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RESEARCH ARTICLE

Ensuring the security of synthetic biology—towards a 5P governance strategy

Alexander Kelle

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Abstract Over recent years the label "synthetic biology" has been attached to a number of diverse research and commercial activities, ranging from the search for a minimal cell to the quick delivery of customized genes by DNA synthesis companies. Based on the analysis of bio-security issues surrounding synthetic biology during the SYNBIOSAFE project, this paper will first provide a rationale for taking security, in addition to safety aspects of this new field, seriously. It will then take stock of the initiatives and measures that have already been taken in this area and will lastly try to map out future areas of activities in order to minimise the security risks emanating from this promising new field of scientific inquiry and technological progress.

Keywords Synthetic biology · Security · 5P strategy

Introduction: why think about the security of synthetic biology?

Synthetic biology (SB) has developed into one of the most dynamic sub-fields of the life sciences and has come to be used as the umbrella term for different approaches ranging from large-scale assembly of DNA to the developments of new tools and technology platforms to the search for the minimal cell and the origins of life. While there is widespread hope related to the positive benefits that might be derived from this new "techno-science" (Schmidt et al. 2009), the discourse on the societal implications has also witnessed a healthy dose of analysis of the potential risks SB might entail. In addition, a first prioritisation of the societal issues of immediate concern has been undertaken (SYNBIOSAFE 2009).

There are at least three sets of issues that warrant a separate and systematic analysis of potential SB security risks. Firstly, bio-security concerns are not just a relabeling of bio-safety issues that may have been addressed during debates on genetically modified organisms. While bio-safety measures aim at the prevention of unintentional exposure to harmful or potentially harmful biological agents and material, or their accidental release, bio-security measures focus on preventing the misuse through for example loss, theft, diversion or intentional release of harmful or potentially harmful biological agents and materials. While the pursuit of bio-safety and bio-security goals is thus mostly complementary with a large area of overlap between them, there are certain instances in which the bio-security and bio-safety goals may point at contradictory policies.

One such example is provided in a background paper of the Implementation Support Unit (ISU) for the 1972 Biological and Toxin Weapons Convention (BWC). Having been set up by the sixth quinquennial Review Conference of the BWC, the ISU is tasked to assist BWC member states in implementing the provisions of that treaty and in preparing and conducting the annual meetings of BWC experts and states parties. The 2008 ISU background paper states that a "common example of conflict arises with the transport of dangerous pathogens: in the interests of bio-safety, such pathogens should be clearly labelled during transport, but from a biosecurity perspective, labelling the pathogen being shipped may increase the risk of theft or diversion" (ISU 2008, p. 3). The same background document prepared by the ISU also pointed out that "[b]iosafety is a well-established concept with a widely accepted

A. Kelle (✉)
University of Bath, UK and IDC Vienna, Vienna, Austria
e-mail: a.kelle@bath.ac.uk

meaning and international guidance on how it is put into practice at the national level. Biosecurity is a comparatively new term, with divergent meanings depending upon the setting in which it is used" (ISU 2008, p. 2). It is thus fair to conclude that among the core areas of past research and debate on the ethical, social and legal implications of the revolution in the life sciences it is the bio-security aspect that has received least attention.

The second set of concerns is related to a pattern of past misuse of advances in the life sciences. As Dando (1999) has demonstrated, major scientific developments in the life sciences have led to ever more sophisticated offensive state-level biological weapons (BW) programmes throughout the twentieth century. Insights into bacteriology gained in the late nineteenth century found their way into the rather crude biological sabotage programmes of the First World War (Wheelis 1999). Likewise, advances in aerobiology and virology in the middle of the twentieth century were utilised by "major global powers" who "invested substantial resources to develop a strategic BW capability aimed at the military forces, civilian populations, or agricultural resources of their adversaries" (Wheelis et al. 2006, p. 1). Later on, the early stages of genetic engineering were utilised in the clandestine Soviet BW programme of the 1970s and 80s (Hart 2006). This pattern of past misuse raises the spectre of twenty-first century advances in the life sciences—including synthetic biology—also being misused as part of efforts to produce advanced BW (Petro et al. 2003) or to simplify the acquisition of known biological warfare agents. However, as the above listing shows, the often voiced assessment that the major bio-security risks at the beginning of the twenty-first century are resulting from terrorist groups' interest in the acquisition of BW may be based on a fundamental misjudgement of the history of biological weapons acquisition by states. Although some still equate the major bio-security risk stemming from SB with bio-terrorist activities (Balmer and Martin 2008) or maintain that the use of biological weapons by terrorist organisations such as Al Qaeda is practically inevitable (Hellmich and Redig 2007), other scholars have warned not to overstate the bio-terrorist threat (Sprinzak 2000), sought to set the historical record of actual bio-terrorist incidents straight (Tucker 2000) and cautioned that a thorough threat assessment has been sorely missing from US government predictions of the likelihood of a future bioterrorist event (Leitenberg 2005). Although the occurrence of such events cannot be excluded completely, given this past record as well as the technological hurdles involved in misusing SB or its applications in order to do harm, it is more likely that the "fruits" of SB will be first abused in a state-level program. Should a bioterrorist event occur, it is more likely that traditional biological warfare agents will be utilised. It is therefore all the more important that the SB community and the BW arms control community—the latter of which continues to try to prevent state-level BW programmes—expand the initial contacts that have been established in recent years.

The third set of issues that necessitates taking the bio-security risks of SB seriously is related to the fact that SB has been identified by the bio-security community—beyond those concerned with BW arms control—as an area of concern. Most notably, the *Committee on Advances in Technology and the Prevention of their Application to Next Generation Bioterrorism and Biological Warfare Threats*, the so-called Lemon-Relman committee of the US National Research Council (National Research Council 2006) has urged analysts and policy makers to look beyond lists of potentially harmful biological agents, like those for example on the US select agents list. Rejecting a list-based approach as too limited, the Committee adopted a classification scheme for scientific and technological advances containing four different groups, focussing on features that different technologies have in common. Synthetic biology features in relation to two of these four groups: "technologies that seek to acquire novel biological or molecular diversity" and "technologies that seek to generate novel but pre-determined and specific biological or molecular entities through directed design" (National Research Council 2006, p. 3). Following from this assessment, one of the recommendations contained in the committee's report advocates the adoption of 'a broadened awareness of threats beyond the classical "select agents" and other pathogenic organisms and toxins, so as to include, for example, approaches for disrupting host homeostatic and defense systems, and for creating synthetic organisms' (National Research Council 2006, p. 177). As a set of interviews with leading European SB practitioners revealed, their awareness of the Lemon-Relman committee, its report and the implications flowing from its work was very low indeed (Kelle 2007).

Thus, bio-security awareness raising efforts are clearly required as part of a more comprehensive strategy to address the bio-security implications of SB. Different approaches to come to terms with the bio-security of SB will be briefly discussed in the following section before the elements of a comprehensive 5P strategy are outlined thereafter.

How to think about securing synthetic biology—towards the 5P strategy

Self-regulatory and technology-focused approaches to bio-security governance of synthetic biology

Over the past few years two different trends have emerged in relation to the bio-security governance of synthetic

biology. The first of these is technology driven and has been initially discussed by a large section of the SB community, e.g. during the SB2.0 conference in May 2006 (Conferees, SB2.0 2006) and has more recently been advocated by representatives of DNA synthesis companies and their industry associations. Over the past few years the emergence of two such organisations could be observed: the International Consortium for Polynucleotide Sequencing (ICPS) and the Industry—now renamed into International Association Synthetic Biology (IASB). While ICPS has been revolving around mostly US-based DNA synthesis companies, IASB founding members have been German gene synthesis and bio-informatics companies. It is worth noting that ICPS and the IASB are in the process of merging and—in addition to the activities and proposals described below—have begun outreach efforts to DNA synthesis companies located outside Europe and the United States.

The first of these groups, the ICPS has proposed a "tiered DNA synthesis order screening process" (Bügl et al. 2007). With it they propose that

> individuals who place orders for DNA synthesis would be required to identify themselves, their home organisation and all relevant biosafety [sic] information. Next, individual companies would use validated software tools to check synthesis orders against a set of select agents or sequences to help ensure regulatory compliance and flag synthesis orders for further review. Finally DNA synthesis and synthetic biology companies would work together through the ICPS, and interface with appropriate government agencies (worldwide), to rapidly and continually improve the underlying technologies used to screen orders and identify potentially dangerous sequences, as well as develop a clearly defined process to report behavior that falls outside of agreed-upon guidelines (Ibid, p. 627).

DNA synthesis companies and their industry association would reside at the centre of a governance structure that would rely on "agreed-upon guidelines". Such guidelines would be put into effect inter alia through lists of "select agents or sequences" that would determine whether and how to process DNA synthesis orders on the part of those companies that follow the guidelines.

IASB activities agreed upon during a 2008 meeting also put emphasis on DNA order screening, but additionally emphasise the formulation and implementation of best practices across the industry. One key element of such a scheme is the agreement on an industry-wide code of conduct. Oversight and enforcement of standards, however are not regarded as falling into industry's area of responsibility. As clearly spelled out in the IASB workshop report, "[u]ltimately, the definition of standards and the enforcement of compliance with these is a government task" (Industry Association Synthetic Biology 2008, p. 14).

The second, diverging, trend seems to be driven by those in the synthetic biology community who are advocating self-governance by the scientific community as the most promising approach to follow. However, the evidentiary basis of the assertion by some that "initiatives developed by the synthetic biology community may be more effective than government regulation precisely because they are more likely to be respected and taken seriously" remains somewhat in the dark (Maurer and Zoloth 2007). Clearly, DNA synthesis companies and their associations, who are currently at the forefront of formulating proposals and thus setting the agenda for technical solutions to bio-security risks of SB, are not adverse to government oversight and regulation. This clearly comes out of the above mentioned proposals and reports. Also, as one of the industry contributors to the SYNBIOSAFE e-conference in spring 2008 pointed out, such oversight and regulation make two important contributions to a larger governance system. It firstly will "reassure the public that biosafety and biosecurity concerns are addressed" and it secondly "would provide legal security to the industry, by defining clear compliance rules" (SYNBIOSAFE 2008, p. 45).

The 5P strategy

In spite of the limitations of the above governance approaches, they both serve an essentially important purpose in that they contribute to raising the awareness of the SB community about bio-security issues related to their work. In light of the low level of bio-security awareness among synthetic biologists—especially in the European academic SB community (Kelle 2007)—any bio-security governance system will have to include efforts to raise such awareness in the scientific community. In addition, for the SB subfield of DNA synthesis, the efforts currently under way including those aiming at the wide-spread adoption of screening by DNA companies for potentially harmful sequences and the adoption of a code of conduct for the industry, plus the potential expansion of order screening to oligo-providers in the future (Fischer 2009), are important building blocks for a more comprehensive bio-security governance strategy for SB.

When conceptualising such a more comprehensive strategy it is important to take into consideration the limitations of one of the core international instruments available at the international level to prevent the misuse of the life sciences for nefarious purposes, i.e. the BWC. Most importantly, Article I of the BWC does not cover research on BW, but just development, acquisition, or stockpiling of BW. It is therefore essential for any comprehensive bio-

security governance system to be able to address the BWCs shortcoming on the international level of not being able to address dual-use ***research*** activities that could be misused for nefarious purposes.

Such a broader-based approach also needs to include all stakeholders in the development of synthetic biology as a discipline and its potential future applications. Ideally, it would be equipped with some flexibility to be able to respond to different trajectories along which the field might develop. Such an overarching governance structure, based on the 5P-strategy outlined below, would focus on five different policy intervention points: the

- **p**rincipal investigator (PI), the
- **p**roject, the
- **p**remises, the
- **p**rovider (of genetic material) and, its
- **p**urchaser.

The first three "Ps" would take into account the research character of much of what currently is synthetic biology and thus provide important additions to the policy intervention points recommended by the study on synthetic genomics conducted by researchers at the Massachusetts Institute of Technology (MIT), the Center for Strategic and International Studies (CSIS) and the J Craig Venter Institute (JCVI) (Garfinkel et al. 2007). The options discussed in their report on synthetic genomics are both too narrow and too wide in order to serve as a comprehensive bio-security governance strategy for SB: they are too narrow, because they focus only on synthetic genomics which the authors of the report understand to combine "methods for the chemical synthesis of DNA with computational techniques to design it" (Garfinkel et al. 2007, p. 1). This clearly covers only one of the subfields of synthetic biology identified by O'Malley et al. (2008), Schmidt (2009) or Deplazes (2009). At the same time the options discussed are too wide because they do not only focus on bio-security, but also take into account laboratory bio-safety, environmental protection and other concerns such as to "minimize costs and burdens to government and industry" (Garfinkel et al. 2007, p. 49).

In the first instance, the matrix provided below is intended to serve as a heuristic device to indentify and discuss a number of different measures that are theoretically possible at each of the five policy intervention points in order to address different bio-security risks, which vary in their severity. As quite a few of these are potential future threats whose actual manifestation cannot be predicted in detail, at this point in time no definite risk assessments can be conducted and consequently the appropriate level of response cannot be known. In principle, the bio-security measures for synthetic biology range from awareness raising on part of the involved synthetic biologists to education and training of current and future generations of SB practitioners, codes of conduct, guidelines, regulation, national laws, and international treaties.

The following table maps these types of bio-security measures against the five policy intervention points. It should be noted that the goal of constructing this matrix is not to try and fill all of the resulting fields necessarily with content. One outcome of the proposed exercise may well be not to advocate or pursue a particular policy intervention. However, utilising the matrix as a heuristic device should enable SB stakeholders to identify governance structures that are already available and applicable to SB, either from a bio-security point of view, or from a related, e.g. bio-safety informed, perspective. In extension of the above quoted study by Garfinkel et al. it is proposed here not to mix bio-safety and bio-security concerns, but instead to take into due account the above mentioned limitations in utilizing bio-safety measures in addressing bio-security risks. In other words: to the extent that bio-safety measures are "borrowed" for bio-security risk analysis they need to be investigated for their adaptability for a bio-security governance structure. On this basis the matrix can then serve as a tool for discussing steps that need to be taken additionally in order to arrive at a bio-security governance structure that provides the greatest possible protection against the misuse of SB.

Potential bio-security measures in the context of the 5P-strategy

Potential bio-security measures	Policy intervention points				
	Principal investigator	Project	Premises	Provider	Purchaser
Awareness raising					
Education/ training					
Guidelines					
Codes of conduct					
Regulation					
Natl laws					
International treaty/ agreement					

An initial assessment of bio-security measures that have already been mentioned would lead one to populate the fields marked in the provider column, as those relate—at least partly—to the DNA screening and other activities of gene synthesis companies discussed above. These efforts, however, are also embedded in international agreements and national laws and regulations. The BWC for example requires in Article IV all its member states to implement its prohibitions within their own jurisdictions. Concerning the

non-transfer of BW-related materials, technologies and know-how many states thus have established national export control laws and regulations, which in turn have been harmonised by a group of some 30 states in the so-called Australia Group (AG) (Australia Group webpage 2006). The AGs guidelines and control lists are of relevance in this context as are the counter-terrorism measures contained United Nations Security Council 1540 resolution and implemented by the Committee established through this resolution. The 1540 Committee (1540 Committee webpage 2007) aims at analysing which controls UN member states have in place in order to prevent the unauthorised access to nuclear, biological and chemical material, thus having a rather indirect effect—as does the BWC—on the activities of individual researchers or organisations. In contrast, the Australia Group control lists' references to genetic material of controlled pathogenic micro-organisms are much more SB-specific and have a direct bearing especially on the activities of DNA synthesis companies and their servicing of DNA orders from customers abroad. The international layer of a SB bio-security governance system could be further strengthened if the proposal for a convention to criminalise BW-related activities under international criminal law were to be adopted by states (Meselson and Robinson 2001).

As these examples show, many national measures, be they in the form of laws, regulations or guidelines, are informed by international agreements. However, such a link does not always exist. A case in point are the regulations put in place to ensure the safety of biotechnology-based research, development and production. As a recent study on this issue has sought to demonstrate, certain domestic bio-safety measures developed in a national context during past debates on the ethical, social and legal issues (ELSI) concerning rDNA based products are of relevance for the first generation of SB products (Rodemeyer 2009). As it addresses a mix of measures ranging from self-governance to government regulation, this report provides a good starting point for discussing bio-security governance measures at a national level. Yet, as has been pointed out above, past ELSI debates have not systematically included consideration of bio-security issues. Thus a change in focus of the risk assessment is needed.

Some guidance about such risk assessment can be derived from current thinking about laboratory bio-security measures that aims at preventing the theft and malicious misuse of dangerous biological agents. According to Salerno and Gaudioso (2007) the bio-security risk in a laboratory environment is the product of the threat potential of a biological agent being stolen and the consequences of such an act involving the misuse of the agent. Salerno and Gaudioso usefully also break down laboratory bio-security into different component parts that require different measures for different types of risks. They distinguish between physical security, personnel security, material control and accountability, transport security, and information security. While such an agent-focussed approach would need adapting to the characteristics of SB, especially as the field progresses and one moves away from the current focus on the DNA synthesis subfield, it would clearly allow to address the double deficit of the security-deficit in past ELSI debates and of international agreements like the BWC which a priori excludes research activities to be addressed.

Lastly, the above mentioned study by Rodemeyer also provides a useful reminder of the product driven focus of US rDNA bio-safety regulations. ELSI debates and bio-safety measures in Europe, in contrast, have been much more process-focussed, with the mode of production, i.e. the genetic modification of a product, being of considerably greater relevance than in the US context. These differences between product and process-focussed approaches to risk assessment might also enter the discourse on the most appropriate set of bio-security governance measures that the 5P matrix presented above seeks to facilitate.

Conclusions

This paper set out to provide a rationale for the separate bio-security assessment of SB, in addition to the traditional ELSI domains that have become familiar through the discourse on genetically modified organisms. It has identified three elements of such a rationale for taking the bio-security of SB seriously: first, there is a clear pattern of past misuse of advances in the life sciences for BW purposes; second, bio-security is not equal to bio-safety, and in some instances these two concerns may actually lead to conflicting policy measures; third, at least since the publication of the Lemon-Relman committee report in 2006 SB has been shining up on the radar screens of bio-security analysts as one of the subfields in the life sciences that need monitoring.

Proposals for the bio-security governance of synthetic biology broadly fall into two categories: those that put a emphasis on self-governance by the SB community to prevent misuse, and those that emphasises technical solutions. As discussed, the second category provides necessary building blocks for a comprehensive governance system, but is not sufficient to address the full range of bio-security risks. This limitation is shared by all supply-side measures that seek to restrict access to materials, technologies or know-how through list-based controls. Attempts to establish a code of conduct are therefore as useful and necessary a complement as systematic awareness raising and educational activities would be to the more technically orientated supply-side control measures that have received the greatest attention so far.

Efforts to address SB-related bio-security risks need also to be broadened to include the different strands of the scientific field to which DNA synthesis contributes. In this context, a 5P-strategy has been outlined that would consider five different policy intervention points for which adequate measures would need to be elaborated. It would thus not only focus on the provider and purchaser of synthesised DNA, but also the principal investigator, the project, and the premises at which research is being conducted. Such an integrated SB governance system would need to be based on a bio-security risk assessment that could well take current thinking on laboratory bio-security as its starting point for a discourse involving all stakeholders in this new and dynamic subfield of the life sciences. There currently exists a window of opportunity for such a dialogue that may close once SB applications reach a "plateau of productivity" (Schmidt 2009).

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