Imperial Blast
BIOMECHANICS & BIOPHYSICS

2010

# Imperial Blast current work



Imperial Blast Biomechanics & Biophysics

Imperial College London


9 Dec 2010

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**Imperial Blast Biomechanics & Biophysics**

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**London, December 2010**

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# Foreword

I am delighted to introduce this first report of Imperial Blast's activities which demonstrates the considerable progress made since this collaborative research model was conceived 18 months ago.

Bringing together multidisciplinary research teams and business, the shared goal of Imperial Blast is to address the particular injuries borne by our Armed Forces, both service men and women.

The core focus of the research within Imperial Blast is the pattern of injury resulting from explosions. The approach encompasses both mitigation technologies to prevent wounding in the first place, as well therapies to enhance subsequent recovery. The output from this group has the potential to save lives and limit injuries through bringing world-class research to bear on these pressing problems.

On behalf of Imperial College London, I would like to thank all supporters for their work over the past 18 months which has enabled Imperial Blast to go from strength to strength. I hope that in reading this report, you will find it rewarding to see the level of achievement so far, and the potential for further impact and success.

**Sir Keith O'Nions**

**Rector, Imperial College London**

# Introduction

The conflicts in Iraq and Afghanistan have been epitomised by the insurgents' use of the Improvised Explosive Device (IEDs) and anti-vehicle (AV) mines against vehicle-borne security forces. These weapons, capable of causing multiple severely injured casualties in a single incident, pose the most prevalent single threat to Coalition troops operating in the region. Improvements in personal protection and medical care have resulted in increasing numbers of casualties surviving with complex lower limb injuries, often leading to long-term disability.

Imperial Blast is a collaborative whose efforts are uniquely able to address the disabling injuries of current and previous conflicts. The group is a careful balance of scientists, engineers and clinicians, from both the Ministry of Defence and academia, ensuring the right questions are asked, the difficult answers addressed, and the most appropriate technologies innovated, constantly aware of the Operational imperative to deliver tangible results in the shortest time possible.

Imperial Blast's approach to improving mitigation against, and recovery from, these injuries is to use a tri-modal scientific approach: clinical data analysis from the battlefields of Iraq and Afghanistan, Bioengineering experiments using physical and computational models of human tissue and Biophysical simulation of the effect of blast on living tissues are all brought to bear in a multidisciplinary environment with great effect. The following report summarises Imperial Blast's current work in each mode of endeavour, and describes our future direction.

# Clinical focus

## Introduction

When an AV mine detonates, the blast wave from the explosion causes the release of a cone of super-heated gas and soil to impact the floor of the vehicle. This results in rapid bending of the floor, transmitting a large crushing force to the lower limb in contact with it (Fig. 1).

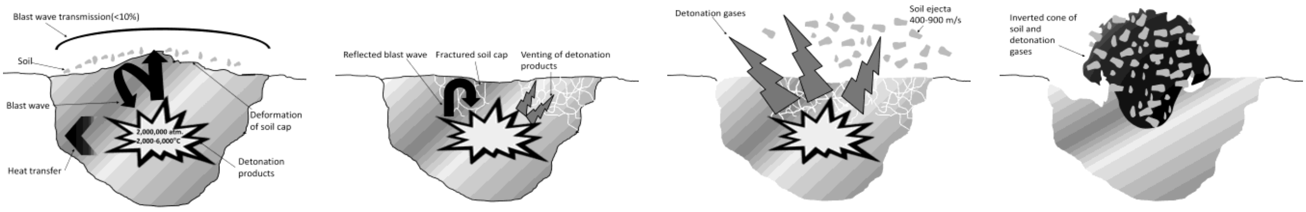


Fig. 1: An AV mine blast

Typically this produces injuries very similar to people who have fallen from heights in excess of 3 stories. This injury pattern is of particular concern as it has been shown that patients with foot and ankle injuries have significantly greater disability compared to those without. These injuries are frequently so severe, that surgical reconstruction may not produce a good clinical outcome for these patients (Fig. 2). The high physical demands placed upon Service Personnel is such, that the long-term effects of these injuries are likely to play a significant role in their ability to return to full military duty.

One of the most significant deficits in vehicle explosion protection research has been the dearth of clinical information of in-vehicle blast casualties. Central to the success of any mitigation system is the ability to protect the soldier not only from lethal injuries, but also to reduce the possibility of long-term harm. In order to achieve this aim, a fundamental requirement is to accurately define the injury profile that is likely to result in disability in our young, highly active military population. Due to the lack of this clinical data, Defence research organisations have resorted to extrapolate injury criteria from automotive industry data. It is clearly apparent that military blast injuries are not similar to road-traffic accidents and the functional requirements of our population is likely to be significantly different.

Fig. 2: A typical blast injury to the foot, showing a severe injury to the heel and the shin. This leg required amputation 2 years after injury.

One of the core features of the Imperial Blast group is its focus on driving research priorities based upon contemporary battlefield injury data and long-term functional outcomes of military injury. This is facilitated by its strong partnership with the Royal Centre for Defence Medicine, and the integration of military surgeons with operational experience into this uniquely collaborative research group. This ensures that the group's research is entirely focused in understanding the injuries sustained, and protecting against the threats that might injure UK Service Personnel who are currently deployed on military operations.

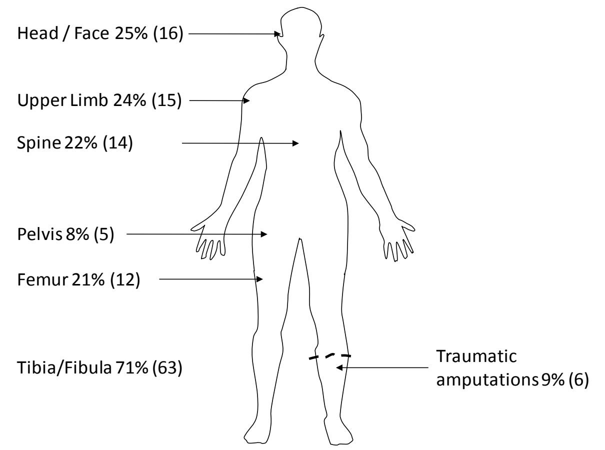


Fig. 3. Injuries associated with foot and ankle trauma.

## Clinical Data

In this section we summarise Imperial Blast's recent work describing some of the disabling clinical effects of battlefield injuries. Unlike in most civilian type injury patterns, combat injuries frequently affect many body regions, resulting in the severely ill multiply injured casualty. This is particularly the case in the casualty from blast. In our clinical review of 63 casualties (89 lower limbs) injured in vehicle explosions, only 3 suffered isolated injuries to the lower leg. Nearly a quarter had associated spinal injuries and head injuries (Fig. 3). Overall these casualties had an average New Injury Severity Score (NISS) of 16 (15 denotes 'severely injured').

Twenty-six lower limbs (33%) injured from an under-vehicle explosion required amputation (Fig. 4). Thirteen limbs were amputated at the field hospital, and 7 amputated when the patient returned to the UK. At a mean 18 months post injury, a further 6 casualties required amputation for chronic pain problems. When including the 6 legs that were traumatically amputated in the blast, it can be seen the significant burden of injury this places on our injured Service Personnel.

At 33 months post-injury, 75% of injured lower limbs had significant on-going clinical problems (Fig. 5). This includes a high proportion of patients suffering from traumatic arthritis of the foot and ankle as well as those having problems from infection, impaired bone healing and chronic pain. Given that the mean age of these casualties was 26 years, these issues are likely to have a significant effect on their quality of life for several decades.

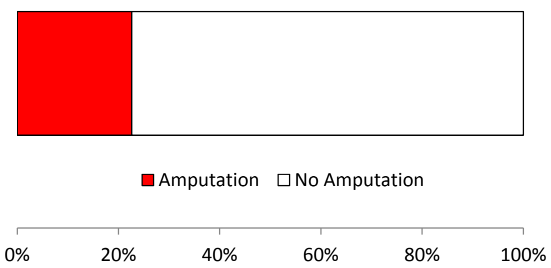


Fig. 4: Amputation rates of severe foot and ankle injuries at 33 months.

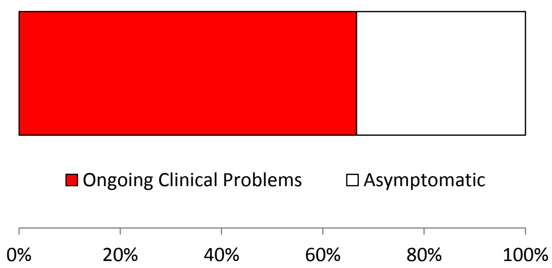


Fig. 5. Ongoing clinical problems of severe foot and ankle injuries at 33 months.

Almost 3 years after injury, only 9 (14%) of the casualties in this study were able to return to full military duty. Significantly, over 60% of those with a foot and ankle injury were only able to return in a sedentary role or were deemed unfit for any military service (Fig. 6). This study clearly demonstrates that foot and ankle injuries from AV mine blasts are associated with a poor clinical outcome. Given the nature of these injuries, the key in reducing the injury burden lays in primary prevention. By understanding the pattern of injury from blast, we are able to produce appropriate experimental tools to investigate and mitigate against this devastating injury pattern.


Fig. 6: Occupational outcomes at 33 months.

# Engineering focus

## Introduction – Approach

Imperial Blast engineers use clinical data and expertise in order to design and develop experimental and computational tools that can be utilised to understand injury of the human lower limb, evaluate the mitigating capacity of existing technologies, and assess the potential of novel mitigation strategies (Fig. 7).

## Experimental *vs*. Computational models

Experimental and computational models of human injury and of mitigation technologies are necessary in order to understand the physical mechanisms involved and to allow for developing new and improved evaluation criteria, techniques, materials and designs in a cost-efficient manner. Full scale experiments (e.g. the combat boot, the vehicle, the human leg under impact) give us an understanding of the whole 'structure' under fairly controlled, repeatable conditions; however, these are expensive, time consuming and labour intensive, albeit invaluable. Individual-component experiments (e.g. materials testing of combat boot components, of vehicle components, of soft and skeletal human components) are well controlled and repeatable, allowing us to understand component behaviour, and therefore to build accurate computational models able to predict the behaviour of the 'structure' based on the interaction of its components. Computational models that have been validated against relevant experiments allow for multiple virtual experiments to be conducted in a cost-efficient, repeatable, well-controlled manner. They allow us to alter inexpensively parameters related to geometry, materials, and environment and look at their effect on overall behaviour; hence, they allow us to experiment with novel designs and material combinations that could potentially result in novel, better mitigation strategies.

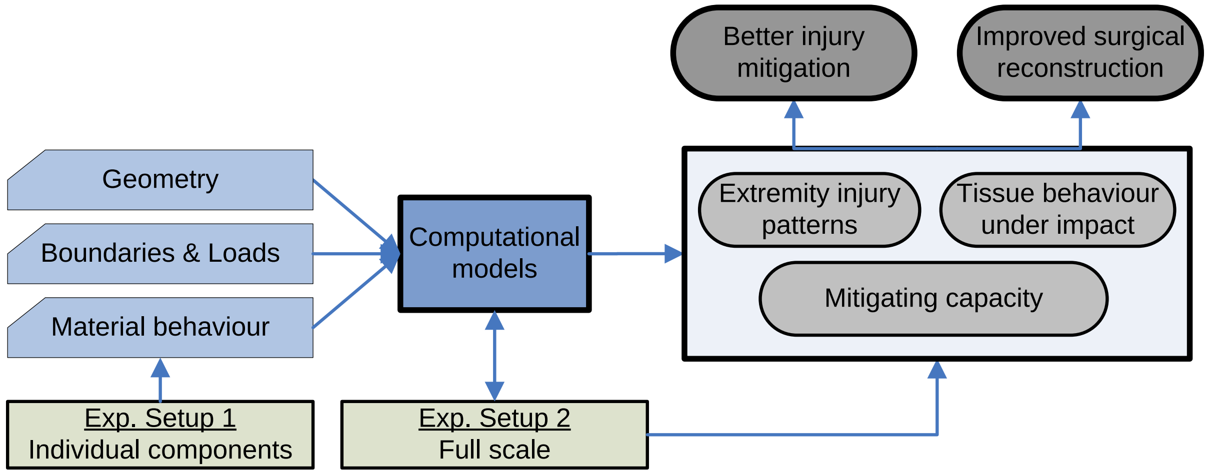


Fig. 7: Biomechanical modelling approach of Imperial Blast.

## Mitigation technologies

Combat boots currently deployed in the theatres of operation have been tested and modelled by Imperial Blast (Fig. 8). The sole of the boots was impacted in a drop-weight test rig and its behaviour under impact was quantified. The individual components of the boots were also tested in order to quantify their material behaviour; this was used as an input in the computational models of the boot; the drop-weight experiment was simulated computationally with success. Now, the computational model of the boot can be combined with that of the leg to investigate the boot's role in extremity injury. Shock attenuating materials are currently being evaluated by Imperial Blast that can be used in future boot and vehicle designs.

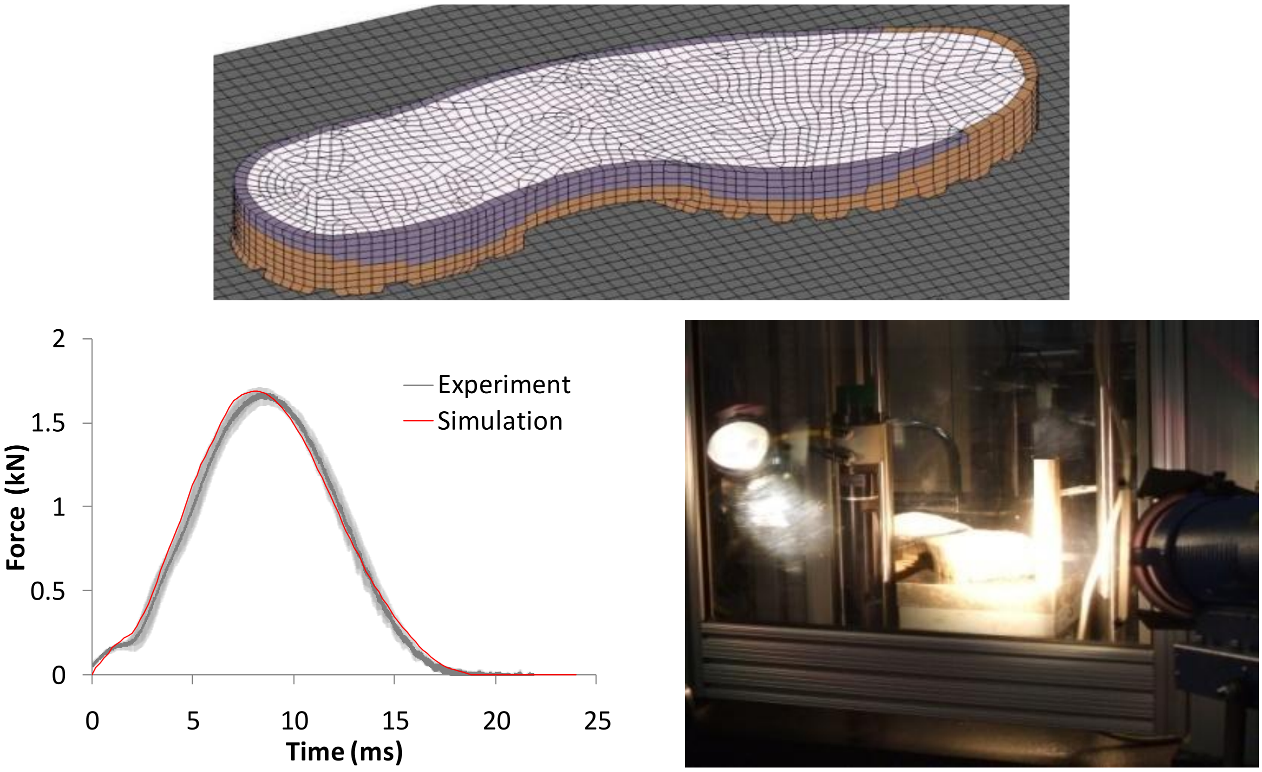


Fig. 8: The sole of the combat boot was tested under impact and the experiment was modelled computationally. There is good agreement between experiment and simulation.

## Lower extremity

A computational model of the lower extremity provides Imperial Blast with an internationally unique capability to conduct multiple virtual experiments in order to assess its behaviour under various impact conditions, simulating those seen in the theatres of operation. The geometry of a $50^{th}$ percentile male's leg has been reconstructed utilising medical imaging and special software (Fig. 9). In order for the behaviour of a computational model to be biofidelic, accurate material models of its components' behaviour are mandatory. Whereas skeletal and soft tissue behaviour is fairly well understood in slow loading-rate conditions, this is not the case in higher loading-rate conditions, such as those seen in blast. Ligaments and bones are currently being tested by Imperial Blast across a range of loading rates in order to quantify their material behaviour (Fig. 10).

 

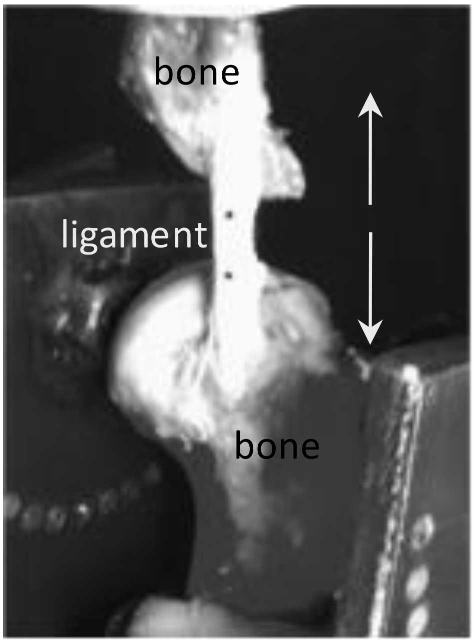


Fig. 9: A knee ligament tested in tension in our lab.

Fig. 10. Computer model of the leg.

## The Imperial Blast impact rig (AnUBIS)

The Imperial Blast AnUBIS (Anti-vehicle Underbelly Blast Injury Simulator) is a pneumatically driven device able to accelerate a 40 kg plate up to velocities seen in the floor of vehicles when targeted by a mine (Fig. 11). It is therefore capable of simulating the loading environment a vehicle occupant's leg will face. This capability is internationally unique. Combining multiple-sensor data, high speed video, and medical imaging, the conditions causing, and the mechanism and the severity of, the injury sustained by the leg can be quantified. This information is invaluable in order to inform and validate the computational models, to assess the effect of leg orientation and positioning on injury severity, to assess the biofidelity of surrogates, and to assess the effectiveness of full-scale mitigation technologies in reducing injury severity.

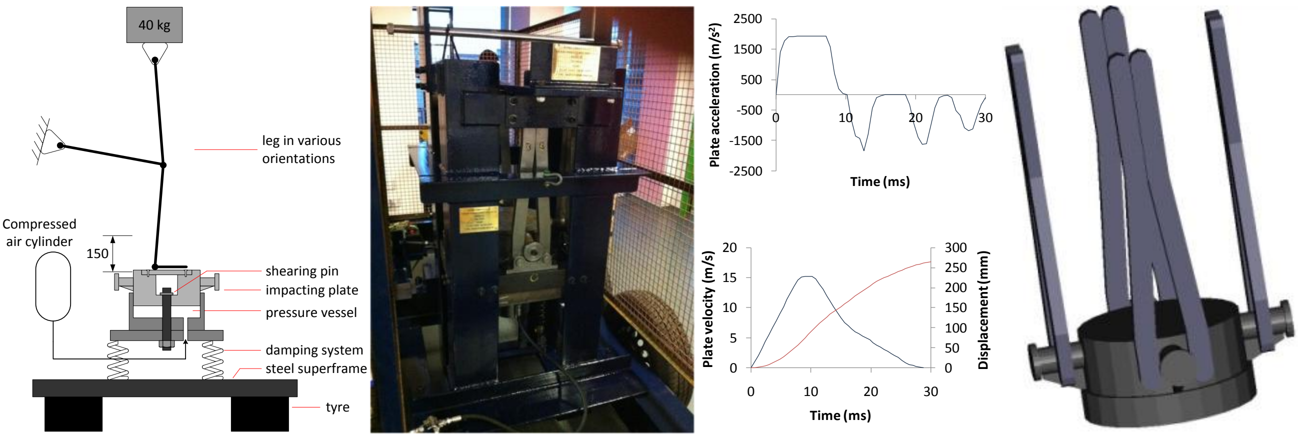


Fig. 11: The Imperial Blast impact rig (AnUBIS) is able to simulate impact seen in AV-mine blasts.

# Biophysics focus

## Introduction

The Improvised Explosive Device (IED) is the leading cause of injury and mortality in UK troops on the current battlefields of Afghanistan and Iraq. Detonation of an explosion produces a short-duration shock (blast) wave, which is an extreme over pressure of air travelling faster than the speed of sound. The interaction of the blast wave with the human body causes many battlefield injuries, including blast lung, damage to the ear, bowel injury and is an important mechanism in traumatic limb amputation. There is also clinical evidence that that a primary blast wave can have an adverse effect on coagulation and tissue healing. Late complications of Injuries caused by explosions include a high incidence of infection, nerve injury and formation of abnormal bone within muscle (heterotopic ossification). The consequences to wounded troops are disabling injuries, often associated with pain, long-term loss of function and many needing multiple surgical procedures.

Understanding how blast waves damage human tissue is critical to preventing and treating many of the disabling consequences of explosions. However, little is known about the effect of blast waves on cellular and molecular damage in biological tissue. Dramatic advances in the fields of biochemistry, cell and molecular biology, genetics, biomedical engineering and materials science give hope to fill in this gap. The following sections describe the experiments Imperial Blast is performing to understand the effects of blast waves on living tissue.

## Approach

Assessment of the cellular and molecular basis of overpressure damage requires testing live tissue under extreme mechanical impacts. The appropriate equipment must be used to subject cell samples to compression waves. Here, we present the design and initial assessment of a chamber that can be used in a split-Hopkinson pressure-bar system (Fig. 12) to subject live cell cultures to high intensity compression waves.

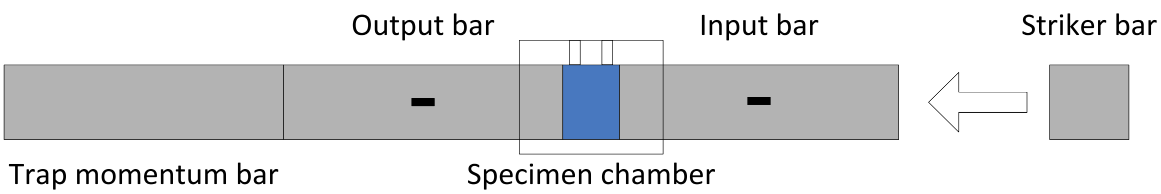


Fig. 12: Modified split-Hopkinson pressure-bar system.

## Blast chamber design and production

The chamber design (Fig. 13) has focused on: the use of suitable materials, the possibility to recover the samples after impact for further analysis, and the flexibility to perform experiments on different controlled conditions. The main chamber's components are made of polycarbonate, this biocompatible material been chosen because it offers a combination of strength, rigidity and the ability to keep the liquid confined during impact. The chamber has two 1 mm holes to allow the insertion and collection of liquid samples using a syringe. Initial compression tests with the modified split-Hopkinson pressure-bar system have been performed on water. The results show that the chamber is structurally resilient up to impact velocities of 34 mph corresponding to pressures in water of approximately 20 MPa. Moreover, no leakages were found during the tests.

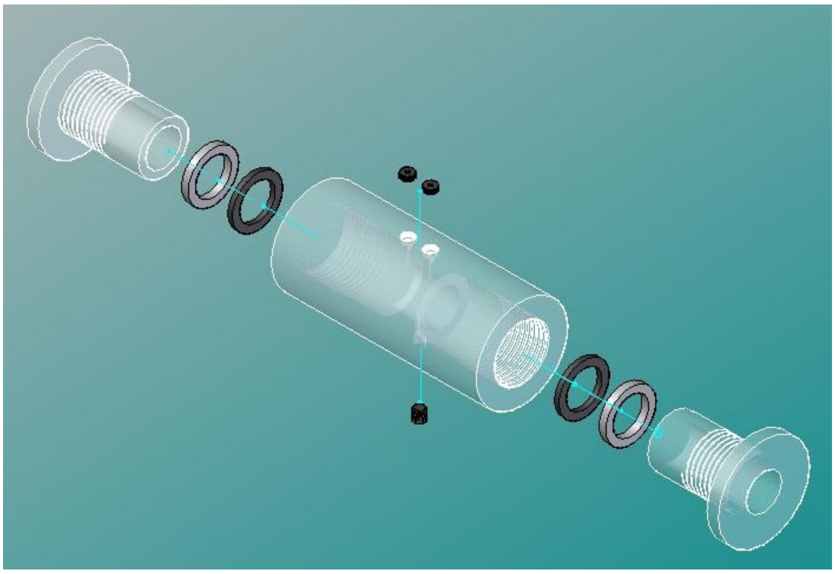

Fig. 13: Chamber design.

## Preliminary results

An initial assessment of the chamber's biocompatibility has been conducted, inserting mouse Mesenchymal Stem Cells (MSCs) for different periods. The samples have then been recovered and the number of live cells counted to control for adhesion problems or undesired route of cellular damage. These cells are relevant to Imperial Blast's research efforts because they are the pre-cursors for many of the tissues commonly injured by explosions.

## Future direction

The first tests conducted on the biological samples will focus on the research of impact parameters (peak pressure, impulse duration) that can cause damage. This will be achieved using different bar materials, projectiles of different lengths and different impact velocities. Physiological conditions should be reproduced inside the chamber (temperature control, $CO_2$ cycle), hence several modifications to the first design are in progress.

The cell cultures will be analysed with fluorescence confocal microscopy pre and post the compression event to determine dead versus live cells concentration, membrane integrity and subcellular damage. Genomic studies including transcriptomic and proteomic analyses will be used to follow biomarkers in damaged cells.

# External Collaboration

## Imperial Blast, and its place at Imperial College London

Since its foundation in 1907, Imperial has enjoyed a reputation for excellence in research and technological innovation that today attracts the most talented minds of international quality, consistently ranking the University within the top 10 in the world (top 5 in Europe). Indeed, 14 Nobel Prize winners and two Fields Medal winners are amongst Imperial's alumni and current faculty.

Imperial's unique approach to successfully answering real-world issues is founded through fostering multidisciplinary working internally, and encouraging wide collaboration externally. In doing so, it remains committed to exploring the interface between science, engineering, medicine and business, delivering practical solutions that improve the quality of life.

Imperial College London's multidisciplinary collaborations and partnerships now include internationally recognised initiatives to address Operational and National Security issues. It is for this reason that Imperial is the natural home for the Imperial Blast research group, founded to address the scientific issues related to the signature injuries of recent conflicts by leveraging the expertise developed through this network.

Unlike other academic institutions, Imperial College London has a clear vision to make a demonstrable economic and social impact through the translation of its research into practice both in the UK and abroad. Imperial Blast is uniquely placed to achieve these aims by collaboration with professionals from many different world-leading departments within the College. The multidisciplinary work has already engaged internationally renowned experts in the fields of Shock Physics, Mechanical Engineering, Civil Engineering, Histopathology, Biology, Biochemistry and Aeronautics.

To date, Imperial Blast has benefited from the engagement of a number of different organisations, including the Royal Centre for Defence Medicine (RCDM) and the Defence Science and Technology Laboratory (Dstl).

## The Royal Centre for Defence Medicine

The Royal Centre for Defence Medicine in Birmingham has unrivalled experience in the clinical management of combat injury. Integral to RCDM's multidisciplinary approach to the management of these injuries is its ability to translate novel and emerging basic research findings into rigorous applied scientific advances in medical and surgical care. The volume of injury from recent and current conflicts managed by RCDM has enabled the development of powerful wound prediction and outcome tools that inform the clinical relevance of all basic research endeavours.

## Defence Science and Technology Laboratory

The Defence Science and Technology Laboratory orchestrates the Science and Technology (S&T) sector’s response to the Ministry of Defence’s current and future needs. Dstl interfaces with industry and academia to maximise the impact of S&T for defence and security requirements, and in doing so, delivers battle-winning technologies.

Dstl project manage a number of large defence contracts, often requiring the outsourcing of work to academic and industry expert partners.

## Blast research and the future

It is clear that there exists a pressing need to create a well funded, Blast Research Centre that brings together a critical mass of clinicians, engineers and basic scientists, collaborating to focus new and emerging technologies on applications to improve the fundamental understanding, mitigation, surgical management and recovery in the short, medium and long-term of injuries sustained by Military Personnel as a result of blast.

Such a research centre should continue to draw upon the leading experts in complementary fields to focus on the single clinical issue with unrivalled effect, leveraging emerging, world-leading technologies from the Imperial Blast Group Collaboration to address the signature injuries of recent coalition conflicts; that is, injury to the lower limb, the axial skeleton and the thorax.

# Economics and risk management in innovation and development

## Introduction

Whether the pursuit of new knowledge at public or charitable expense is seen as an end in itself, or as an investment aimed at producing benefits for Society, it is inescapable that the resources used to undertake such research could otherwise be put to alternative use in benefiting society; all uses of resource, including research, have *opportunity costs*. Research needs to be of demonstrable value to justify denying people opportunities to benefit from that which they forgo in order to pay for it, particularly in the current economic climate.

In science, particularly medical science, it is relatively easy to find examples of specific research that has led to enormous benefits (cardiovascular disease, mental health, diabetes, trauma care to name but a few). But understanding the nature, extent and processes involved in the return on investment in research is largely dependent upon the requirements of individual stakeholders, and therefore, is not standardised. In most cases, there is a degree of tension between economic assessments to inform future priorities (how much to spend, on what areas or categories of research, using which funding systems or mechanisms) and assessments demonstrating the value of past spending. With this tension, the narrow line between objective analysis and selective advocacy has the potential to be blurred.

In our current economic environment, we feel it is incumbent upon the recipient of research funding to make an appropriate analysis of the economic cost *vs*. potential impact, and present these in a comprehensible format. It is in this understanding that the following sections address the economics of innovation and development, and the mechanisms for managing innovation risk to be employed by Imperial Blast in demonstrating the true value of both tangible and intangible outputs to a wider audience.

## Economics of innovation and development

Significant improvements can be made to the way Research and Development is managed with the refinement of tools to measure its value. During the early 90's, there was a fashion to 'nail down corporate R&D spend'. Discounted cash-flow and net present value financial techniques were applied to R&D projects, with the result that projects were often found wanting. This forced R&D managers to analyse and measure the value of what they were doing, or face having it cut.

However, by the end of the 20th century, the technology pendulum started to swing the other way. New financial techniques were developed based on real option value thinking, which better captured the true value of R&D. This was in line with a more general trend to express the value of R&D in terms of the options for future action that it could buy a corporate partner. *Options* thinking improved commercial technology management, as R&D managers sought to balance a portfolio of options to deliver maximum future value to their firms.

The Defence sector, however, was immune to this thinking; it made little sense to measure only the financial value of Defence R&D projects because there was overarching imperative to optimise fighting-power. What would the net present value of a Defence project matter, if the resulting equipment delivered inferior military utility?

Detailed regression analysis conducted in recent years by a number of authors, however, shows a statistically valid correlation between the levels of R&D investment and the quality of a military's equipment 25 years later. The regression model uses a 25-year time lag for R&D to *pull-through* into equipment deployed in the field, which is realistic judging from the development cycle times of combat technologies launched in the past few decades.

Remedial action is possible to address military technological advancement, but difficult, as time lags mean that simple *spend now* solutions will not *pull-through* in time for Operations resulting from our current Foreign Policy. However, process improvements and technology insertion into equipment that is already in procurement can yield real results. And often, innovative solutions don't require a return to the drawing board.

## Managing innovation risk

Conventionally, fundamental research

- is open-ended,
- is unpredictable (scientists, politicians and funders are bad at predicting success),
- has many dead-ends; some fruitful,
- has long timescales,
- may result in unanticipated outcomes.

The risk is high, as are the potential gains, both financially and for humanity, but the chance of failure is ever present. However, the process of innovation, and hence research and development, can be process managed to ensure timely *pull-through* of technologies, whether physical or intangible devices.

The terms research and technology (R&T), and research and development (R&D) are sometimes confused or used interchangeably. Here, R&T will refer to early stage technology generation activity (TRL 1-3), sometimes also termed *blue skies* research or, in UK Defence circles, *corporate and applied research*. R&D encompasses R&T activity as well as *development*, which is mainly focused on a known application (TRL 1-6). Development is often mainly concerned with the demonstration of technology, risk reduction, system integration, trials and tests, and evaluation activity. Imperial Blast has the capacity to operate at all of these TRLs.

Imperial Blast operates in Technology Readiness Levels 1 to 6 (Fig. 14), encompassing the innovative end of the R&D spectrum, with the capacity to conduct TRL 9 analyses to inform the innovation cycle.

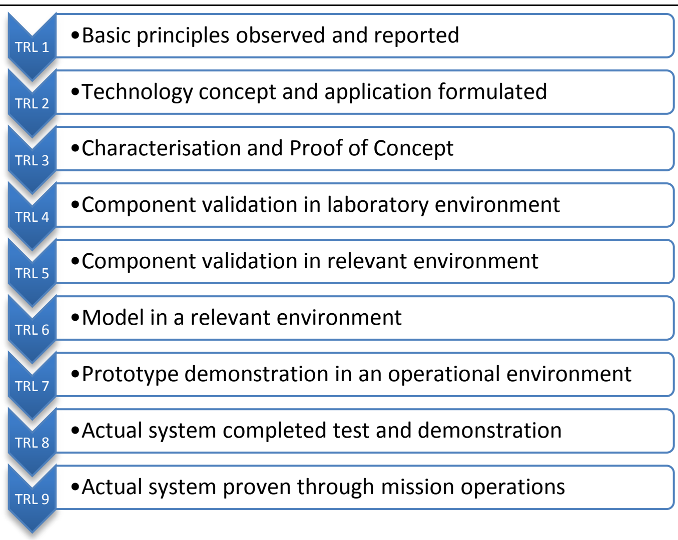


Fig. 14: Technology Readiness Levels (TRL).

Through optimising the balance between in-house expertise/experience and processes/systems (Fig. 15), innovative solutions to technological challenges can be achieved in an appropriately timely fashion.

## Summary

Imperial Blast will assess each innovation, whether it is tangible or intangible in this manner to determine whether the cost of development through to appropriate output is possible. This will allow funders to make an appropriate funding decision based upon comprehensible economic costs of deliverables. It is through this mechanism that we are keen to continue to engage with the MoD and third sector in managing future innovation for the benefit of our Soldiers, past and present.

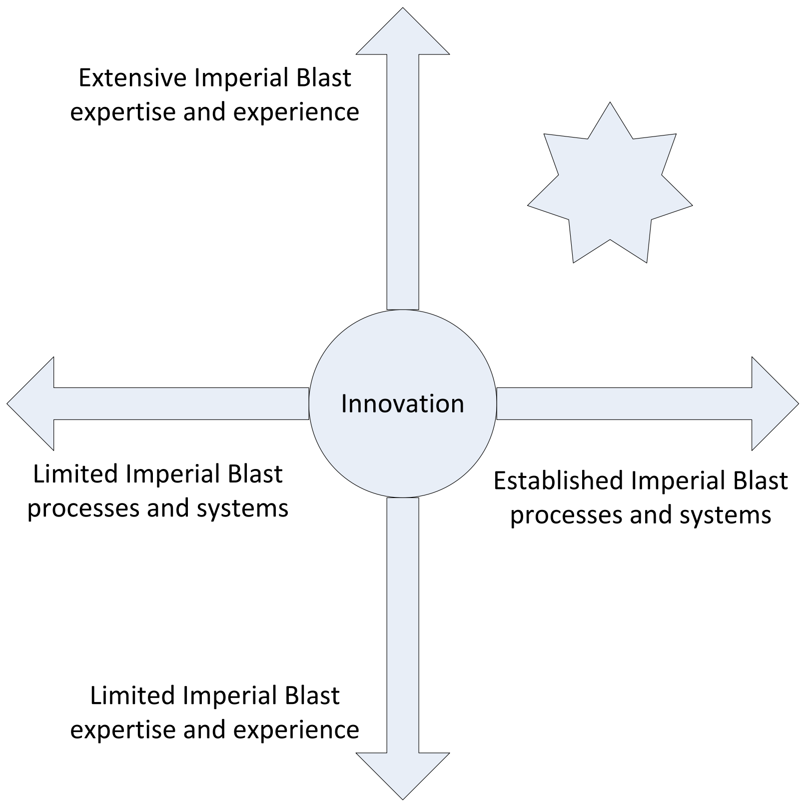


Fig. 15: Innovation space.

# Research group biographies

### Professor Anthony Bull PhD DIC ACGI BEng CEng FIMechE

Anthony is Professor of Musculoskeletal Mechanics in the Bioengineering Department at Imperial. His research is in the area of the mechanics of human joints in which he has published more than 200 papers at conference and in peer review journals. The main focus of Anthony's research is into mechanical factors related to osteoarthritis in human joints and its prevention but also the effect of activity, injury, surgery and rehabilitation on the loading of the musculoskeletal system, which has led him to look into whole-body mechanics as well.

### Professor Jon Clasper MBA DPhil DM FRCSEd(Orth) L/RAMC

Jon is the Defence Professor of Trauma and Orthopaedics within the Academic Department of Military Surgery and Trauma. His main clinical interests are in trauma and upper limb surgery, particularly instability and shoulder pain, both of which involve multidisciplinary approaches. He is responsible for the orthopaedic research focus within the British Military.

### Professor Steven J Rose PhD FInstP

Steven joined Imperial College London as the Head of Plasma Physics in December 2006. Prior to this he was at Oxford University as a William Penney Visiting Professor and Keeley Visiting Fellow of Wadham College. Professor Rose has worked in plasma physics for all his career, with a particular emphasis on plasmas produced using high-power lasers. He has spent much of that time at the two high-power laser facilities in the UK: the Rutherford Appleton Laboratory's Central Laser Facility where he became the Associate Director for Physics and at AWE where he was the Head of Plasma Physics. Most recently he has been appointed the Director of Imperial College's Institute for Shock Physics.

### Dr William G Proud PhD FInstP C.Chem C.Phys

Bill was recently appointed Reader in Shock Physics in the Institute of Shock Physics and the Department of Physics at Imperial. Prior to joining the college, Bill was head of the Fracture and Shock Physics group at the Cavendish Laboratory in Cambridge. Research areas are broadly those which involve dynamic stimuli, impact or explosion, affecting the mechanical or chemical characteristics of materials.

### Dr Katherine Brown PhD DIC FRSC

Kate is the Reader in Biochemistry in the Department of Life Sciences at Imperial College. Her research is covers a wide range of functional and structural studies of proteins which play roles in disease and in particular microbial infections. She has a long-standing interest in therapeutic development and has worked closely with Dstl and others in the area of vaccine development. Her recent interests include studies of the molecular effects of blast injury on human cells including susceptibility to microbial infection.

### Dr Jens Balzer PhD MA

Jens is a material scientist who was introduced to the area of material testing under quasi-static and medium strain rates during his five year MA course in Germany. His interests lie in material testing of metal specimens and alloys. He worked in the same area for his PhD at the Cavendish laboratory, where secondary explosives, propellants and thermites were impacted under medium strain rate loading and high speed photography was used to record the impact event.

### Dr Adam Hill MB PhD CEng MIMechE MRCS RAMC

Adam is a Surgeon-Engineer whose consultancy specialises in three key areas applied to human injury: outcomes from trauma, numerical and cadaveric testing and device design, publishing in excess of 60 papers at conference and in peer reviewed journals in these areas. Adam has been awarded 13 prizes in Surgery and Engineering in the last 5 years, and currently holds a commission in the Royal Army Medical Corps'.

### Dr Andrew Phillips PhD MEng CEng MIMechE

Andrew is a Lecturer in Structural Engineering and Structural Biomechanics at Imperial. His recent research has focused on creating finite element computational models of the pelvis and femur. He has a continuing interest in the development of constitutive models to represent bone, with his most current work investigating the orthotropic orientation and distribution of bone material properties about the hip joint, with a view to fracture prediction and improved treatment.

### Dr Spyros Masouros PhD DIC Dipl.Eng AMIMechE

Spyros is a Research Associate in the Bioengineering Department at Imperial and holds a diploma in mechanical engineering and a PhD in biomechanics. His current interests lie in finite element computational modelling of the lower limb and soft tissue characterisation at high rates of strain.

### Dr Arul Ramasamy MA MRCS DMCC MFSEM RAMC

Arul is an orthopaedic surgeon working in the Imperial Blast Biomechanics Group and a doctoral candidate in the Bioengineering Department at Imperial. As a serving Army officer he has published extensively on military trauma and has served on operational tours in Iraq and Afghanistan. His current research interests include the development of a cadaveric test rig to simulate lower limb injuries in mine blasts.

### Dr Tim Bonner MBChB MSc MRCS RN

Tim is an orthopaedic surgeon working in the Imperial Blast Biomechanics and Biophysics Group and a doctoral candidate in the Bioengineering Department at Imperial. He is a serving medical officer in the Royal Navy with experience of trauma management from his operational deployments to Iraq, Afghanistan, the Persian Gulf and Northern Ireland. Tim has published work about the patterns and treatment of injuries caused during combat.

### Mr Nicolas Newell MEng AMIMechE

Nic is a doctoral candidate in the Bioengineering Department at Imperial studying the fracture mechanics of the lower limb under high strain rates. He is particularly interested in the mechanisms of injury around the foot and the possible mitigation through redesigning the army boot.

### Ms Chiara Bo MSc BSc

Chiara is a doctoral candidate in the Physics Department, Institute of Shock Physics, studying the molecular basis of shock-induced damage in biological tissues. Particularly she is interested in the assessment of the effects produced by high rate dynamic impact loads on different cell cultures.

# Publications and reports

Below is a list of the documents produced by Imperial Blast. The documents that are open access can be found at http://www.imperialblast.org.uk/current-work/.

## Publications in peer-reviewed journals

Ramasamy A, Hill AM, Masouros SD, Gibb I, Bull AMJ, Clasper JC. *Environmental influence on blast-related fracture patterns: a forensic biomechanical approach*. Journal of the Royal Society: Interface, 2010, *in press*.

Ramasamy A, Newell N, Masouros SD, Hill AM, Proud WG, Brown KA, Bull AMJ, Clasper JC. *Extremity injuries from improvised explosive devices: current research and future focus*. Philosophical Transactions of the Royal Society Part B: Biological Sciences, 2010, *in press*.

Ramasamy A, Hill AM, Clasper JC. *Improvised Explosive Devices – Pathophysiology, Injuries and Surgical Management*. Journal of the Royal Army Medical Corps. 2009; 155(4): 265-274.

Ramasamy A, Hill AM, Hepper AE, Bull AMJ, Clasper JC. *Blast Mines: a background for clinicians on physics, injury mechanicsm and vehicle protection*. Journal of the Royal Army Medical Corps. 2009; 155(4): 258-264.

Ramasamy A, Harrisson SE, Midwinter MJ, Stewart MPM. *Penetrating Missile Injuries during the Iraqi Insurgency 2006*. Annals of the Royal College of Surgeons of England. 2009; 91: 551-558.

Ramasamy A, Harrisson SE, Clasper JC, Stewart MPM. *The roadside bomb in Iraq*. Journal of Trauma. 2008; 65(4):910-4.

Ramasamy A, Harrisson SE, Lasrado I, Stewart MPM. *A review of hostile action casualties during the Iraqi Insurgency; A British Military Hospital experience in Southern Iraq*. Injury. 2009; 40: 493-497.

## Manuscripts submitted for publication in peer-reviewed journals

Ramasamy A, Hill AM, Masouros SD, Gordon F, Clasper JC, Bull AMJ. *The blast mitigating effect of mine-resistant vehicles: historical lessons in vehicle design*. Accident Analysis and Prevention, *under review*.

Ramasamy A, Hill AM, Gibb I, Philip R, Bull AMJ, Clasper JC. *The deck-slap injury: outcomes from calcaneal blast injuries*. Journal of Trauma, *under review*.

Newell N, Masouros SD, Ramasamy A, Hill AM, Clasper JC, Bull AMJ. *A comparison of 2 endurance footwear soles under high-strain rate testing*. Journal of Footwear Science, *under review.*

Ramasamy A, Hill AM, Gibb I, Philip R, Bull AMJ, Clasper JC. *AIS is not a predictor of poor clinical outcome in lower limb blast injuries: implications for blast research*. Awaiting security clearance.

## Government reports

DSTL/TR48994. The effect of seating position on lower limb injuries in under-vehicle explosions.
IB/DSTL/011209/01. *Finite element modelling of the combat boot*.
IB/DSTL/010410/02. *Finite element modelling of the lower limb*.
IB/DCT/010910/01. *Comparative behaviour of combat boots currently deployed to UK troops*.
IB/MEINDL/010910/01. *Mechanical behaviour of the Meindl Desert Fox combat boot*.

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