initiated a shift towards what Etzkowitz et al. (2000) has described as the ‘‘entrepreneurial university’’ model. Emphasizing the need to make the university more entrepreneurial, he created a new division in the university that has come to be known as NUS Enterprise, and hand-picked as the CEO of the new organization a professor from the engineering school who had been among the earliest to spin-off a company to commercialize his invention. Under the broad mission to inject a more entrepreneurial dimension to NUS education and research, the CEO was given great latitude to define and implement new initiatives to make the university ‘‘more enterprising’’. After some early experimentation, NUS Enterprise began to re-shape a number of key university policies with respect to governance of technology commercialization. Among the key changes introduced, the technology licensing office was re-organized to become more ‘‘inventor friendly’’, with less emphasis on maximizing licensing revenue, and greater focus on getting greater deployment of NUS technology to the marketplace, whether through licensing to existing firms or spinning off new firms. A new Venture Support (NVS) unit was also created with the explicit aim of providing assistance to NUS professors to commercialize their inventions and knowledge. Besides the provision of Incubator facilities, NVS also launched a seed fund that providing seed funding to NUS spin-off companies. A student start-up fund was also established to provide seed funding to new ventures started by students.

In terms of education program, a university level Entrepreneurship Centre was also established within NUS Enterprise with the mission to teach entrepreneurship to all students on campus, particularly students in engineering, computing and science, including life science and medical students. The centre was also given the task of building a network of entrepreneurs, venture capitalists and angel investors to provide NUS spin-offs with mentoring by practitioners and access to external venture funding.

Besides pushing for greater enterprise, the new university vice-chancellor also seeks to ‘‘globalize’’ the university, arguing that, with growing global competition for faculty, students and resources, NUS needs to adopt globally competitive governance and practices to stay competitive. Indeed, he adopted ‘‘Towards a Global Knowledge Enterprise’’ as the vision statement for NUS. Under this globalization drive, he began to shift the emphasis away from local manpower development to incorporate a twin objective of making the university a global educational hub, attracting top foreign students and faculty in increasing competition with other leading universities in the world. In line with this globalization drive, NUS began revising her faculty compensation and policy, making it more flexible to allow the university to pay more to attract top talents. Tenure and promotion policy was made much more stringent and performance-based in line with the benchmarks of leading universities in the US. Intake of foreign students also increased, while a larger share of local students are encouraged to go on exchange program abroad for at least a semester.

A new initiative that integrated both dimensions of globalism and entrepreneurship was introduced via NUS Enterprise—the so-called NUS Overseas College Program (NOC), under which the university would send her brightest undergraduate students to five entrepreneurial hubs in the world to work as interns in high-tech start-up companies for one year, during which they would also take courses related to entrepreneurship at partner universities in each of the regions. The first NOC program was launched in Silicon Valley in 2002, followed by Philadelphia in 2003, Shanghai in 2004, Stockholm in 2005, and Bangalore in India in 2006. The choice of Philadelphia is noteworthy, as it was deemed a major hub for pharmaceutical companies and hence serves to nurture entrepreneurial interest in life sciences in particular.

4.3 NUS' life science strategies

Besides the broad shift towards a US-model of university governance for attracting and keeping talent, international benchmarking for promotion & tenure, and "inventor-friendly" technology commercialization policy, the university also made specific policy and organizational changes in life science education and research. An Office of Life Sciences (OLS) was set up formally in 2001 with the mission to make NUS into a world-class hub for life sciences. It aims to accomplish its mission by coordinating, integrating and facilitating Life Science throughout the University and affiliated institutions. In line with the Government's emphasis on Life Sciences as the next pillar of Singapore's economy, the OLS is also charged with launching new research initiatives and teaching programs.

Among the new educational initiatives that OLS has introduced include a new integrated Life Science Undergraduate Major Program that involves the participation of five core faculties (Computing, Dentistry, Engineering, Medicine and Science). A new bio-engineering division was also set up in the Engineering School that crosses traditional departmental boundaries within the school.

In terms of research, OLS also brought together researchers from the five core faculties to collectively identify and agree to 10 strategic areas of research, grouped under two broad headings of Diseases and Platform Technologies. Under *Diseases*, the priority areas identified comprise Cancer, Neurobiology/Ageing, Vascular Biology/angiogenesis, Hepatology and Infectious Diseases. Under *Platform Technologies*, the five priority areas identified consist of Bioinformatics /Registries/ Molecular Epidemiology, Structural Biology/Proteomics/Genomics, Immunology, Bioengineering and Experimental Therapeutics /Medicinal Chemistry/Toxicology/ Clinical Trials. In forging consensus on these 10 core areas, OLS hoped to ensure greater strategic focus of research within NUS as well as to provide strategic directions for developing new collaboration with other research institutes within and outside NUS, as well as with renowned international institutes.

As a further indicator of the strong commitment of NUS to strengthen her life science expertise, the university recently obtained approval by the government to establish a second medical school. Unlike the existing medical school, which is in the British tradition of taking students directly from high schools, the new school was modeled after the US post-graduate, professional medical school, with students drawn from graduates from various disciplines and faculty recruited to emphasize research excellence. The school was established in collaboration with a leading US medical school (Duke University), and was located next to the largest public hospital (Singapore General Hospital) to facilitate close interactions, particularly in research and clinical trials. Through this new initiative, NUS as a university is now closely linked to the two largest public hospitals in the country through two different medical school models, thereby encouraging competition and exploration of different innovative models in university-industry collaborations.

4.4 Summary of changes to the Triple-Helix nexus for life science commercialization

Table 6 summarizes the key changes among the actors in the Triple-Helix nexus for life science in Singapore. In essence, at the risk of over-simplification, the period of

Table 6 Summary of changes in the Triple-Helix Nexus for life science in Singapore

Structure of Triple-Helix Nexus	Period up to the late-1990s	Period from 2000
Large pharmaceutical companies	Primarily manufacturing operations by foreign MNCs	Continued expansion of foreign MNC manufacturing, But some R&D activities by foreign MNCs are emerging
Manpower recruitment role	Primarily to staff manufacturing operational needs	Recruiting for both manufacturing and R&D
Research sponsorship role	Relatively minor	Increasing in importance
DBFs	Negligible presence	Emergence of a cluster of DBFs, including both locals and foreign implants
Government		
Public research institutes	Relatively small presence (IMCB)	Significant growth: 5 major PRIs
Physical infrastructure	General science park; No specific life-science focus	Ambitious Biopolis plan adjacent to NUS
Finance infrastructure	General VC industry promotion, no life science focus	Sizable life-science VC funds, but mostly government-funded
	Public R&D funding not significantly dedicated to life science	Significant dedicated strategic public R&D funding allocated to life science via BMRC
Manpower development	Scholarships not significantly targeted for students in life science	Significant dedicated scholarship program for life science studies
		Foreign talent attraction program
Policy infrastructure	General IP framework, not life-science specific	Bio-ethics guideline
Public healthcare institutions	High regulatory control, limited competitions	Controlled competition
Universities		
Mission	Traditional University model: Primarily manpower development, some basic research	Entrepreneurial University model: Manpower development, research & technology commercialization
Organization of research & teaching	Compartmentalization by traditional disciplines Ambiguous relationship with university hospital	Emergence of cross-disciplinary integration (OLS) University hospital an integral part of Life-Science Program; new post-graduate Medical School model introduced
Institutional support for tech commercialization	Embryonic TLO, limited support services (mainly patent filing)	Revamped TLO, broader marketing role
	No Spin-off support	Venture Support Program, Incubator facilities & seed funding
	No training program	Training program and seminars
Tech commercialization governance policy	Tech commercialization policy in flux , royalty revenue oriented	Clear policy favourable to inventor and spin-off founders, equity in lieu of royalty

the early 2000s can be characterized as a period of great flux, with the role of government dramatically increased, an embryonic DBF sector starting to emerge alongside increased R&D presence by subsidiaries of global pharmaceutical firms. At the same time, the university sector itself, both responding to the new government and industry agenda on life science as well as the university's own effort to reform itself, began transition from a traditional teaching school model to the "entrepreneurial university" model.

As can be seen from Table 6, the impacts of the changing government and industry contexts on NUS are multi-faceted, having both competitive as well as synergistic elements. For example, the PRIs were generally able to offer more flexible and generous employment packages, not to mention the prestige of having anchor star researchers and newer facilities and equipment, and thus created competitive pressures on NUS in terms of scientific manpower recruitment. Their strong research focus on key strategic areas also made them more attractive partners than NUS for collaboration with global MNCs in some cases. On the other hand, with the close proximity of Biopolis to NUS, potential synergies are being created where NUS research competence may be complementary to the PRIs. The growth of the embryonic DBF sector has so far not been sufficiently large to draw talents away from NUS, although the potential for conflict may exist in the future, as occurred in other leading biotech hubs in the world.

5 Impacts on university life science commercialization

5.1 Overview of NUS life science commercialization performance

Consistent with her significant role in biomedical research in Singapore, NUS represents the single largest biomedical patent holder in Singapore, accounting for 25 out of 86 US patents granted in the field of biomedical technology over the period 1996–2004, or nearly one-third (see Table 7). However, these 25 biomedical patents represent only 16.0% of all patents granted to NUS, a share that is lower than electrical and electronics (32%) and computer technology (25%) (Table 8). Compared to the estimated 25% biomedical share of total R&D expenditure in NUS

Table 7 Breakdown of Singapore life science patents by assignee, 1977–2004

	No. of patents	%
Private	32	37.2
NUS	25	29.1
Government and PRIC	16.5	19.2
Individual/unassigned	11	12.8
Other IHL (foreign)	1.5	1.7
Total	86	100.0

Note: Singapore assigned patents and patents with at least one Singapore inventor. Two patents had two assignees; half a count was given to each assignee

Source: Calculated from USPTO database. Following the NBER technological categories, life science patents are taken to be those in drugs, surgery and medical instruments, biotechnology and miscellaneous-drugs and medical

Table 8 Breakdown of NUS patents by technology category, 1990–2004

Technology category	No. of patents	%
Electrical & Electronic	52	32.1
Computers & Communications	40	24.7
Chemical	24	14.8
Life sciences	26	16.0
Mechanical	13	8.0
Others	7	4.3
Total	162	100

Note: The NUS figure for life sciences does not correspond to that given in Table 7 because a full patent was counted to NUS even when it was jointly assigned

Source: Calculated from USPTO database

in recent years, the above suggests that the R&D cost to generate commercializable IP in the biomedical field is higher than in other disciplines.

In terms of spin-off companies, 11 out of over 40 companies (25%) that were spun-off by NUS up to 2004 were in biomedical related fields. As can be seen from Annex Table 6, virtually all the companies were in biomedical technology rather than in therapeutic drug discovery. Moreover, the amount of external venture funding attracted by these spin-offs remained modest, with the majority being funded by the founders themselves and business angel investors, rather than by formal VC firms.

In terms of technology licensing, NUS' market reach has been somewhat more extensive. Not counting a number of prior biomedical licenses that had expired, there were 31 active licensees of biomedical related patents, ranging from NUS spin-offs to local DBFs and global pharmaceutical companies at the end of 2004. Although the cumulative amount of royalties generated to-date was not published, it was likely to remain modest, since the majority of the licensing deals were concluded only over the last 2–3 years.

Overall, the aggregate statistics shows that the extent of biomedical technology commercialization from NUS, while still relatively modest, has visibly increased in recent years, both in terms of licensing deals as well as formation of spin-off companies. Seven of the eleven biomedical spin-offs were from 2000 onwards, as were the majority of the licensing deals.

The above aggregate picture is further reinforced by my findings from several in-depth case studies conducted with founders and inventors from NUS. In particular, it is instructive to compare and contrast the experience of two faculty members who sought to start their own biomedical ventures, one before the recent policy shift towards technology commercialization, and one after.

Lynk Biotechnology was founded by Assoc. Prof. Lee Chee Wee at the beginning of 2000, after he received US$1 million angel investor seed funding. Although the initial plan for the company was to focus on drug discovery work, this was abandoned when the company ran out of money and could not secure any follow-on VC investment. It also did not help that the technology licensing office at NUS at that time drove a hard bargain in terms of licensing negotiation, resulting in the company having to pay a hefty upfront royalty fee to the university. The founder was also not able to rent any part of his university lab facility to conduct research for his company, and had to move out to commercially rented facility outside the university.

Concluding from his experience that the classic US model of drug development would not work in Singapore, he subsequently changed his business model to developing health supplements that do not require FDA approval, as well as new trans-dermal techniques for delivery of approved FDA compounds. Pouring in his own money to fund his new business model, and without any help from NUS, he was able to develop a number of products (including a cream for relieving arthritis pain) that started to generate good revenue. With annual revenue reaching S$5 million, the company managed to attract in late 2004 a S$2.5 million investment by a local private equity firm Whiterock Investments that specializes in medical technology. With the new investment, the company was able to embark on a new research and production facility not only to expand his current production, but also to support his earlier proteomics research work. The company also started development work to make biodegradable soaps for industry.

In contrast to the earlier experience of Lynk Biotechnology, a more recent biomedical-related venture, Chiral Sciences, has a much smoother start-up experience. Co-funded by two professors from the chemistry department in 2002 to commercialize their technique for separating left-handed molecules from right-handed ones, the company was able to quickly obtain an exclusive technology licensing agreement with NUS that involved equity in exchange of royalty payment. The company also received seed funding from NVS Seed Fund in 2004 on fairly generous terms, and was given space in the NVS Business Incubator to operate. Financial assistance was also given to the company to co-finance a trip to the US to pitch to potential venture capitalists and to seek prospective business partners.

The experience of two other life science inventors in licensing their technologies to large pharmaceutical companies over the two different periods also prove instructive. A husband and wife team of microbiologists, the two professors were among the first NUS faculty members in the life science field who became interested in commercializing their inventions in the early-1990s. Their interests initially grew not out of encouragement by NUS, but from a visiting professor from the US who pointed out to them the commercial potential of their discoveries. Lacking prior experience—they did not even know what a patent was at that time—they went to the then relatively newly established NUS technology licensing office to help them prepare and file several patents. Although the patents were eventually filed and granted, they found that the process was more costly and incurred longer delay than should have been the case, due to lack of experience on the part of the technology licensing office at NUS at the time. Moreover, they found that the office was of no help in the subsequent marketing of their patented technology; not only did they have to spend their own money to go on road-shows in the US and UK to pitch to potential licensee companies, they also found that there was little follow-up by the NUS technology licensing office on the leads they provided. In the end, their invention was serendipitously discovered by an American company, after the company CEO saw a BBC TV program where the two researchers were interviewed on their discovery. This led to the eventual licensing of their technology to the US company, but on terms that in hindsight may have been less favourable than it could have been, had the NUS licensing office conducted a more thorough due diligence on the potential value of the invention to industry. The two professors also had a second invention in the late 1990s that they tried to license to local industries without any success, as none of them was interested in investing in the further work needed to develop their invention into end products. In the end, the technology was licensed to another foreign company (in UK), which provided the specialized legal expertise to draft the patent. By the time the pair came out with yet another discovery in 2003, however, they were able to find much more assistance from the NUS technology licensing office, which by then had divisionized its operation into separate technology areas staffed by better qualified specialists, including one on life science. Assistance in marketing and publicity was also provided. Suitably encouraged, the two professors are now seriously considering commercializing their latest invention through their own spin-off company instead of licensing to external parties.

As these three cases illustrate, there had been tangible improvements in the NUS technology commercialization policy and infrastructure support in recent years. Nonetheless, this had not led to any drug discovery-type of spin-off from NUS yet. Interestingly, a number of applications proposing drug development could not be considered for funding by the NVS seed fund, because its charter was limited to seed funding ventures that have a good prospect of receiving a sizable follow-on external funding by VCs or business angels, and none of the life science VCs operating in Singapore expressed any interest. Thus, there appears to be a limit to what the university on its own can do to encourage drug-discovery type of commercialization; the external venture support ecosystem also needs to further improve. In contrast, NUS was better able to facilitate the commercialization of biomedical technologies that have lower investment requirements or shorter gestation period to bring products to market: All eight NUS spin-offs in the biomedical field so far are in biomedical equipment, bioinformatics and non-drug products.

6 Conclusion

Singapore's strategy to develop the island state into a leading biomedical hub in the world has emphasized leveraging foreign firms and talents. This has been manifested in a much stronger emphasis on creating new de novo public research institutions to host largely imported foreign scientific talents, as well as attracting foreign MNCs to extend R&D operations in Singapore in addition to manufacturing operations. The development of indigenous capabilities of the local universities is emphasized, but perhaps at a lower level of priority, partly because of limitations on how fast and how much the local universities can be adapted to meet the national agenda.

Notwithstanding this, my analysis of the changes in policies and organizations of NUS, the largest and leading research-based university in Singapore, shows that the university has responded relatively quickly to the changing national agenda. Although these changes have not yet led to significant commercialization leading to major new drug-discovery, there has been a tangible increase in the pace of spin-offs and technology licensing in areas such as bioinformatics, biomedical equipment and non-therapeutic products, where the venture financing requirements are less daunting.

While the focus on fast execution by the Singapore government, no doubt motivated by a concern for seizing advantages in a global competitive race, necessitated the strategy of high reliance on foreign talents and firms, this strategy carries a longer term risk of indigenization failure (Tsui-Auch, 2004). A key challenge is therefore how to ensure a sufficient number of foreign talents would eventually decide to settle down in Singapore. While a variety of incentives have been offered by the Singapore Government to retain foreign talents, including investment in cutting edge R&D facilities, ready availability of research grants, practice of meritocracy and offer of citizenship, coupled with conducive factors such as cosmopolitan culture, excellent international schools and a clean and green living environment, how successful Singapore is in retaining the various top foreign scientists remains to be seen, given that the government of the home countries of these scientists are likely to want to attract them back in the future.

The experience of NUS suggests that universities in developing economies need to make a transition from the traditional university model to the ‘‘entrepreneurial’’ university model before they can play an effective role in the Triple-Helix nexus for commercialization of life science. Otherwise, the local universities risk being marginalized, as government development agencies, in their haste to catch up in the global biotech race, put priority on autonomous public research institutes. However, while the shift towards the entrepreneurial university model can arguably speed commercialization of university biomedical technologies that have shorter gestation and lower financing requirements, major drug discovery efforts are unlikely to result from policy changes at the university level alone; more fundamental changes in the overall life science eco-system, including the presence of sophisticated life science venture capital, access to big pharmaceutical companies, and collaborative links with local hospitals, are necessary.

Last but not least, the experience of Singapore also suggests the need for policy makers to pay greater attention to ensuring a more balanced Triple-Helix structure of university-government-industry linkage in life science cluster development. In particular, while there is a temptation by government developmental agencies to favor autonomous public research institutes to spearhead life science R&D in the short-run, this may be counter-productive in the long-run without a synergistic integration between the public research institutes and the local universities (Lehrer & Asakawa, 2004). While emphasizing the development of PRIs, the Singapore experience suggests that the role of local universities has not been neglected. In the global race among nations to develop biotech industrial capabilities, Singapore’s competitive edge may well be her adaptive ability to evolve quickly and flexibly a balanced Triple-Helix nexus of players from the private, government and university sector. Despite starting relatively late, Singapore’s track record in rapidly putting in place the key Triple-Helix elements through an aggressive and targeted policy of attractive foreign companies and talents, a strong public sector commitment in investing in PRIs and supporting infrastructure, and a responsive university with an entrepreneurial orientation, provides ground for optimism that Singapore will indeed emerge as a major biotech industrial hub in the world in the longer run.

Annex

Annex Table 1A Profile of the Singapore pharmaceutical products sector, 1990–2004

Year	Number of firms	Number employed	Output S$million	Net value added S$million	Net fixed assets S$million	Val. add/labour $'000	Fixed asset/labour $'000	Output/firm $million	Val. add/output %
1990	19	1,664	1,020.8	809.1	na	486.2	na	53.7	79.3
1995	18	1,855	1,339.0	1,083.5	583.7	584.1	314.7	74.4	80.9
1996	17	1,758	1,695.8	1,428.3	339.7	812.5	193.3	99.8	84.2
1997	20	1,698	1,803.2	1,526.0	650.4	898.7	383.0	90.2	84.6
1998	19	1,629	2,857.3	2,437.6	640.0	1,496.3	392.9	150.4	85.3
1999	22	1,840	4,913.6	4,404.5	687.2	2,393.8	373.5	223.3	89.6
2000	25	1,928	4,839.1	2,998.4	858.6	1,555.2	445.3	193.6	62.0
2001	28	2,375	5,134.2	2,796.8	2,085.3	1,177.6	878.0	183.4	54.5
2002	38	3,203	8,170.6	4,892.5	2,607.1	1,527.5	814.0	215.0	59.9
2003	40	3,584	10,216.9	5,746.1	3,200.7	1,603.3	893.1	255.4	56.2
2004[p]	na	3,851	15,166.5	8,980.2	na	2,331.9	na	na	59.2
Average per Annum Growth Rate (%)									
1990–1995	–1.1	2.2	5.6	6.0	Na	3.7	na	6.7	
1995–2004	10.5[a]	8.5	31.0	26.5	23.7[a]	16.6	13.9[a]	16.7[a]	
1990–2004[b]	5.9[b]	6.2	21.3	18.8	na	11.8	na	12.7[b]	

[p] Preliminary figures

[a] 1995–2003

[b] 1990–2003

Note: Data for 1990 is from SSIC 35220 (Medicinal & pharmaceutical products), and from SSIC 242 (Pharmaceutical products) for all other years

Source: *Report on the Census of Industrial Production* (various years), Economic Development Board.

Report on the Census of Manufacturing Activities(various years), Economic Development Board.

Economic Survey of Singapore 2004, Ministry of Trade and Industry

Annex Table 1B Pharmaceuticals' share of the Singapore manufacturing sector, (Percentage), 1990–2004

Year	Number of firms	Number employed	Output	Value added	Net fixed assets
1990	0.51	0.47	1.43	4.90	na
1995	0.45	0.50	1.18	4.05	2.21
1996	0.42	0.48	1.41	5.22	1.17
1997	0.49	0.46	1.43	5.20	1.76
1998	0.47	0.46	2.35	8.67	1.72
1999	0.56	0.54	3.68	14.56	1.78
2000	0.62	0.56	2.96	7.70	2.03
2001	0.69	0.69	3.71	8.76	4.33
2002	0.44	0.90	5.55	13.46	5.44
2003	0.47	1.02	6.44	15.51	6.99
2004[p]	na	1.09	7.99	19.02	na

[p] Preliminary figures

Source: Same as Annex Table 1A

Annex Table 2 Major foreign pharmaceutical companies operating in Singapore

	Company	Business Focus	Date of establishment[1]	Size of operation[2]
Manufacturing	GlaxoSmithKline (GSK)	Bulk active biomanufacturing & regional headquarter	1989	> S$1 billion invested. As of 2004, GSK announced an additional $100 million to expand existing manufacturing facility and $50 to develop a Process Technology Centre (to be completed in 2005)
	Schering-Plough	Bulk active biomanufacturing (Clarityne)	1994 1997—began production	3 of 6 manufacturing plants built in Singapore with a total investment of US$730 million in Singapore, 29,000 employees worldwide[3]
	Genset Singapore	Oligonucleotide manufacturing	1997	536 employees worldwide (2000) with manufacturing sites in US, Japan, Singapore
	Wyeth-Ayerst	Biomanufacturing (Infant nutritional, Premelle)	1999 2002—began operation	Will employ up to 600 employees at full capacity[4]
	Aventis	Bulk active biomanufacturing (Enoxaparin)	2000	65,000 employees worldwide
	Pfizer	Active ingredient biomanufacturing	2000 (fully operational in 2004)	241 employees in Singapore as of mid-2003, 98,000 worldwide.
	Merck Sharp & Dohme	Bulk active biomanufacturing (Vioxx, Singulair)	1993[5] (operational in 2001)	> 200 employees in Singapore[6], 62,000 employees worldwide
	Proligo	Oligonucleotide manufacturing	2002[7]	
	Novartis	Pharmaceutical production	2005—ground-breaking of facility. (Completion in 2008)	S$310 million. Will employ 200 people
	Ciba Vision	Contact lens manufacturing	2004—construction of facility began	Will employ > 500 employees
	Lonza	Biopharmaceuticals production	2005 August	Will have 4 Mamalian bioreactor trains when completed in 2 years' time
	Fluidigm Corporation	R&D and manufacturing of integrated fluidic circuits	2006	

Annex Table 2 continued

	Company	Business Focus	Date of establishment[1]	Size of operation[2]
Clinical research and trials	Novo Nordisk	Administration, clinical trial coordination	1989—regional HQ 1999—clinical trial center	50 employees in Singapore, 18,221 employees worldwide
	Quintiles	Clinical research organization	1995	60 employees in Singapore, 800 employees in Asia-Pacific, 18,000 employees worldwide Investment of $10 million for clinical trial supplies facility
	Covance	Clinical research organization	1996—Clinical development 2000—Lab site	118 employees in Singapore, 7,900 employees worldwide Investment of > US$1 million
	Pharmacia & Upjohn	Clinical research & medical services	2000	See note [8]
Research & Development Center	Genelabs Diagnostic	Diagnostic biotechnology	1985	42 employees in Singapore in 2001, 70–90 employees worldwide
	Becton Dickinson	Instrumentation, medical products	1986—Medical product 1991—Regional HQ	1,000 employees in Singapore, 2,500 employees in Asia Pacific
	Oculex Asia	Ophthalmic drug delivery systems	1995	13 employees in Singapore, 59 employees worldwide (mid 2000)
	PerkinElmer	Thermal cycler	1998	Opened S$10 million manufacturing and R&D facility
	Sangui Singapore	Blood supplements and therapeutics	1999	5–15 employees in Singapore, 30 employees worldwide (mid 2002)
	Cell Transplants International	Cardiac myoblast therapeutics	2000	15 employees in Singapore
	Schering-Plough	Pilot plant, development laboratories, supplying materials for late-stage clinical trials	2000	Constructing US$25 million Chemical R&D center

Annex Table 2 continued

Company	Business Focus	Date of establishment[1]	Size of operation[2]
Surromed	Biomarker discovery tools	2001	25 employees in Singapore (2002), closed down in 2004
Affymetrix	Microarray	2001	R&D center is US$25 million investment, 877 employee worldwide (2000)
Lilly Systems Biology	Systems biology R&D	2001	29 employees in Singapore, 41,000 worldwide[9]
ViaCell	Stem cell therapeutics	2002	US$4 million invested over a 5-year period. 138 employees worldwide (2000)
PharmaLogicals Research	Cancers and other diseases in Asians	2002	S$142 million over the next three years into research on drugs
Novartis	Institute for tropical diseases	2002	Will house 70 scientists in Singapore, 77,200 employees worldwide
GlaxoSmithKline	Treatment for neurodegenerative diseases and schizophrenia	2004	Investing S$62 million in preclinical research facility. Will employ 30–35 scientists
Isis Pharmaceuticals	Micro-RNA and antisense drugs to treat Severe Acute Respiratory Syndrome (SARS), cancer and blood diseases	2004	12 scientists by end 2005
Essilor	New coating and materials technologies	2004	Current staff strength of 8 people, will grow to 25 staff by 2007
Olympus Corporation[10]	Higher order brain functions	2004	
Albany Molecular Research	Chemistry technologies	2005	
Biosensors International	Development and production of drug eluting stents	2005	
SpineVision	Develop next-generation implants and instruments for non-fusion spinal surgery	2005	

Annex Table 2 continued

	Company	Business Focus	Date of establishment[1]	Size of operation[2]
	CombinatoRx	Development of drug candidates for infectious diseases	2006	US$20
HQ and Distribution	Ferrosan	Supplements and lifestyle products	2003 (2004 – conferred International Headquarters Award)	
	Miltenyi Biotec	Magnetic cell separation (HQ Operations)	2004	
	Philips Medical	Medical imaging equipment (regional distribution centre)	2004	
	Schering AG	Pharmaceuticals	2005	

[1] Date established in Singapore

[2] Sources are from company websites or the US Securities and Exchange Commission unless otherwise indicated

[3] http://www.schering-plough.com.sg/spsingapore.ht.. Accessed Jun 1, 2003

[4] http://www.asiabiotechnology.com.sg/kh-biotechnology/readmore/vol6/v6n08/wyeth.html. Accessed Jun 1, 2003

[5] Establishment date of Sales and Marketing arm

[6] Approximately 150 employees in manufacturing while the remaining are employed in sales, marketing and administration. http://www.biomed-singapore.com/bms/browse_print.jsp?artid = 79. Accessed Jun 1, 2003

[7] Proligo's operations in Singapore began when it acquired Genset in 2002

[8] On April 16, 2003 Pharmacia was acquired by Pfizer

[9] Source from Sudhanshu Patwardhan at LSB

[10] Olympus partnered Waseda University to establish the Waseda-Olympus Bioscience Research Institute

Source: updated from Finegold, D., Wong, P.K. and Cheah, T.C. (2004) based on information from Bio-med Singapore website, http://www.bio-singapore.com and company websites

Annex Table 3 Profile of Life Science Public Research Institutes/Centres in Singapore

PRIC	Established	Description
Institute of Molecular and Cell Biology	1987	Established to help develop and support biomedical R&D capabilities in Singapore. Has core strengths in cell cycling, cell signaling, cell death, cell motility and protein trafficking.
Institute of Bioengineering and Nanotechnology	2002	Founded to conduct research at the cutting-edge of Bioengineering and nanotechnology. Has six research areas: nanobiotechnology, delivery of drugs, proteins and genes, tissue engineering, artificial organs and implants, medical devices, and biological and biomedical imaging.
Genome Institute of Singapore	2000	Initially established as the Singapore Genomics Program. GIS pursues the integration of technology, genetics, and biology towards the goal of individualised medicine. Its focus is to investigate post-sequence genomics; to understand the genetic architecture of pan-Asian populations with emphasis on cancer biology, pharmacogenomics, stem cell biology and infectious diseases.
Bioprocessing Technology Institute	1990 (as Bioprocessing Technology Unit); re-designation in 2001	Established to develop manpower capabilities and establish technologies relevant to the bioprocess community. Its core expertise in expression engineering, animal cell technology, stem cells, microbial fermentation, product characterisation, downstream processing, purification and stability, with supporting proteomics and microarray platform technologies.
Bioinformatics Institute	2001	Established to train manpower and build capabilities in bioinformatics. BII's research focus centres around knowledge discovery from biological data, exploiting high-end computing in biomedicine, advancing molecular imaging of biological processes, modelling of drug design and delivery, computational proteomics and systems biology.

Source: Websites of individual research institutes/centres

Annex Table 4 Dedicated Biotechnology Firms (DBFs) founded in Singapore

	Company	Business Focus	Products/services	Date of Establishment
Drug Discovery	S*Bio	Drug discovery	N/A	2000
	Lynk Biotechnology	Drug discovery and development	Biolyn^{TM} Hair Serum	2000
	APGenomics	Genomics-based products, services, and technology	Dengue SmartPCR^{TM} diagnostic kit	2000
	Qugen	Gene therapy	3 products nearing clinical	2001
	Agenica	Breast cancer treatment	N/A	2001
	Merlion Pharmaceuticals	Drug discovery	N/A	2002
	ProTherapeutics	Sublingually delivered peptide therapeutics	Analgesic peptide	2004
Medical Devices	Biosensors	Minimally invasive surgical devices	Catheters, transducers, stents	1990
	Forefront Medical Technology[11]	Medical devices used in anaesthesia	Contract manufacturing	2000
	Attogenix Biosystems	Integrated molecular analysis chip with microfluidic technology	High throughput reaction array biochip (AttoChip) and real time sequence detection system (AttoCycler)	2002
	Merlin Medical	Minimally-invasive medical devices	Coronary stent	2002
Stem Cell	Promatrix Biosciences	Hematopoietic stem cell (HSC) therapy	Has developed a method of constructing multi-cellular tissue to resemble normal tissue	2002/3
	ES Cell International	Stem cell research and production	Human embryonic cell lines	2000
	CordLife	Stem cell banking & therapeutics	Sample collection and counseling services	2001
Bioinformatics	ReceptorScience	Bioinformatics software	ReceptoMiner^{TM} database and tools	2000
	KOOPrime	IT solutions for life sciences	Platforms, engines, databases	2000
	HeliXense	Bioinformatics platform	Genomics Research Network Architecture	2000
Others	Mycosphere	Fungal diversity, bioprospecting	Contract research	1997
	AP Metrix	Healthcare and patient monitoring	RemoteC@re^{TM} (patient-provider management platform)	2000
	BioSurfactants	Surfactants manufacturing & development	N/A	2001
	Maccine	Preclinical service provider supporting drug development and safety assessment	GLP laboratory facility will be ready by Q1 2006	2003

Annex Table 4 continued

Company	Business Focus	Products/services	Date of Establishment
A-Bio Pharma	Biologics contract manufacturer	Partnership with GlaxoSmithKline to develop and manufacture vaccines	2003
NeuroVision	Non-surgical treatment for low-grade myopia and amblyopia	Neural Vision Correction technology	2004-treatment centre

[11] Forefront Medical Technology is a 50–50 joint venture between Singapore company Vicplas International and UK-based Laryngeal Mask Company

Source: updated from Finegold et al. (2004). ''Adapting a Foreign-Direct Investment Strategy to the Knowledge Economy: The Case of Singapore's Emerging Biotechnology Cluster'', based on information from Bio-med Singapore website http://www.bio-singapore.com and company websites

Annex Table 5 Milestones in the Singapore Biomedical Sector

1987	Setup of Institute of Molecular and Cell Biology (IMCB)
1995	Setup of Bioprocessing Technology Institute (BTI)
1998	Setup of Centre for Drug Evaluation (CDE)
	World-renowned Johns Hopkins University setup Johns Hopkins Singapore
1999	Setup of Genetics Modification Advisory Committee (GMAC)
2000	Singapore became first Asian country to accede to the Pharmaceutical Inspection Co-operation Scheme, Geneva
	Setup of Genomics Institute of Singapore (GIS)
	Setup of Life Sciences Ministerial Committee
	Agency for Science, Technology and Research (A*STAR) established Biomedical Research Council (BMRC)
	Setup of Bioethics Advisory Committee (BAC)
	Setup of Biomedical Sciences International Advisory Council (IAC)
	Tuas Biomedical Park
2001	Formation of Biomedical Sciences Manpower Advisory Committee (BMAC)
	Lilly setup Biology R&D Centre focused on systems biology
	Setup of Bioinformatics Institute (BII)
	Groundbreaking of Biopolis
	Setup Norvatis Institute for Tropical Diseases (NITD) in Singapore
	BioMedical Sciences Innovate ’N Create Scheme
2002	Setup of Singapore Tissue Network (STN)
	Merger of Laboratories for Information Technology and Institute for Communications Research to form Institute for Infocomm Research (IIR)
	Setup of Institute of Bioengineering and Nanotechnology (IBN)
	Setup of Cancer Syndicate
2003	Centre for Natural Product Research privatized to become MerLion Pharmaceuticals
	Launch of SingaporeMedicine
	Launch of Proof of Concept (POC) Scheme
	Opening of Biopolis
2004	Setup of The Regional Emerging Diseases Intervention (REDI) Centre
	Setup of The Centre for Molecular Medicine (CMM)
	Setup of Chemical Process Technology Centre (CPTC)
	Opening of Swiss House
	Launch of Singapore Researchers Database
	Passage of the Human Cloning And Other Prohibited Practices Bill
	Setup of GSK Corporate R&D Centre
	Launch of BioSingapore
	The National Advisory Committee for Laboratory Animal Research (NACLAR) announced amendments to the Animals and Birds Act to prevent inhumane treatment of lab animals
	Bioethics Advisory Committee (BAC) announced the publication of \‘‘Research involving Human Subjects: Guidelines for IRBs\’’
2005	Launch of Medtech Concept
	Launch of Medtech Local Supplier Group

Source:http://www.biomed-singapore.com/bms/sg/en_uk/index/about_biomedical_sciences/milestones.html

BMSG, BIO*ONE AND BMRC. (2006). ‘‘Biomedical Sciences Industry Maintained Growth Momentum In 2005’’, downloaded from: http://www.biomed-singapore.com/bms/sg/en_uk/index/newsroom/pressrelease/year_2006/2006_biomedical_sciences.html

Annex Table 6 Profile of NUS biomedical-related spin-off companies

Incorporated Date	Name	Nature of business	Founders fromNUS	Department
1995	Allegro Science Pte Ltd	Produce and market sequencing and DNA labeling kits	Dr Victor Wong Wong Thi	Biology
1999	BioMedical Research and Support Services	Biological evaluation of medical devices and equipment	Assoc Prof Eugene Khor	Chemistry
2001	BioNutra International Pte Ltd	Nutraceuticals and biopharmaceuticals	Mr Victor Ong Yek Cheng, Assoc Prof Paul Heng, Assoc Prof Yong Eu Leong	Pharmacy
2002	Chiral Sciences & Technologies Pte Ltd	Pharmaceutical and biopharmaceutical intermediates and fine chemicals	Prof Ching Chi Ban, Assoc Prof Ng Siu Choon	Chemistry
2000	ES Cell Pte Ltd	Embryonic stem cell technology	Scientific Advisor, Dr Ariff Bongso	Medicine—Obstetrics and Gynaecology
2000	KOO Prime Pte Ltd	IT solutions provider for the life sciences, bio-mining software	Mr Lim Teck Sin	Center for Natural Product Research
2000	LYNK Biotech Pte Ltd	Drug development technology	Assoc Prof Lee Chee Wee	Medicine—Physiology
1997	Oribiotech Pte Ltd	Develop tumor markers.	Dr Ng Wee Chit	Medicine
2003	OsteoPore Pte Ltd	Biodegradable Bone Scaffold	Prof Teo Swee Hin Dr. Dietmar Hutmacher	Bio-engineering
2003	Quantagen Pte Ltd	Label-free detection technology for gene analysis	Prof Casey Chan	Orthopaedic
2004	ProTherapeutics	Sublingual delivery of peptide therapeutics		Medicine

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