Institution: Imperial College London

Unit of Assessment: 15 (General Engineering)

A. Overview

The Department of Bioengineering was formed in 1998 from internationally-renowned research groups at Imperial College that helped lay the foundations of the subject in the 1960s. The Department is still growing strongly in numbers, space and strength. During the REF period academic staff FTEs increased from 17.5 to 28 whilst Research Assistants/Associates (RAs) and PhD students increased by 111%, giving a current average of 1.8 RAs and 4.2 PhD students per academic. Our grant portfolio rose from £9.3M in 2008 to £33.7M in 2013, equivalent to >£1M per academic. (Because of our rapid growth, metrics which divide time-averaged figures by current staff numbers significantly underestimate our performance.)

The Department has five Research Themes and also leads the Institute of Biomedical Engineering (IBME) that manages cross-College Networks and Centres.

Our Themes are:

Biomechanics; Cell and Molecular Bioengineering; Detection, Devices, Design; Implants and Regenerative Medicine; and **Neurotechnology**.

The IBME Centres and Networks we lead are:

Synthetic Biology; Cancer Engineering; Blast Injury Studies; and **Medical Engineering Solutions in Osteoarthritis.**

These groupings are changed as the discipline evolves, and most staff belong to more than one.

The Department has a multidisciplinary ethos, employing academic staff whose backgrounds range from pure mathematics, through engineering to the natural sciences and medicine. *ALL* staff are being returned to REF (28 FTEs). We are also returning: 2 Research Fellows (*Chadderton, Kedgley*); 2 former staff, now in the USA, who still work closely with, and are employed part-time by, the Department (*Ethier, Shefelbine*); a Visiting Professor who participates in the Department's research and uses it in clinical practice (*Clasper*); and 2 close collaborators from the Faculty of Medicine active in our Networks and Centres (*Elson, McGregor*). Our total FTE return is 33.5.

B. Research strategy

B.1 Vision

Our vision is that bioengineering will become as essential to society, as relevant to industry and as attractive to students as established branches of Engineering; and that *our Department will play a leading role in that transformation* by expanding and extending its research excellence into new fields and applications. This vision follows on from our RAE 2008 aims which were "to *expand* whilst *maintaining research excellence and a leading position* in bioengineering."

B.2 Achievement of aims during the assessment period

B.2.a Expansion

The Department made a commitment in RAE 2008 to appoint 6 more academic staff. We have almost doubled that goal, growing by 10.5 FTEs (*a 60% increase*) during the REF period. Our substantial student numbers (257 undergraduates and 87 on MSc courses) in combination with our considerable research income have provided the necessary financial strength and stability.

Recruitment of high-quality staff has increased our research strength. Expansion also lowers individual teaching and administrative duties, improving research focus; average yearly teaching contact hours reduced more than 20% over the assessment period. We have recruited extra support staff to further improve research focus; numbers have increased from 7 to 32.5 since 2008.

Targeting our recruitment has enabled us to enter strategically-important areas. As a result, we have formed two new Research Themes: Cell and Molecular Bioengineering, and Implants and Regenerative Medicine. They are important to our vitality and sustainability since engineering techniques and knowledge are required to measure, understand and create processes at the cellular and molecular scales, where biology is advancing fastest, and because implants and regenerative medicine are fields where bioengineering has transformational translational potential.

B.2.b Maintaining research excellence and a leading position in bioengineering

Our Research Themes foster a striking level of collaboration between academic staff (58% are returning a publication to REF co-authored by another member of academic staff). The Themes

promote research talks, journal clubs, co-supervision of students, and joint grants; they provide a multidisciplinary environment, generating ideas and discussion across traditional boundaries. Our vibrant Departmental seminar series attracted 79 international speakers during the REF period.

Excellence and leadership are shown by our staff returning 27 papers in *Science*, *PNAS,* and *Nature journal*s. They chair, and actively participate in, major bioengineering committees (RAEng Biomedical Engineering Panel, IPEM, IMechE Biomedical Engineering Association, Bioengineering Society), and by the following REF2 highlights from our staff, outlined by Research Theme:

Biomechanics: Achievements in our established strengths of respiratory, orthopaedic and vascular biomechanics include: a musculoskeletal dynamics model that contributed significantly to GB Rowing success at the 2012 Olympics (*Bull, McGregor*); studies contradicting the decades-long consensus concerning haemodynamic causes of atherosclerosis (*Weinberg, Ethier*); a method to predict aneurysm rupture, now being developed by Philips (*Krams*); and a study of respiratory blood splatter that decided the outcome of the UK's longest murder trial (*Schroter*). Staff appointed for our entry into ocular and developmental biomechanics produced a new, mechanically-based neuroprotective strategy in glaucoma (*Overby, Ethier*) and the first evidence that forces acting on the womb influence skeletal development, suggesting new therapies for birth defects (*Nowlan*).

Cell and Molecular Bioengineering: This new Theme has made breakthroughs in understanding cellular mechanotransduction at the molecular level, including: use of nanotechnology to show that protein unfolding is a key mechanism; a paradigm shift in understanding the roles of the major proteins involved; and elucidation of the maturational dynamics of the molecular complexes in cell adhesion (*Del Rio*). Our IBME Centre for Synthetic Biology has also produced transformational work: the first design-led project using forward-engineering to go from libraries of biological parts to working genetic devices; the first synthetic biology investigation of how stochasticity in biological networks defines differentiation of eukaryotic cells (*Ellis*); and development of biological logic gates (*Kitney*). Our strength in biomathematics has led to: a new paradigm in the use of control engineering methods for investigating complex biological systems; proof that the biological clock both regulates and is regulated by metabolism; and the first mathematical model of activation-induced apoptosis, leading to a method for diagnosing immunological failure in HIVb (*Stan*).

Detection, Devices, Design: Medical ultrasound remains a departmental strength, with notable outcomes including: the first demonstration of large molecule delivery to localized areas of the brain, using ultrasonically-activated microbubbles (*Choi)*; the first model-based algorithm to correct for attenuation artefacts in contrast-enhanced ultrasound imaging, enabling quantification of tissue perfusion; and the first technique for imaging elasticity of deep tissues using acousto-optical detection (*Tang*). Our strength in low-power circuitry is exemplified by development of the world's highest dynamic range and lowest power consumption circuit mimicking the basilar membrane, suitable for cochlear implants, and the world's first sub-milliwatt and fully-integrated pulse oximeter front end (*Drakakis*). Our new devices for cancer therapy, which have had huge clinical impact (Case Study: CS1 *Dickinson*), include: a bipolar radiofrequency device reducing blood loss in liver resection, which has saved around 1000 lives; novel methods for electronically steering and focusing ultrasound therapy, in clinical trial for solid tumour ablation; and an endoscopically-delivered catheter capable of ablating malignant tissue, now in production. Collaboration with the Neurotechnology Theme has helped in developing rapid sampling microdialysis for monitoring brain injury in hospitals worldwide (CS2 *Boutelle*) and in creating the first robotic controller able to adapt to unstable interactions typical of tasks with tools (*Burdet*).

Implants and Regenerative Medicine: This new and growing Theme has generated highlights that are related to our biomechanics expertise, such as quantifying the mechanical effect of knee meniscus replacement, which led to a novel patented implant design (*Bull*), and the first study to relate stent-induced artery wall stress to vessel narrowing (*Moore*). Key publications from *Stevens* (appointed 50:50 with Materials, and returned to REF by them) include a nano-analytical electron microscope study of how bone cells mineralize extracellular matrix and the first demonstration that embryonic stem cells sense topographical features of gold nanoparticles, showing the influence of nanoscale topography on stem cell differentiation.

Neurotechnology: This Theme, which was new in RAE 2008, has grown rapidly in strength. Research on neural information processing has produced several highlights: a new conceptual framework explaining how cortical neurons process information about sound location (*Chadderton*); and the first demonstration that our brains can optimally trade off sensory and

movement uncertainty, used for hospital assessments of neurological development (*Faisal*). Synaptic plasticity is an area of particularly fundamental advances: demonstration of an essential role of inhibitory plasticity in functional cortical circuitry; a theoretical demonstration that synaptic plasticity can be explained solely by spike pairs and triplets; and elucidation of how cortical microcircuits develop before and after the onset of sensory experience (*Clopath*). New staff have produced important work concerning sensory processes, including: a foundational framework for defining efficiency in quantum energy transfer, relevant to retinal photoreception (*Lee*); and a novel analysis of how frequencies <4 kHz can be detected by the inner ear, leading to a new bioinspired active microphone design (*Reichenbach*).

B.3 Strategic Plans and their Delivery

Our research strategy is to maintain and develop our flexible Research Themes and our IBME Networks and Centres in order to lead the evolution of the discipline, stimulate collaborations with other Departments and extend our clinical reach. In particular, we will realise our vision by:

- extending our growth in the strategically important field of Implants and Regenerative Medicine;
- expanding the thriving Theme in Neurotechnology to become an IBME Centre;
- strengthening the embryonic IBME Network in Cancer Engineering;
- developing an IBME Centre in Big Data in Medicine (to be realised in part through a recently-signed Memorandum of Understanding between Huawei and Imperial); and
- developing a new IBME Network in the applied area of Sports and Rehabilitation Engineering to address the health and exercise agenda of primary importance to an ageing population.

We will engage new appointees as well as current staff in this strategy. We will recruit a further 10 academic FTEs within 4 years, and provide laboratories and space including at Imperial's new campus (Imperial West) to house these new staff and the new activities.

Our research strategy is overseen by the Director of Research (DoR) as part of the Departmental Management Committee (DMC), assisted by a Research Development Director appointed to the IBME. The DoR advises the DMC on emerging trends in the discipline, allowing it to make recommendations to the Head of Department on strategic areas for staff recruitment. The DMC makes decisions on capital equipment expenditure, and works with the Departmental Laboratory Manager and Technical Services Manager to align the provision of technical services with research needs. The DoR stimulates research income by horizon-scanning and circulating funding opportunities. Grant applications are incentivised by assigning 4% of Departmental income from each grant to the applicant for research-related spending. We hold workshops to help staff writing grants, including expert talks by members of grant awarding panels and feedback on draft proposals. We also maintain a repository of exemplar grant proposals and provide mock interviews for all candidates shortlisted for funding interviews. The success of this approach is shown by the more than doubling of the total portfolio of awards held per academic staff over the REF period.

C. People

C.1 Staffing Strategy and Staff Development

Our people are our greatest asset and our staffing strategy is to recruit existing or potential research leaders. Strategic investment in salaries and facilities allows recruitment and retention of internationally-leading researchers. Up to 105 applications have been received in calls for non-professorial academic staff, and we select only those whom we believe can rise to the level of professor at Imperial. A call at professorial level attracted 15 applications from established chairs around the world including 6 full professors in the USA. Up to 110 applications have been received for a single RA post. Our RAs have won prizes, awards and fellowships whilst at the College that include: the RAEng Global Research Fellowship, the RAEng Sir George Macfarlane Award, two Bodosakis Foundation Scholarships, the Nature Communications prize, the Heidelberg Engineering Extreme Research Lecture Award, an Alexander von Humbolt fellowship, a Dorothy Hodgkin Research Fellowship and a Marie Curie Intra-European Fellowship. During the REF period, ten have gone on to gain academic staff positions at NUS (Singapore), COMSATS (Abbottobad), CNRS, King's College London, the Royal Veterinary College, Imperial College London and the Universities of Nagaoka, Brighton, Exeter and Surrey. The number of RAs has increased faster than that of academic staff, from 14 to 49.8, meaning that the ratio of research staff to academic staff has more than doubled and now stands at over 1.8:1 even though a high fraction of our academic staff have not been in post sufficiently long for their research groups to reach a steady size: 54% were appointed within the last 5 years and 29% within the last 2 years.

C.1.a Staffing Strategy in relation to research strategy

Our RAE 2008 objectives were to "*hire in the areas of neurotechnology, systems biology and bionanotechnology as applied to molecular imaging, with a particular emphasis on the cell and molecular level*…". These aims were fulfilled by appointing: *Mehring, Harris, Faisal, Reichenbach* and *Clopath* in neurotechnology; *Tanaka, Ellis* and *Stan* in systems/synthetic biology; and *Overby, Del Rio, Ladame, Lee* and *Choi* in imaging, bionanotechnology and cell/molecular bioengineering.

Our more recent strategy of expanding into implants and regenerative medicine led to the appointment of Professors *Stevens* and *Moore*, and Lecturers *Masouros* and *Weaver*. We entered developmental biomechanics by appointing *Nowlan*. Links with traditional disciplines were strengthened by jointly appointing five staff with other departments in Engineering: *Stevens* and *Weaver* (deceased) with Materials, *Harris* (now at UCL) and *Mehring* with Electrical & Electronic Engineering, and *Faisal* with Computing.

C.1.b Staffing Strategy in relation to physical infrastructure

As the Faculty of Engineering's main priority for growth, the Department has been given newly refurbished space for offices, desks and labs commensurate with current - and planned - growth. This space is contiguous and provides staff with high quality research facilities. All academic staff have individual offices that are large enough for tutorial meetings. All RAs have desks in shared offices of the same high standard. Additional growth will be facilitated through the allocation of space for new IBME Centres and Networks at the *Imperial West* campus.

C.1.c Career Development Support for All Levels of Research Staff

Academic Staff Career development is formally supported through the annual Personal Review and Development Plan (PRDP) process, in which every member of academic staff meets with the Head of Department to review performance and assist with research and career development. All staff are considered for promotion every year, even if they do not apply, by a committee that includes an elected representative. 100% of staff put forward for promotion by the Department have been successful at their first attempt (5 lecturers to senior lecturer, 4 senior lecturers to reader and 3 readers to professor). Staff have benefitted from the management and leadership programmes in Imperial's Learning and Development Centre (LDC) including one-to-one coaching, master classes and writing retreats; 5 senior staff have taken the LDC's Senior Academic Leadership Programme, which equips them with the practical skills and awareness required for organisational leadership. *Bull* is a member of the "In Conversation" Senior Academic Forum.

New Academic Staff Practical start-up support comprises at least £30k of flexible funding, a minimum of one PhD studentship, reduced teaching hours, minimal administration, regular networking lunches with other new staff, and priority in competitions for Departmentally-funded PhD studentships and equipment. All probationary staff have a mentor who gives advice and helps develop a research funding strategy. Successes include ERC awards (*Nowlan, Del Rio*), EPSRC First Grant awards (*Ellis, Stan, Overby*), and named co-I status on grants >£1M (*Masouros, Stan, Ellis*). All staff have secured external funding within two years of appointment. New staff have taken College courses on academic performance and career development.

Research Assistants The College, which formally employs our RAs, has fully implemented the Concordat to support the Career Development of Researchers and was awarded the European HR Excellence in Research Badge (2012). RAs have a contractual obligation to spend 10 days per year on professional development. They receive a tailored programme of support from the Postdoc Development Centre, which was runner up in the "Outstanding Support for Early Career Researchers" category at the THE Awards (2010, 2012). Like academic staff, RAs have annual PRDPs and are encouraged to take Departmental training courses in microscopy, programming, etc.; all are considered for discretionary pay awards every year. They are given the opportunity to teach, under supervision, with formal recognition by inclusion in our student on-line evaluation. Before the end of their contract, RAs receive a career consultation from an HR advisor and automatic short-listing for relevant College vacancies.

C.1.d Personal Fellowships

During the REF period, staff in the Department have held a Royal Society University Research Fellowship (*Weaver*), a Royal Society Industry Fellowship (*Schultz*), an EPSRC Leadership Fellowship (*Harris*), an EPSRC Career Acceleration Fellowship (*Tanaka*), an MRC Career Development Fellowship (*Chadderton*), a Marie Curie International Incoming Fellowship, a BHF Intermediate Basic Science Fellowship, a Rio Tinto Sports Bioengineering Fellowship, and an

Army Benevolent Fund Fellowship (*Masouros*). Additional personal awards won in open competition include an ERC Starter Grant (*Nowlan*), an ERC Advanced Investigator Award (*Del Rio*), and three Wolfson Merit Research Awards (*Harris, Moore, Ethier*).

C.1.e International staff appointments, recruitment and visiting scholars

Of 18 new academic staff during the REF period, 11 were recruited from abroad, including 5 from the USA (Columbia, Rockefeller, Rutgers, Texas A&M, Tulane). A further 5 were foreign nationals recruited within the UK. Considering all staff, 67% came from 30 non-UK countries.

During the REF period, the Department hosted 31 visiting scholars, including: *Associate or Vice Deans* from Temple University (USA) and South West University (China); *Professors* from Nice Sophia Antipolis, Georgia Tech, Monterrey Institute of Technology (Mexico), Duke University, NTU Singapore, MIT and the Universities of Arizona, Xidian, Nanjing, Valencia, Calgary, Elche (Spain), Pittsburgh, Maryland; and *industrialists* from Scientifica Ltd, GE Healthcare and Allergan (USA).

C.1.f Support for equality and diversity

The Department is committed to diversity and equality. Four of the Department's 18 academic staff appointees during the REF period are women and 4 are from ethnic minorities. In 2013, the Department registered for a Bronze Athena SWAN award. It finances a termly female academic and postdoc lunch and an annual female academic, postdoc and PhD student lunch to allow communication and motivate female postdocs and students to pursue their careers with confidence. An elected female member of academic staff sits on the Departmental Management Committee; all appointments and promotions panels have female members. Teaching timetabling takes into account childcare arrangements. We represent the Faculty of Engineering on a College task force to increase the number of female junior academics. A female member of staff commented, "the Department has been extremely supportive of women."

Our female staff also receive support from the College, which was a founding member of the Athena SWAN Charter and has a Silver award. All four junior female academic staff in the Department have participated in the LDC's Female Academic's Development Centre which supports non-professorial women in academic positions. (The Postdoc Development Centre has a parallel programme.) Three female staff have taken part in the Springboard Women's Development Programme or the Ambassadors for Women scheme. There are special schemes for adoption, surrogacy and maternity leave, as well as an OFSTED "outstanding" College-run nursery which has been used by 4 staff from the Department. The College's Elsie Widdowson Fellowship Awards allow female academics to concentrate fully on their research upon returning from maternity leave by funding 50% of their salary costs for 12 months; we have held three during the REF period.

C.2 Research Students

The PhD and MD(Res) programme is overseen by the Director of Postgraduate Research, who sits on the Departmental Management Committee, and a Postgraduate Committee which s/he chairs. It is subject to annual internal review and to reviews with external assessors.

C.2.a PGR recruitment and discipline-specific issues

Because of our rapid expansion, 46% of academic staff have not yet had time to graduate a student. Despite this, student numbers have doubled from 65 in 2008/9 to 117 in 2012/13; we now average 4.2 PhD students registered per staff FTE. In addition, the strongly multidisciplinary nature of our research work has involved the supervision of *76 students registered in other departments* and not included in these numbers.

We attract outstanding students with diverse backgrounds, ranging from mathematics to medicine including all branches of engineering. During the REF period, 30% of students were Home, 30% EU and 40% Overseas; 33% were female. The ratio of applicants to places is high: our four most-recently advertised studentships attracted an average of 44 applicants each. Applicants must submit a research statement so that we can assess creativity and independence, and all short-listed candidates are interviewed by at least 2 staff. Evidence for the quality of the students is that 72% have competitively awarded scholarships; 14 students received ORS, Rectors, Imperial College, Hans Rausing, Lee or China Scholarship Council studentships, which are allocated in small numbers College-wide in an extremely competitive process. Twelve students obtained scholarships as part of special arrangements between Imperial and Thailand or Singapore; only the top candidates from each country are selected. Additionally, the Department has funded PhD studentships totalling £1.2M across the REF period, including studentships in start-up packages, 21 studentships allocated through an annual competitive process, and an industrial PhD scheme

(see below). In recent years, past students have gained academic staff positions at Universita de La Plata (Argentina), KACST (Saudi Arabia), King Mongkut's Institute of Technology (Thailand), Universiti Teknologi (Malaysia; 2), CNRS, Imperial College (2), King's College London, St Mary's University Twickenham, Surrey University, Wayne State University (Detroit), Brunel University, University of Galway and the University of Mexico.

C.2.b Training and support mechanisms

All PhD and MD(Res) students have a mentor and access to the Postgraduate Tutor for pastoral matters. The students elect representatives who bring collective concerns to the Postgraduate Committee. They attend a Departmental induction day, and receive a Departmental PhD Handbook. Funding for conference attendance is provided by the Department through the supervisor's staff account. In the national Postgraduate Research Experience Survey 2011, 79% of our students agreed that their supervisors provide helpful feedback on progress, and 82% agreed that their supervisors are available when needed; in these and related questions, Bioengineering scored well above the Russell Group benchmark.

We complement supervision with three further elements of training: (i) departmental courses and seminars; (ii) courses and seminars taught elsewhere in the College; and (iii) compulsory courses from the College's Graduate School, which provides transferrable skills/professional development training (the only such programme to have twice won the Times Higher Education Award for Outstanding Support for Early Career Researchers).

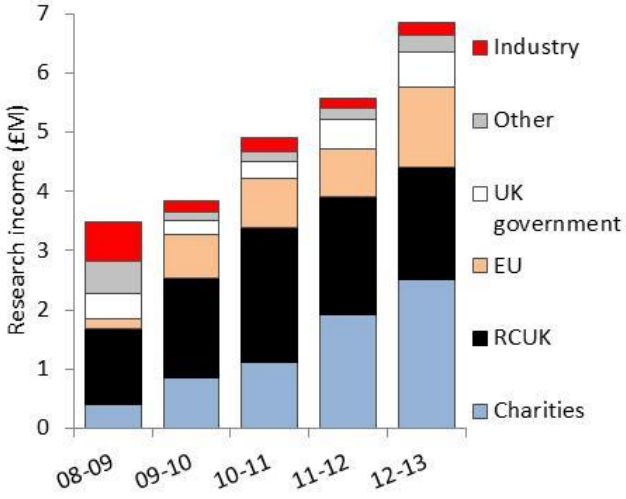
C.2.c Progress Monitoring

At 8 weeks, students submit a research plan that is assessed by the supervisor, mentor and Director of Postgraduate Research. A brief progress report, assessed by the same team, is then submitted every six months. An Early Stage Assessment at 9 months and a Late Stage Review at 18-24 months involve written and oral presentations, and are assessed by two non-supervisory staff. In their third year, students give a Departmental talk.

D. Income, infrastructure and facilities

D.1 Research funding portfolio

The Department has been successful in increasing its external research income, showing sustained year-on-year growth to double its annual research spend despite new appointments being predominantly made at junior level, where the ability to attract large grants is more limited. Across the REF period, the portfolio consisted of 249 grants with a budget total of £56.6M. Our sustainability is strengthened by having a balance of funders: 37% of funds are obtained from charities, 28% from Research Councils, and 20% from the EU; industry, other UK government and smaller funders make up the balance.



We have had particular success in attracting large-scale research funding, including 9 awards with Departmental components over £1M during the REF period, from: the Royal British Legion £3.7M for blast injury studies; Wellcome Trust & EPSRC £4.8M for osteoarthritis research; MRC £1.2M for work on perception; BHF £1.2M for atherosclerosis research; ERC £1.4M for work on cellular mechanotransduction; Wellcome Trust & Department of Health £1.3M for work on microdialysis; and EPSRC £4.0M and £3.8M and the EC £3.1M for systems/synthetic biology.

Our future plans include the specific goal of increasing the proportion of our income that comes from industry. The UK bioengineering industry is, with some exceptions, small and fragmented, without strong links to universities, which has led us to appoint a full-time Industrial Liaison Manager, with the remit of increasing university-industrial links. We also have the specific goal of raising funds for a Doctoral Training Centre.

D.2 Consultancies and professional services

Departmental staff are extensively involved in consultancy for industry. This is managed through the College's in-house company ICON, through which, during the REF period, we carried out 58 consulting projects for 52 clients in the UK, USA, Italy and Germany including DSTL, Dairy Crest Group plc, Humanetics Innovative Solutions Inc., Ci ESSE srl, and Covidien AG.

D.3 Investment in infrastructure and facilities

The Department moved into newly-refurbished offices and laboratories immediately prior to the REF period. Since then, commensurate with growth in Departmental staff and research students, we have invested heavily in further space and refurbishment, doubling our departmental space to around 4,300 m^2, of which research space accounts for half (including 1,000 m^2 of labs). We have been allocated an extra 150 m^2 of laboratory space for our immediate needs and the College intends to provide additional space for our planned expansion over the next few years. The College is developing a new campus "Imperial West" at White City, as part of a >£1bn capital investment programme. The Department, through its interdisciplinary Networks and Centres, is a priority for allocation of space at Imperial West.

We invest continuously in research equipment and facilities, with a total spend of £1.9M on equipment items over £10k during the REF period. Advanced microscopy/histology is given as an exemplar: we purchased a live-cell laser scanning confocal microscope, three two-photon microscopes, a single-molecule AFM microscope (one of 3 worldwide), a laser capture microdissection system, an optical projection tomography system, a robotic device for high-throughput 3-D imaging of embedded specimens, an automated tissue processor and a cryostat, as well as standard fluorescence microscopes. Collectively these provide staff with state-of-the-art tools for imaging cells and tissues. We also purchased molecular biology equipment, which was not previously available to the Department (space precludes a detailed list), and increased our cell culture facilities from one to three labs, as required by our move into Cell & Molecular Bioengineering and Synthetic Biology. Other investments include animal facilities, neurotechnology rigs and blast injury simulators. The Department holds competitive internal equipment funding rounds and provides the institutional component for equipment on RCUK applications.

We operate a shared laboratory system: labs are defined by function and open to all. Specialist infrastructure (e.g. confocal microscopy, electronics, 3-D printing) is run as bookable facilities supported by our technical staff, who have quadrupled in number from 2.5 to 10.33 during the REF period. We employ a dedicated Research Computing Support Officer and have established the post of Laboratory Manager to oversee technical support and Health and Safety systems.

Where it is cost effective, and supporting our collaborative ethos, we run facilities with other departments. For example, Bioengineering, Materials, and Earth Sciences & Engineering together run an Advanced Manufacturing Facility, which was constructed during the REF period at a cost of £2.5M, and the Departments of Electrical & Electronic Engineering, Bioengineering and Computing operate a Smart Environment Laboratory which cost £0.25M. The Department also contributes through user charges or direct funding to specialist infrastructure provided at College level. For example, the College has invested £5M over the REF period in a High Performance Computing facility with 14,000 cores (one of the UK's largest) and these are used by the Department.

E. Collaboration or contribution to the discipline or research base

E.1 Research collaborations

E.1.a Support for and exemplars of research collaborations

We co-ordinate and assist widespread collaboration between College departments at the interface of biomedicine and engineering through our leadership of the IBME. The IBME organises Technology Networks to build capacity and stimulate large grant proposals, and it provides administrative support and hub space for the Centres that arise when large grants have been obtained. An IBME Research Development Manager with a relevant doctorate and industrial experience of translation assists with these processes. The IBME houses four Centres: Bio-inspired Technology, Synthetic Biology; Blast Injury Studies; and Medical Engineering Solutions in Osteoarthritis and runs Technology Networks in emerging areas.

Our staff also collaborate independently of the IBME, resulting in 114 externally-funded projects across the REF period. The portfolio, worth a total of £16.1M, involves departments in the Faculties of Engineering (48 projects, £6M), Natural Sciences (33 projects, £5M), and Medicine (31 projects, £5M), and the Business School (2 projects, £250k). Our supervision of 76 PhD students registered in other Departments, mentioned above, is a further indicator of our extensive collaboration.

Externally, we have 21 funded projects with other institutions in the UK (KCL, Peninsula, Kennedy Institute, UCL, Newcastle, Nottingham, Surrey) and abroad (Belgium, Germany, Italy, Sweden and the USA). The portfolio has a total value of £5.3M. An exemplar showing widespread collaboration is the application of rapid sampling microdialysis to brain injured and other patients (CS2); it

involves clinical studies in 7 hospitals in the UK, Germany and the USA.

E.1.b Support for and exemplars of interdisciplinary research

All of our research is interdisciplinary; supporting mechanisms and funding are described above. Here we note that the Department represents the Faculty of Engineering where the latter has biomedical research interactions with the other faculties, the Academic Health Sciences Centre, Imperial's NHS Trust, the Institute of Chemical Biology and the Crick Institute.

As an exemplar, we focus on Synthetic Biology. *Kitney* initiated and chaired a RAEng working group defining the scope, applications and implications of Synthetic Biology. His report (*Kitney* Output 1) persuaded government and RCUK to invest heavily in the area; Government ministers recently predicted that the global synthetic biology market will grow to £11bn by 2016 and that the area is 2nd amongst 8 future technologies where the UK can lead. An IBME Centre was established in 2009 to develop foundational tools for Synthetic Biology and to use them for generating innovative biological applications in academia, healthcare and industry. It has equal inputs from Bioengineering (Co-Director *Kitney, Ellis*, and *Stan*) and Molecular Biosciences. In parallel, the Centre's researchers from KCL (*Marris, Lentzos*) explore the social, political, economic and ethical dimensions essential for public acceptance. The Centre has received funding with Departmental totals of £11.9M during the REF period (see above), with a further £3.7M awarded for commercialization (see REF3a).

E.2 Collaborations with research users and how they inform research

We collaborate with industry through sponsored PhD studentships, where industrial supervisors and/or student time spent in the sponsoring company directly inform the research. Examples are three studentships fully-funded by Toumaz Technology, ATR/Intelligent Wound Care and Pulsecor (New Zealand), and eight CASE studentships with Philips, Medicsight, DSTL, Toumaz Technology (2), GSK, Smith & Nephew and Vicon. As part of our strategic goal of increasing interactions with Industry, the Department has set up its own industrial PhD scheme, which provides matched funding with industry for tuition fees and bursaries. Four such studentships have been funded to date, with Microsoft, Johnson & Johnson, JRI Orthopaedics and TMO Renewables.

We encourage formal exchanges of senior staff between the Department and industry or clinical practice. Examples include Schultz, who is seconded to work with Scientifica (50% FTE) on two-photon imaging through a Royal Society Industry Fellowship, and holds a BBSRC Industry Partnership Award with them. In the other direction, Woodward, Senior Director of Biological Sciences at the U.S. pharmaceutical company Allergan Inc, holds a visiting professorship in the Department and participates in our research on glaucoma, osteoarthritis and obesity. Additionally, Colonel Clasper, Defence Professor in Trauma and Orthopaedics, holds a visiting professorship in the Department and participates in the research of our Centre for Blast Injury Studies; the full research strategy of the Centre was developed with the MoD (the Surgeon General), DSTL and the Royal British Legion (representing veterans and families).

Stevens has maintained industrial involvement through Technology Strategy Board grants totaling >£1M (Departmental component is 50%) on cell therapy with companies including BioCeramic Therapeutics, Plasticell and Finsbury Orthopaedics, and on point-of-care diagnostics with Mologic.

There are many other examples of end users collaborating in and informing our research, ranging from sports biomechanics (where we have a strong relationship with GB Rowing and the MCC, who have funded three CASE studentships and a full studentship, respectively), through application of our biosensor research to brain injury in hospitals worldwide, to image processing where commercial requirements for automation with high throughput and accuracy have stimulated us to examine and mimic how the neural system performs such tasks. Further details are given in Section B.2.b, in our Impact Case Studies and in our Outputs.

E.3 Leadership

E.3.a Leadership of the Discipline

The Department is taking a lead in developing structures for the discipline of Bioengineering that has few of the institutions, honours or awards seen in more established branches of engineering. In 2008 it established the Bioengineering Society as a national academic forum and the Society has held annual symposia attracting up to 250 delegates; its first two chairs (*Ethier, Weinberg*) are Departmental staff. The Society is currently in discussion with what was the IMechE Engineering in Medicine Division (former Chair: *Bull*) and IPEM (Departmental staff on the Engineering Advisory Group and the Academic Advisory Group) about possible mergers and accreditation.

We have instigated two unique administrative roles to promote bioengineering in the UK for the benefit of our Department and the discipline nationally. Our Outreach Manager works closely with schools to communicate bioengineering to a potential future generation of researchers, with the general public to raise awareness of bioengineering, and with policy makers to influence the future of the discipline. One success has been obtaining a higher level coding for bioengineering from the HESA Joint Academic Coding System. This has important implications for student applications, league tables and data collection. In 2012 the Department also hired an Industrial Liaison Manager to work with the bioengineering industry, in order to increase industry-academic interaction.

We have worked to raise the academic profile of the discipline by establishing the prestigious Bagrit lecture series. Lecturers were Don Ingber (MIT, 2011), Ed Boyden (MIT, 2012) and Lihong Wang (Washington, 2013). George Whitesides (Harvard) will give the 2014 lecture. These three mechanisms complement the strong academic leadership we are taking in emerging areas.

E.2.b Exemplars of individual leadership in the academic community

Staff are members of national and international advisory boards and panels including for government (EC expert group in synthetic biology – *Kitney*; Australian Government Reviews - *Kitney*; Japan Science and Technology Agency – *Tanaka*; MoD Blackett Review Panel - *Kitney*), for universities (Indian Institute of Sciences – *Ethier*; Limerick – *Ethier*; Sheffield – *Bull*; Purdue – *Bull*; National University of Ireland - *Boutelle*), for funders (BBSRC – *Krams*; ARUK – *McGregor*; NIHR – *McGregor*; DISCS – *McGregor, Schroter*), and for industry (Oxford Biosensors – *Boutelle*).

We have given 64 invited keynotes and plenaries during the REF period and hold 53 editorships and editorial board memberships including: PLoS Computational Biology (*Faisal*), Royal Society Journal Interface (*Kitney*), Annals of Biomedical Engineering (*Elson*), ACS Nano (*Stevens*), PLoS One (*Krapp*), and Proceedings Royal Society A (*Caro*). Departmental staff hold visiting appointments in the UK (*Kitney* – LSE, King's; *Mehring, Burdet, Faisal* - UCL), in the US, (*Stan* – MIT; *Nowlan* – Boston U; *Clasper* - Carolina's Medical Centre), in France, (*Burdet* – Paris VI; *Lee* – Nice; *Moore* - Ecole Supérieure d'Ingénieurs de Luminy, Marseille) and in the Far East (*Kitney* – NTU; *Tanaka* – RIKEN; *O'Hare*, National Kaohsiung University).

The Department has two Fellows of the Royal Academy of Engineering (one elected in the REF period – *Stevens*) and staff have fellowships in the medical (e.g. FRCP – *Caro*), engineering (e.g. FIChemE – *Schroter*), and science (e.g. FRCS – *O'Hare*) domains.

The Department shows leadership in industry, commerce, learned societies, and professional bodies, including, for example, membership of standards committees (*Masouros* – NATO HFM committee; *Schroter* – British Standards technical committee SVS/2/5); learned society leadership (*Weinberg, Ethier* – Bioengineering Society; *Ethier, Schroter* – World Council of Biomechanics; *McGregor* – Society for Back Pain Research); and professional body leadership (*Bull* – Biomedical Engineering Association of the IMechE; *O'Hare* – RCS Faraday Medal Committee)

Our staff have been awarded best paper prizes (e.g. *Burdet*, King-Sun Fu Memorial IEEE Transactions on Robotics Best Paper Award; *Krapp*, Journal of Navigation; *Moore*, Richard Skalak Best Paper Award, ASME Journal of Biomechanical Engineering), young investigator awards (e.g. *Weaver*, Macro Group Young Investigator's medal; *Stevens*, CRS Young Investigator Award), and many science and industry awards (e.g.*Mehring*, Paxinos and Watson prize of the Australian Neuroscience Society; *Burdet*, Apple Research and Technology Support Award; *Clopath*, Vasco Sanz Prize [Swiss Neuroscience Prize]; *Moore*, ASME Distinguished Service Award; *Reichenbach*, Arnold-Sommerfeld PhD prize; *Stevens*, EU40 Award, European Materials Research Society, 2012; *Stevens*, Griffith Medal and Prize, IOM3, 2012; *Stevens*, Clifford Paterson Award Lecture, The Royal Society, 2012; *Stevens*, Controlled Release Society, 2011; *Stevens*, Rosenhain Medal and Prize, IOM3, 2010; *Stevens*, Norman Heatley Award, Royal Society of Chemistry, 2010; *Stevens*, Polymer International Award for Creativity in Polymer Science, 2010; and *Stevens*, ACES Amgen Life Sciences Award, Science Business Innovation Board, 2009).

SUMMARY: Over the REF period the UoA increased:

FTE(A) submitted by 60%; PhD students by 80%; RAs by 256%; and Research income by 262%.

The UoA published 27 papers in *Science, PNAS, and Nature journals*.

Staff are recognised research leaders through prestigious fellowships, editorial board leadership, advisory board membership, prizes and awards.

Further significant growth in academic staff and research income is planned, as described above.