Institution: King's College London

Unit of Assessment: UOA 15 General Engineering

a. Overview: The King's College London (KCL) Division of Imaging Sciences and Biomedical Engineering, based at St. Thomas' Hospital, is dual-affiliated to the School of Natural and Mathematical Sciences and the School of Medicine. KCL is a partner in King's Health Partners (KHP), one of the five Academic Health Sciences Centres accredited by the Department of Health and includes three Biomedical Research Centres (BRC) funded by the National Institute of Health Research (£113M). Imaging and Biomedical Engineering forms one Clinical Academic Group (CAG) within KHP and one Research Theme of the BRC, and there is unified leadership across Division, CAG and BRC. The Division contains over 350 staff and graduate students who are supported by state of the art experimental and clinical research facilities.

The Division's overriding goal is delivery of scientifically informed solutions to biomedical problems by combining fundamental research in engineering, physics, mathematics, computing, and chemistry with medicine and biology. 67% of the academic team are engineers or physical scientists, who work closely with clinicians and biologists focusing on diseases of world-wide significance: cardiovascular disease, cancer, the problems of early life & musculoskeletal disease.

The Division has five Departments with Biomedical Engineering and Imaging Chemistry & Biology developing fundamental technologies that are refined and translated into clinical applications by Cardiovascular Imaging, Cancer Imaging and Perinatal Imaging. The administration and delivery of research is overseen at Divisional level to maintain inter-disciplinarity and translation.

b. Research strategy: Our goal is the delivery of scientifically informed solutions to healthcare problems that involve **the acquisition, reconstruction, processing and analysis of pre-clinical and clinical data, which is predominantly imaging based, and the use of this information, including it's integration within biophysical models, to answer clinically important questions.** Our strategy is the delivery of the this goal bound by 3 important principles:

1. Basic science excellence in the underpinning engineering and physical sciences
2. Inter-disciplinary work, with staff and graduate students located not by discipline or department but in groups focused on particular programs or disease themes
3. A focus on areas of greatest translational impact in order to better understand the mechanisms of disease and/or improve the diagnosis and treatment of particular clinical conditions

This strategy was adopted in 2006, when the Division comprised only 6 academics and 10 researchers, and at the last RAE we laid out our objectives for change and growth. Implementation of our strategy and institutional investment in new appointments and facilities has allowed us to build a critical mass and we now have 60 academics and over 300 researchers.

Meeting RAE 2008 Objectives: We achieved our scientific objectives from RAE 2008 in our areas of focus: diagnosis & treatment of cardiovascular disease, and development & application of novel tracers/contrast agents. Outcomes include: generating novel atherosclerotic plaque-specific contrast agents *(Nature Medicine, 15 publications, 3 patents)*; combining multi-modal image data with catheter tracking technology to create new tools that are in first-in-man trials *(30 publications, 6 patents, Impact case studies)*; accelerating cardiovascular MR imaging using spatio-temporal under-sampling techniques *(20 publications, 3 patents, Impact case studies);* developing quantitative cardiac MRI including cardiac diffusion fibre tracking, which is also progressing to industrial translation *(20 publications, 2 patents)*; creation of new chelators for Ga-68, Tc-99m, and Cu-64, thyroid F-18 PET tracer & hypoxia imaging agents for cardiac and cancer applications *(9 publications, 4 patents)*; development and first clinical translation of cell labelling techniques and nanoparticlulate materials for combined modality imaging *(7 publications, 2 patents)*.

Research structure: Our research themes form a synergistic pipeline culminating in clinical translation. There is also a strong focus on reverse translation, where the clinical and biological questions drive the direction of the engineering and physical science research themes. In practice most programmes run across multiple research themes with no artificial barriers between disciplines and themes. **Image acquisition and reconstruction** brings together expertise in imaging physics and engineering in a number of areas such as PET, x-ray and ultrasound, but particularly in MRI. There is complementary expertise in computational and mathematical techniques needed for **image computing** to analyse and extract information from the reconstructed images. Other computer scientists and mathematicians lead programs in

computational modelling and simulation particularly in cardiovascular disease. There are also programs in molecular imaging, pre-clinical and clinical, covering image acquisition, processing and modelling as outlined above, with an additional strong emphasis in **imaging chemistry and associated biology**. Alongside these basic science strengths there is also substantial expertise in **clinical translation** in cardiovascular disease, cancer imaging, and fetal and neonatal neurology.

The translational research ethos also drives teaching and industrial engagement. Undergraduate teaching includes a BEng in Biomedical Engineering, an intercalated BSc in Imaging Sciences and substantial contributions to the MSci in Chemistry with Biomedicine. There are MSc's in Medical Engineering, Medical Physics, Imaging Science, Imaging Chemistry, and Nuclear Medicine supported by EPSRC, MRC and Wellcome. There is an innovative PhD training programme with over 100 students and we have just obtained an EPSRC Centre for Doctoral Training in Medical Imaging. Our Industrial engagement spans a full spectrum of activities from advisory panels, co-funding, joint grant applications, and the housing of industry-funded personnel within the Division.

Current Research Strengths, Future plans & Objectives

Image acquisition and reconstruction: The overall objective is to move to an adaptive framework for image acquisition and reconstruction that achieves isotropic 3D whole organ coverage; with improved image quality and spatio-temporal resolution, faster acquisition speeds, tolerance to motion and comprehensive tissue characterisation of the target organ. We need to transform how imaging modalities are used, consider new ways of combining their capabilities, and integrate acquisition, reconstruction, analysis and modelling into a coherent, comprehensive whole.

- Image Quality and Resolution: MRI parallel-transmit technology offers enhanced control of the radio-frequency (RF) fields enabling MRI examinations to be tailored to the patient, while optimising contrast and signal properties and minimising RF power absorption. First in-vivo applications in volunteers using an 8-channel prototype system *(Hajnal 2 patents, Malik ISMRM Young Investigator 2012)* is now moving beyond the conventional approach, which seeks maximally uniform fields, to a new patient centred paradigm in which optimal signal properties are obtained from dynamically modulated non-uniform fields *(Malik EPSRC fellowship 2013, Hajnal MRC strategic grant)*. Novel MRI motion compensating methods are transformative, particularly for imaging the fetus in utero *(Hajnal)*, and underpin programmes for mapping functional and structural connections in the human fetal and neonatal brain *(Edwards, Hajnal ERC Developing Human Connectome Synergy grant),* and for accurate and automated diagnosis of congenital abnormalities in conjunction with ultrasound technology *(Hajnal, Eckersley, Rutherford, Aljabar, Rhode, Penney, Razavi Wellcome/EPSRC Innovative Engineering for Health grant)*.
- Acquisition Speed: MR acquisition can be accelerated and resolution improved by using novel undersampling strategies *(Schaeffter, Hajnal, Prieto, Razavi EPSRC Programme grant Intelligent Imaging)* which include exploitation of spatial and temporal correlations of the data so that cardiac MRI becomes a high-resolution 3D multi-modal study that can be done in less than 30 minutes *(Kozerke, Nagel, Griel Journal of American College of Cardiology 2011 & 2012)*. Innovative motion compensation techniques using self-navigation *(Prieto, Kozerke, Schaeffter)* complemented by advanced image registration *(Penney)* and novel motion modelling *(King)* will be used within the reconstruction process to achieve accelerated and optimally efficient examinations that utilise all data obtained during free-breathing. This is key for applications in children, the elderly, and others who cannot comply with current breath-hold methods.
- Tissue Characterisation: MR-elastography using macroscopic mechanical wave propagations allows the measurement of mechanical tissue properties and through numerical simulations the derivation of tissue microstructure *(Michler, Sinkus PNAS 2012, 4 patents)*. This has great clinical potential for application in breast and prostate cancer, liver fibrosis, multiple sclerosis, and Alzheimers *(EU PICTURE and DARE-IT)*. Further advances for characterising tissue include fast T1 techniques *(Schaeffter, Botnar, Puntmann)* that allow tissue properties to be assessed before and after administration of target-specific contrast agents, even in challenging areas such as the coronary vessel wall *(Phinikaridou, Botnar BHF Programme grant)*. Our aim is to establish MRI as a fully quantitative technology providing new, easy to use, and validated biomarkers for assessing disease severity and co-diagnostics for therapy guidance. Advances in diffusion MRI and tractography analysis provide a new window to study the connectivity

between different brain structures *(Tournier)*. In combination with newly developed functional MRI techniques *(Hajnal, Counsell)*, these will be used to build a connectome of the developing brain *(Edwards ERC Synergy as above)*.

- Combining Modalities: The use of MRI to guide interventions using active/robotic MR catheters and associated MR-tracking systems and interfaces *(Schaeffter, Rhode, Razavi Wellcome/EPSRC Medical Engineering Centre)* continues, and building on our first in man interventions in structural heart disease to fully MR guided ablation of cardiac arrhythmias in patients *(Circulation 2010)*, moving to robotic navigation intelligently guided by the real time MR images. There is also a strong research focus on simultaneous PET/MR imaging, both on hardware developments and new motion compensated reconstruction approaches *(Reader, Marsden, Botnar; EU SUBLIMA and Wellcome/EPSRC Medical Engineering Centre),* using MR-derived motion fields *(King, Schaeffter)*. The novel motion compensation techniques will be further developed and translated to improve PET resolution in oncology *(Barrington, Cook, Goh, Blower)*, cardiology *(Nagel, Razavi),* and neurology *(Gee, Hammers)*.

Image Computing: In concert with improved acquisition and reconstruction methods, the objective is to develop computational and statistical techniques that allow automatic analysis of images in a quantitative way, accurate fusion of images to guide interventions, and building atlases from large image datasets that help with the understanding of pathophysiology.

- Quantitative Analysis: We are developing new techniques *(3 patents joint with Philips Healthcare)* that allow full quantitative analysis such as trans-myocardial gradients, temporal dephasing, and voxel-wise quantification *(Chiribiri, Nagel)* for assessing myocardial perfusion by MRI. In addition, computational methods to measure tumour heterogeneity in PET, CT, and MRI *(Cook, Goh NIHR BRC Programme)* are showing promise as new biomarkers in cancer.
- Image Fusion: A core area of research is the development of novel image registration, motion compensation and fusion techniques to guide cardiovascular interventions, as described in 2 Impact case studies *(Penney, Rhode, King, Clough, Razavi, Schaeffter 5 patents)*. Further work will create new automated techniques, incorporate non-imaging data, and involve development, validation, and clinical translation in partnership with Philips, Siemens *(TSB grant 2013)*, St. Jude, Biosense Webster, and KCL start-up Cydar Ltd *(Penney)*.
- Big Data Atlases: We are developing methods that combine large image and secular datasets using new statistical classification and high-dimensional embedding techniques *(Aljabar, Montana)* and are using them to analyse complex cerebral connectivity analysis and brain growth and development. Graph theoretical methods and machine learning tools will be applied to biomarker discovery, brain connectivity analysis, and to explore linkages between image and genetic data in neonates *(Edwards; MRC Strategic and ERC Connectome grants as above)* and in patient cohorts with Alzheimer's disease, cancer, and cardiovascular disease.

Computational modelling and simulation: The objective is to achieve insight into mechanisms of disease by creating a mathematical and computational framework of electro-mechanical and computational fluid dynamic models using pre-clinical and clinical imaging and other data.

- Electro-mechanical computational models: We are using personalised multi-scale models to characterise fundamental physiological parameters and clinically applying them to improve patient stratification *(Smith, Lamata, Nordsletten EU VPH-SHARE, Wellcome Fellowship, BHF grant)*. We will develop these further integrating detailed cell models *(Niederer, Aslanidi EPSRC grant, BHF grant)*, high-resolution ex-vivo imaging of cardiac tissue structure (Bishop EPSRC grant), and in-vivo structural data *(Kozerke EPSRC grant)* to study the mechanisms of cardiac arrhythmias and anti-arrhythmic therapies. Clinically, we will integrate multiple data from imaging and clinical electro-anatomical mapping within biophysical modelling frameworks to create single representations of individual patient physiology and pathology *(Schaeffter, Rhode Wellcome/EPSRC Medical Engineering Centre)*. These approaches will be applied to investigate patient selection, device development, and implantation procedures for cardiac resynchronization therapy in heart failure and ablation of ventricular tachycardia and atrial fibrillation *(Razavi EU VP2HF)*.
- Computational Fluid Dynamics: Advanced biomedical images of anatomy, function, and flow *(Schaeffter, Kozerke EPSRC grant)* are used to extract high-resolution meshes and velocity boundary conditions of vessel structures to simulate the 3D hemodynamics *(Figueroa, Alastruey-Arimon ERC and BHF Fellowships)*. These models will allow: investigation of spatio-

temporal changes of blood flow *(Lamata, Smith)* including haemodynamics in aortic coarctation *(Greil, Figueroa TSB programme with Philips)* and aortic dissection *(Clough, Figueroa)*; development of novel biomarkers in hypertension *(Alastruey-Arimon)*; and simulation of myocardial perfusion *(Smith Wellcome/EPSRC Medical Engineering Centre)* to optimise and better interpret MRI, CT, and invasive physiological measures of myocardial ischemia.

Imaging Chemistry and associated Biology: The objective is to address the two major chemical challenges of imaging: synthesising innovative molecular probes and new platform chemical technologies, in order to improve quality and accessibility. We will also evaluate the resulting new probes in vitro and in vivo and identify new biomedical targets that could be addressed by innovative probe chemistry.

- Molecular Probes: We have programmes developing metallic radionuclides and bioconjugate probes *(Blower, Yan)*, small organic molecules *(Gee, Kealey, Yan)*, metal complexes *(Blower, Torres, Ma)*, nanoparticulates *(Torres, Green Angewandte Chemie, Nature Nanomaterials),* and hyperpolarised NMR *(Eykyn)*. Further down the pipeline clinical trials are in place for Cu-61/64-ATSM for imaging tumour hypoxia in head and neck cancer, F-18-BF4 for thyroid cancer, and Tc-99m-labelled iron-oxide nanoparticles for sentinel node detection in breast cancer *(Blower, Torres, Cook, Goh Wellcome/EPSRC Medical Engineering Centre)*. We will improve understanding of the design of new probes using computational molecular modelling through collaboration with the new Division of Chemistry. Future translation will focus on molecular imaging for transplant medicine, stem cell therapies, skeletal biology and vascular calcification *(Blower, Frost, Mullen, Cook)*. We will also expand current activity in neurosciences *(Gee, Blower, Hammers and IoP collaborators)* and immunology and cell tracking *(Blower, Mullen)*.
- Platform Chemistry: We are developing new generic technologies including ultra-fast chemistry for ultra-short half-life radioisotopes such as Cu-62 and N-13 *(Blower, Gee)*, pre-targeting by separating the targeting moiety and the radionuclide tracer *(Blower, Ma Royal Society Netwon Fellowship)*, and smart probes that report on microenvironment *(Torres)*. We will also develop platform chemistry that combines tracers for different modalities *(Torres, Yan, Green)* which will complement new devices such as PET-MR and demonstrate them pre-clinically and clinically.
- Biomedical Targets: The clinical targets for our chemistry programme are identified because of their high potential impact and an unmet need and have led to molecular-, nanoparticlular- and protein-based tracers for: atherosclerotic plaque *(Botnar Nature Medicine)*; prostate cancer *(Mullen)*; thyroid cancer *(Blower)*; myocardial hypoxia *(Southworth, Blower, Nagel)*; neuro-psychiatric disease *(Gee, Blower, Hammers)*; apoptosis *(Mullen)*; sentinel lymph nodes *(Torres, Green);* and cell tracking *(Blower, Mullen)*. Biological targets are also important and we have developed generic imaging reporter genes and combined them with novel radiotracers that allow imaging of in vivo molecular mechanisms *(Mullen, Blower, Fruhwirth)*.

Clinical Translation: Translation of scientific advances to practical benefit is a key component of all our research themes. In this section we highlight a selection of programmes that demonstrate the pipeline from science and engineering to clinical implementation and sometimes back again.

- Developing Human Connectome Project (ERC €15m) 2013-19: This project both develops and applies new methods for imaging structural and functional connectivity in the fetal and neonatal brain. Edwards leads the clinical study of 1500 normal fetuses and infants to make the first maps of normal and abnormal brain connectivity.
- VP2HF (EU-FP-7 €3.6m) 2013-16: Treating heart failure with a pacemaker to resynchronise myocardial contraction is an expensive procedure that only works in 50% of cases. Razavi leads this multi-centre trial in 200 patients using state-of-the-art imaging and computational models of the heart for patient stratification to determine clinical and health economic impact.
- MR-INFORM (NIHR £1.1m, Bayer Healthcare £1.2m) 2011-15: A non-invasive way of quantifying myocardial ischaemic burden is needed to replace coronary angiography, which does not adequately select patients that will benefit from treatment. Nagel leads this prospective randomized controlled multi-centre outcome trial that compares our novel MR acquisition and quantitative analysis methods for assessing myocardial perfusion to the gold standard of invasive fractional flow reserve. 620 of the required 918 patients have already been recruited.
- Comprehensive Cancer Imaging Centre (CRUK/EPSRC £7.5m) 2013-17: In cancer we are using new imaging tracers and image acquisition and processing techniques to improve tumour characterisation and prediction of early therapy response. Clinical studies lead by Cook and

Goh are looking at stratification of lung cancer and oropharyngeal cancer for hypoxia modifiers prior to radiotherapy, and using new imaging tools for early therapy assessment in lymphoma, breast, thoracic, renal, gastrointestinal cancers, and skeletal metastasis.

- Other Translational Projects: There are many other clinical trials on-going in cardiovascular disease funded by BHF, NIHR, and MRC grants covering: diffuse myocardial disease using T1 mapping without contrast; atherosclerosis and transplant rejection assessment with new MRI techniques looking at coronary vessel wall enhancement; MR methods for patient stratification and real-time procedure guidance in cases of cardiac arrhythmias and imaging techniques, in order to manage complex vascular disease including aortic dissection and aneurysms; and MR guided cardiac catheterisation techniques, to better understand pathophysiology and stratify the management of patients with congenital heart disease. Similarly in Perinatal Imaging, funded by NIHR and MRC, there are major programmes including a comparison of the clinical and health economic efficacy of MRI and ultrasound in assessing neurological problems, with 511 preterm infants recruited, and prospective randomised clinical trials of melatonin and xenon as new therapies for reducing brain damage after birth asphyxia using MRI as the qualified biomarker.

c. People

Staffing strategy and staff development: The staffing strategy of the Division is focused on recruiting the highest calibre scientists who share our vision of multidisciplinary working and clinical translation. We then consider the 'fit' of their research with the areas of our strategic focus.

Only 6 of the 57 academics being returned were in post at the beginning 2006 and only 1 of the 51 new recruitments was to an already vacant post. The rest, alongside an additional 15 permanent support posts, have been created by KCL on the basis of a compelling strategic vision: **'to build a critical mass able to deliver the highest quality, multi-disciplinary, translational, high impact research in imaging science and associated computational modelling'.** These recruitments have brought high-calibre scientists from leading UK and international groups to both senior and junior/early career faculty positions. Approximately 45% of our REF returns are in the latter category, which presents exciting opportunities for the next 5-10 years. Those recruited just prior to RAE2008 have become well established as leading and productive scientists in the Division. Professors Schaeffter, Blower and Nagel lead the Biomedical Engineering, Imaging Chemistry and Biology, and Cardiovascular Imaging departments respectively, and Professor Botnar chairs the MRI Clinical Research Committee (responsible for the 5 clinical research MRIs in the Division). The Division has a culture of collegiality and both formal and informal support structures, particularly for our more junior colleagues, as detailed below. During the period from 2006 only one academic has left the Division a recruit from Germany who returned there for family reasons.

New recruitments: In the period after RAE2008, we continued our recruitment in line with the strategy outlined above. These recruits are outlined below, divided into the areas of strategic focus.

- **Computational modelling** has been a key area of expansion led by Professor Smith (EPSRC fellow, Oxford) and supported by: Niederer (EPSRC Fellow, Oxford); Nordsletten (MIT); Bishop (Wellcome Trust Fellow, Oxford); Alastruey (BHF Intermediate Fellow, Imperial); Figeroa (Stanford); and Aslandi (Manchester). A complementary strategic development in processing large data is led by Professor Montana (Imperial).
- **PET capability** has been developed by the appointment of Professor Gee (GlaxoSmithkline/Imperial), alongside Yan (UCL), and Keely (Imperial), strengthening our carbon and fluorine radiochemistry offering. Reader (McGill), enhances PET reconstruction, and Professor Cook (Institute of Cancer Research), Professor Goh (Mount Vernon), and Warbey (UCL) strengthen our translational research. Professor Hammers (Lyon) has recently been appointed to lead this growing PET activity.
- **MR capabilities** have been supported by the recruitment of: Professor Sinkus (INSERM, Paris) an expert in MR elastography; and Puntmann (Imperial) to develop translational work; while Professor Korzerke (ETH Zurich) was given a part-time substantive appointment to develop MR physics, supported by Eykyn (ICR), an expert in hyperpolarised MR imaging and spectroscopy.
- **Perinatal Imaging** was relocated, with support from the MRC, from the MRC Clinical Science Centre/Imperial to KCL. This multi-disciplinary group of engineers and clinicians led by Professors Edwards, Hajnal, Rutherford & Counsell comprises Aljibar, Malik, Malamateniou, and Eckersley, and they have recently been joined by Tournier (Florey Institute, Australia). They

add new breadth to our portfolio and their work with others in the Division has lead to the new £10m Wellcome/EPSRC Innovative Engineering for Health programme in fetal imaging.

Developing Talent: Alongside the many recruits from outside of KCL we have also been keen to nurture our internal talent to take on their first substantive academic positions.

- **Fellowships:** During the assessment period 24 fellowships have been awarded to researchers within the Division from: EPSRC (6), MRC (6), Wellcome Trust (3), BHF (4), Royal Society (1), ERC (1), Whitaker (1), and EU Marie Curie (2).
- **Probationary Lectureships:** Our probationary lectureship scheme is an excellent opportunity to retain the brightest early career scientists within the Division. Through a competitive selection process the scheme allows promising post-doctoral researchers to become Probationary Lecturers whilst continuing with fellowships/research funding. They are provided with substantial mentorship and support during a 1-2 year transition and are therefore much better prepared to apply for substantive HEFCE funded positions as they become available. Since 2008 11 of our post-doctoral researchers have made this transition: King, Micheler, Prieto, Phinikardou, Lamata, Torres, Fruwith, Chiribiri, Clough, Hussain and Arichi. Of the above, all but 3 have now secured permanent academic posts within the Division, which were competitively appointed against strong external candidates.

Mentoring and Personal development: Mentoring and personal development is vital and includes MSc and PhD students, post-doctoral researchers, and academics at all levels.

- **Early career mentoring:** The Division adheres strongly to the principles outlined in the Concordat. All PIs are strongly encouraged to mentor postdoctoral researchers through their careers by: developing independent areas of research, building up collaborations, and involvement in teaching, management, and decision-making. This is achieved by partnering each early career researchers with a senior academic mentor who will: actively inform and encourage them to take advantage of training and funding opportunities that exist both internally and externally; and provide training and promote excellence in supervision, research, and academic leadership. The mentoring programme is led by Professor Counsell who has set up a training programme for the senior mentors. There is a strong emphasis on feedback from both mentors and mentees in order to evolve and improve the programme over the coming years.
- **Equality and Diversity:** In the Division we promote equality of opportunity in all areas of work and ensure that all KCL members and prospective members are treated solely on the basis of merit, ability, and potential without any discrimination. We promote a positive working, learning, and social environment free from prejudice, harassment, or bullying. Recruitment and other panels are chosen to reflect diversity in experience and expertise. Schemes such as the B-MEntor scheme, the Career Break Fund, the Women's Network, and the Springboard Women's Development Programme are strongly encouraged. The Division has also put in place a number of initiatives including flexible working hours and lunchtime (as opposed to evening) seminars and meetings to support staff with outside commitments. Building on these initiatives we are actively involved in the School of Medicine's silver Athena Swan application.
- **Personal Development:** This is promoted through comprehensive KCL-wide and Division-specific programmes. The Graduate School-based Researcher Development Unit (RDU) provides training, development, and career advice for post-doctoral staff, postgraduate students, and PhD supervisors. Over 300 workshops are available to all researchers to attend free of charge. These include training in: leadership, becoming a PI, teaching, equality and diversity, conflict resolution, language and IT skills, mentorship, and 1-to-1 coaching. The RDU leads College strategy on personal, professional, and career development for researchers and implements the Concordat for the Career Development of Research Staff. It also hosts the Vitae London Hub which provides input into national policy on researcher development.

Appraisal and Promotions: We provide staff with an annual structured appraisal and use this to develop individual careers, including supporting them through the College promotion process.

- **Appraisal:** To ensure we offer the best opportunities to our team and to enable them to contribute to the full, we engage in an annual appraisal for all academic staff. Appraisal and reflection on the previous year's performance focuses on the individual's needs so that a tailored training and support programme is provided. It also allows any concerns to be raised in a more formal setting and ensures these are addressed at the appropriate level. Our business planning process that is conducted after the appraisal allows each academic and their Head of

Department to plan grant, publishing, teaching, and other activities for the coming year. It allows the Department/Division oversight of the grants and papers to be submitted so as to allow for the planning of recruitments and space utilisation based on anticipated funding. This process also allows us to ensure flexibility in the balance between teaching and research.

- **Promotions:** Annually there is a College wide opportunity for staff promotion and we encourage the most promising members of staff to apply. In the last 5 years we have successfully guided 8 academics through the promotion process. All but 1 of the academics who were in the Division prior to 2008, and not in professorial positions, have been promoted during this period, with 3 progressing to full professorships. This has allowed for retention of key members of academic staff as well as providing encouragement and highlighting the progression process available within the Division.

Research students: We currently have 113 PhD and MD students in the Division. Our Doctoral Training Programme spans the spectrum of imaging and computational modelling from basic science to application in order to provide unique interdisciplinary training.

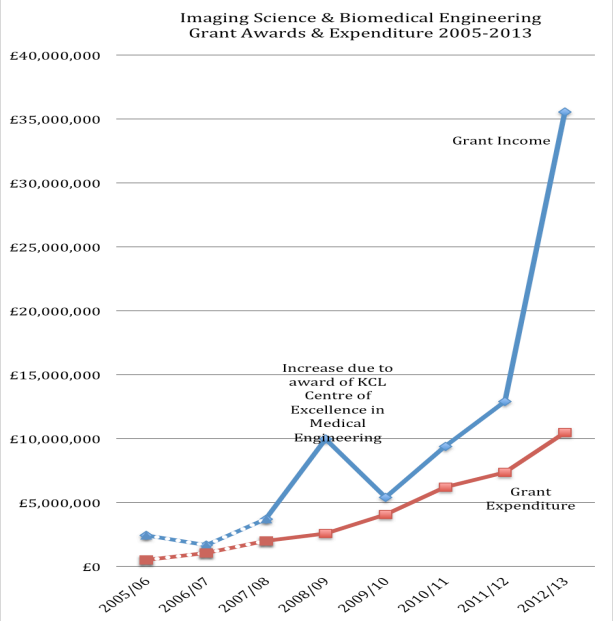
- **Doctoral Training Programme:** Most students undertake a four-year programme, with the first year dedicated to an MRes that includes taught courses covering a wide range of topics related to imaging and computational modelling. There are then more specific modules relating to the student's area of interest such as acquisition physics, computational techniques, or imaging chemistry. The students have an opportunity to participate in a group research project to foster interdisciplinary working. They also have time to work with their chosen supervisors to develop the research ideas for their PhD in the final three years. There is further organised teaching for 0.5 days a week during the final three years of the PhD which covers related clinical aspects, health economics, and a range of hard and soft skills including employability and thesis and grant writing. Although there is a strong emphasis on the individual research topic and scientific excellence, we continue to encourage interdisciplinary thinking, which, in our experience, encourages innovation and scientific breakthroughs. Quarterly reviews with each student are undertaken to ensure that targets are met and theses completed in a timely manner, as well as ensuring submission of research papers to high quality peer review journals. We achieve an excellent 4-year PhD submission rate of over 95% and completion rate of 97%.
- **Clinical and Industrial Translation:** The focus of both our graduate training and individual student research projects is to develop the skills for creating and translating innovative technical solutions through the integration of physical sciences and engineering with biological and clinical disciplines. The research seeks solutions in the care cycle of major disease areas impacting on diagnosis, therapy selection, and assessment of treatment response. Our location within a world-class teaching hospital engenders strong links with the NHS, which provides further enhanced opportunities for clinical translation and career opportunities in healthcare. A central theme within our post-graduate programmes is the translation of innovations into commercially viable products. To enable this we utilise our strong industrial links to create joint PhD projects and enable many students to undertake industrial placements and internships. This provides valuable training and insight for career paths within industry, including in new UK-based small and medium-sized enterprises and start-up companies. The programme has, and continues to, produce scientists with expert knowledge in their chosen field. Our students go on to have wide and varied careers, both in academia (55%), industry (25%), and the NHS (20%). There is high demand for our graduates and, over the last 5 years, all have found employment within academia or industry within 6 months of graduation. Those moving into academia have moved to leading universities nationally and internationally, whilst those moving to industry work for imaging equipment manufacturers such as Philips and Siemens or for imaging users such as major pharmaceutical & device companies (GSK, Pfizer, Astra Zeneca, St Jude and Medtronic). The calibre of our students is often acknowledged through external scientific awards and we have received 34 such awards at major conferences over the REF period.

d. Income, infrastructure and facilities

The strategy of building a critical mass of high quality scientists, working in a multi-disciplinary, translational setting with state-of-the-art infrastructure (over £40M) has resulted in a substantial increase in awards and expenditure over this period. Since RAE2008, the Division of Imaging Sciences and Biomedical Engineering has been awarded over £76.9m in research grant funding. The awards are distributed as follows:

UK Research Councils	£22,942,686	Overseas Industry	£3,364,519
UK Charities	£31,539,804	EU	£15,228,217
UK Government	£1,880,346	Overseas Other	£749,185
UK Industry	£1,085,757	UK Other	£97,000

The graph below gives the total research grant awards and expenditure over the REF period, with the dotted lines extending back to the point where we implemented our new strategy. 2005/06 expenditure was £499,151, and has increased year-on-year. Research income, consistently higher than expenditure, reached £35,554,551 in 2012/13. Alongside the graph are some notable awards:



- **KCL Centre of Research Excellence in Medical Engineering,** Wellcome Trust and EPSRC, 2009, £10.3m (£7.5m to our Division), 1 of 4 in the UK
- **Comprehensive Cancer Imaging Centre,** CRUK and EPSRC, 2008, with UCL £8.5m (£2.2m to our Division). New award, 2013, £7.5 (£1.8 to our Division) 1 of 4 in the UK
- **EPSRC Program Grant,** Intelligent Imaging, 2010, with UCL, Imperial, and ICR, £5.6m (£2m to our Division)
- **MRC Strategic Grant,** 2012, £7.6m to our Division
- **ERC Synergy Grant,** 2013, €15m (€9m to our Division)
- **Innovative Engineering for Health,** Wellcome Trust and EPSRC, 2013, £10m (£9m to our Division), 1 of 3 in the UK.

Research infrastructure: Since RAE2008 there has been extensive investment in Divisional infrastructure that reflects the growth in research funding, critical mass, and College support for our research strategy. The Division has a research administration team of 31 staff (10 with PhDs) who help manage the research and facilitate and interact with the Schools and College infrastructure support teams. These Divisional staff play a crucial role in: identifying external funding streams; supporting grant submission processes; the administration of grants and research staff; research governance; the management of research laboratories and pre-clinical facilities; the management of computer networks and High-Performance Computing (HPC) facilities; and managing commercial interactions with industrial collaborators. Teaching is a key function of the Division and is supported by a dedicated administrative team of 5 who manage our undergraduate and Master's programmes and our Doctoral Training programme. Finally there is a team of 30 staff, including radiographers, nurses, technicians and chemists, who support the Divisional clinical research facilities that include the cyclotron and GMP chemistry facilities. KCL and KHP provide an additional research infrastructure, including public and patient support, processing of ethics applications and contract negotiation through the Joint Clinical Trials Office.

Research Facilities: As outlined in our research strategy, we aim to create a pipeline from imaging chemistry, image acquisition through processing/reconstruction, computational modelling and clinical translation. The College have supported this pipeline with over £40m of funding for research facilities established or refurbished since the end of 2007. The Division is based at St Thomas' Hospital allowing us to maximise synergies between research and clinical translation. Staff are allocated space in order to enhance multi-disciplinary working and, as such, one office/lab may house a physical scientist, an engineer and a clinician working on the same disease area. The Research facilities are as follows:

- 3000 sqm of offices, computer laboratories, and seminar rooms
- 800sqm of state-of-the-art engineering, physics, chemistry and biology laboratories including confocal microscopy, flow cytometry, and HPLC
- Pre-clinical PET-CT, SPECT-CT, PET-MR, and ultrasound and a 9.4T NMR for spectroscopy and imaging with an additional hyperpolariser
- A Biological Services Unit that has recently undergone extensive refurbishment

- A dedicated HPC facility with 640 cores and 5 terabytes of shared memory
- 6 new research clinical MRI scanners including 4 at 3T, 2 in the process of commissioning, each with unique research capabilities. For example, to facilitate interventional research programmes two of the systems (1.5T and 3T) have an XMR configuration with digital fluoroscopy and a table-top that can move easily between the two modalities. One 3T system has an 8-channel transmit capability, unique for a system based in a clinical setting, and we have a 3T system located on the neonatal intensive care unit to facilitate the perinatal research
- A new PET Imaging clinical research facility with 2 state-of-the-art PET-CT scanners. The UK's second PET-MR system is being commissioned as part of the same facility
- A second high-energy cyclotron and substantial expansion of our GMP chemistry facilities, with an additional 25 hot-cells, are also in the process of being constructed
- Divisional facilities contribute to and are further enhanced by institutional core facilities. These include the BRC Experimental Medicine Hub (£18m investment) and Clinical Research Facilities (£35m investment) located on all three clinical campuses. The facility at St Thomas' is adjacent to one of our new research MRI systems and so enables synergistic use of the two facilities.

Research governance policy and practice: KCL has a comprehensive policy regarding the conduct of research, research ethics, integrity, and data management that follows the UK Research Integrity Office Code of practice for research. It recognises that the proper conduct of research requires the maintenance of high standards of integrity in order to protect the research community, participants in research, and the broader community that considers research evidence in the adoption of new policies and practices. Our policy is outlined as follows:

- All staff and students are expected to adhere to the principles of honesty and integrity in all aspects of research; accountability in the conduct of research; excellence when conducting, reporting, and disseminating research; co-operation in working with others; and good stewardship of research on behalf of participants and consumers of research
- Researchers are required to be aware of regulations and policies related to research (e.g. GCP, data protection, and data archiving policy, health & safety, COSSH); to keep clear and accurate records; to employ appropriate research methods; to take responsibility for the trustworthiness of their research; and to be aware of their ethical obligation to weigh societal benefits against the risks inherent in their research
- Researchers must to follow guidance criteria for authorship and acknowledgement of contributions to their research; be fair in their evaluations of other's work; respect confidentiality; disclose any conflicts of interest; and share data and findings openly and promptly once priority and ownership are established. Any research misconduct, such as fabrication of data; falsification of data; plagiarism; deception; fraud collusion is taken very seriously and is reported to the appropriate authorities. The procedures for investigating and resolving allegations of research misconduct and the policy on information disclosure are openly publicised.

Our Departmental and Divisional Head's, managers and supervisors are conversant with the above principles and responsibilities and ensure that students and junior staff receive appropriate training in good research practice. This commences when staff and students first join the Division as part of their compulsory induction process and is then continuously reinforced at group, Departmental, and Divisional meetings. The importance of good research practice is also reinforced for supervisors through compulsory refresher training.

At College level there are a range of procedures to ensure compliance with the above principles and for dealing with allegations of misconduct and other poor research practices, as well as protection for those who report such incidents. Staff and student training and mentoring, Health, Safety and Environment Protection, and adherence to relevant regulations are coordinated at Divisional level. The Division has specific staff responsible for key functions such as Health and Safety, Radiation Protection and Biological Safety. This is overseen by the KCL Health, Safety and Environmental Protection office which carries out regular inspections and audits. Research ethics for work involving human participants, material, or personal data is overseen by the KCL Research Ethics Committee and/or National Research Ethics Committees as appropriate; while for animal-related work compliance with Home Office Regulations is coordinated through the Biological Services Unit and its committees.

e. Collaboration or contribution to the discipline or research base

Collaboration: Translational research that is carried out in the Division is not a collection of standalone academic disciplines, but rather a network of dialogues and interactions between partners in academia, industry, and other stakeholders in healthcare. Such collaborations range from specific projects with our clinical partners, joint research and development programs with our industrial partners, and jointly funded national and international research projects with other leading academic institutions.

- **Clinical Collaboration**: The Imaging and Biomedical Engineering CAG of KHP, our Academic Health Science Centre, unites our research in imaging sciences and biomedical engineering with the different clinical imaging centres and medical physics and engineering departments at Guy's and St Thomas', King's College Hospital, and the Maudsley Hospital. These NHS foundation trusts serve a local population of more than 2m people living in London and provide tertiary services for patients across the UK and internationally. We have also partnered with the BRCs funded by the NIHR. The comprehensive BRC at Guy's and St Thomas' NHS Foundation Trust and KCL is dedicated to translating discoveries into patient care. Imaging and biomedical engineering is one of its eight themes and a key component of its largest of 3 inter-disciplinary clusters *Biomarkers, Imaging, Co-diagnostics and Devises*'.
- **Industrial Collaboration and Commercialisation:** The Division has established close partnerships with 17 industrial partners with joint initiatives in both directions: industrial researchers are based within the Division and internships are undertaken at industrial research and development departments. We have strong links with large multinational imaging companies (Philips, Siemens, GE), device companies (St. Jude, J&J Biosense, Medtronic, Cook), the pharmaceutical industry (GlaxoSmithKline, AstraZeneca, Bayer Healthcare, Roche, Lantheus), and small and medium-sized enterprises (Biotronic 3D, Ixico, Mediso, Imanova, Oxford Instruments). Our team has extensive experience facilitating these collaborations with agreements that enable innovation to be adopted by the companies and taken up into healthcare; while allowing dissemination of the joint developments for the greater good of medicine and science. Master research agreements with most of the listed companies are in place, allowing us to define and perform new research projects under a defined legal framework and allowing KCL to exploit the intellectual property that is generated in a productive way. We have completed a number of joint projects funded by the MRC-DPFS and TSB (Epigram, Margita, Vatmas, E-health, A-Strat) together with large companies (Philips, Siemens) and small and medium enterprises (Primal picture, Centron, Imaging Equipment), which have resulted in commercial prototypes. We also have an extensive track record of industry-sponsored PhD studentships where research projects are defined together with the industrial partner. Since 2008 we filed more than 30 patents, of which 10 are jointly with industrial partners, and started a university spin-out company in the area of image-guided intervention (CyDar).
- **Academic Collaboration:** Our culture of inter-disciplinary and collaborative working extends to our interactions with KCL colleagues outside the Division, academics at other UK universities, and internationally. More than half of our grants are collaborative with people outside of the Division and this is reflected in a large number of joint publications with external collaborators.
  In the School of Medicine, we have close collaborative links with the Cardiovascular Division; partnering together to recently renew our BHF Centre of Excellence (1 of only 2 fully funded), and the Cancer Division; with the recent renewal of our joint Comprehensive Cancer Imaging Centre. We lead 1 of 4 themes within the MRC Centre for Transplantation and the NIHR Biomedical Research Centre facilitates further collaborations with Asthma & Allergy, Infection, and Rheumatology. Through our Medical Engineering Centre, we work closely with colleagues in the Schools of Natural and Mathematical Sciences, Dentistry, and the Institute of Psychiatry.
  Within the UK we have fostered multiple partnerships with leading institutions and this is demonstrated by our many joint grants and the co-supervision of doctoral students. For example, we lead an ERC Synergy grant encompassing KCL, Imperial (ICL), and Oxford and have two EPSRC program grants: Grand Challenges I & II and Intelligent Imaging together with ICL and University College London (UCL), with Grand Challenge having Sheffield as an additional partner. Our Cancer Imaging Centre was established jointly with UCL. As well as multiple joint grants with ICL, we have 15 PhD students who are co-supervised with PIs at the South Kensington Campus. We will also provide PhD training in imaging for the Francis Crick Institute, which is a partnership between ICL, KCL, UCL, CRUK, MRC and the WT.

Internationally we are partners in a number of NIH grants with US colleagues, including one to establish a large international network on computational modelling of physiological systems. We are a partner in a Leducq Foundation transatlantic collaborative award and have 9 EU Framework collaborative grants with colleagues across 8 other European countries. We also collaborate with many world-class academic institutions such as: Sunnybrook Research Institute; University of Wisconsin; Stanford University; Yale University; University of Colorado; Weizmann Institute; Chinese University of Hong Kong; INRIA; Utrecht, Erasmus MC; Leiden University, Ghent University; University of Oslo; Aarhus University; University of Graz; TU-Karlsruhe; TU-Munich; University Muenster; and the German Cancer Institute, all of which involve the exchange of academics and researchers. We have set up a fund to provide financial support for these collaborations. We have also established formal collaboration agreements and exchange programs with the Universities of: Auckland; Melbourne; Santiago de Chile; Memorial Sloan Kettering; UCLA; and the US National Institute of Health. Furthermore, we have established formal PhD exchange programmes in medical imaging with Harvard and ETH-Zurich.

Contribution to the discipline: Department members have actively contributed to shaping national and international landscape of the field during the REF assessment period.

- **Professional Training:** The training of biomedical engineers and medical physicists for the NHS has been an important aspect of the Division's work for the last 20 years. We restructured our MSc in Medical Engineering and Physics in 2011 in line with requirements from the NHS Modernising Scientific Careers and were selected and accredited to deliver one of the 3 NHS MSc programmes in Medical Physics and the only MSc programme in Clinical Engineering in the UK. As of 2013 over 100 students are being trained making ours one of the largest such programmes in the world.
- **Junior faculty:** 45% of our REF returned staff are junior faculty and we take pride in the rapid rate at which they are gaining external esteem whilst developing their reputations internationally. Of the junior faculty, 30% have or have had personal fellowships; 60% have won important prizes from international academic societies; 80% regularly teach at international meetings; and 70% have given plenary talks at premier international meetings in their fields.
- **Professional Societies**: Edwards, Azzopardi, and Adam are Fellows of the Academy of Medical Sciences. Blower and Green are Fellows of the Royal Society of Chemistry. Keevil is a Fellow of the Institute of Physics and the Institute of Physics and Engineering in Medicine. Botnar is a Fellow and was a member of the Board of Trustees (2008-11) of the ISMRM. Nagel is a Fellow of the European Society of Cardiology and the American College of Cardiology. Schaeffter is Chair of the ISMRM interventional study group, Razavi was Chair of the cardiovascular study group (2010-11) and Keevil was Chair of the Safety Study Group (2010-11). Keevil is President of the Institute of Physics and Engineering in Medicine, and was President of the UK Radiological Congress (2012-13). Adam was the President of the Royal College of Radiologists (2007-10) and was awarded a CBE in 2012. Nagel was President of the Society of Cardiovascular Magnetic Resonance (2011-12). Goh is President of the European Society of Oncologic Imaging. Razavi is Chairman-elect of the British Society of Cardiovascular Magnetic Resonance. Marsden is Chair-elect of the IEEE Nuclear Instrumentation and Imaging Sciences Council. Gee is the European Director of the International Society of Radiopharmaceutical Sciences, Chair of the European Association of Nuclear Medicine Drug Development Committee, and Chair of UK Bioimaging probe development and medical imaging committees. Montana is a Fellow of the Royal Statistical Society and Vice-Chair of the Statistical Computing Section.
- **Editorial Boards**: our academics are on editorial boards of 35 major journals including: The Journal of Physiology; International Journal of Computational Methods in Bioengineering; Medical and Biological Engineering and Computing; Nuclear Medicine Communications; Radiology; European Radiology; Clinical Radiology; The British Journal of Radiology; Journal of Nuclear Medicine; European Journal of Nuclear Medicine and Molecular Imaging; Journal of the American College of Cardiology Cardiovascular Imaging; European Heart Journal: Cardiovascular Imaging; Journal of Molecular and Cellular Cardiology; Journal of Ultrasound in Medicine and Biology; Journal of Materials Chemistry; Proceedings of the Royal Society; and the Journal of Experimental Nanoscience, Osteoporosis International.