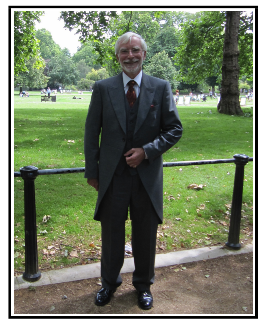
Biological Flow:

A Conference to Celebrate the 70th Birthday of Timothy J. Pedley



DAMTP
University of Cambridge
2-3 April 2012

The London Mathematical Society

Monday 2nd April

0830 – 9000	Registration	
	SESSION 1: GENERAL (Chair: O.E. Jensen)	
0900 – 0920	Natural drinking strategies	
	John W.M. Bush and Wonjung Kim	
0920 – 0935	How to win the 2012 Beverley Triathlon	
	Jon Pitchford	
0935 – 0950	Impulsive generation of viscous vortex rings and propulsion at low Reynolds numbers	
	Houshuo Jiang and Thomas Kiørboe	
0950 – 1005	Statics and dynamics of planar shearable filaments in viscous fluid: a Cosserat rod approach	
	Hermes Gadêlha, Eamonn Gaffney and Alain Goriely	
1005 – 1020	On the liquid lining in fluid-conveying curved tubes	
	M. Heil, A.L. Hazel, S.L. Waters and J.M. Oliver	
1020 – 1040	How to measure the mechanical properties of artificial capsules	
	Dominique Barthès-Biesel	
1040 – 1110	Tea and Coffee (CMS)	
	SESSION 2: RESPIRATORY (Chair: M. Heil)	
1110 – 1130	Unsteady flows to induce endogenous surfactant therapy	
	Donald P. Gaver	
1130 – 1145	Inhomogeneity promotes damage in reopening airway networks	
	Peter S. Stewart and Oliver E. Jensen	
1145 – 1200	Suppression of viscous fingering by elastic membranes	
	D. Pihler-Puzovic, P. Illien, M. Heil and A. Juel	
1200 – 1215	An efficient eigensolver and its application in collapsible channel flows	
	Xiaoyu Luo, Yujue Hao, Zongxi Cai and Steven Roper	
1215 – 1230	Fluctuations of fixed-flux flow in the Pedley Resistor	
	Oliver Jensen, Feng Xu and John Billingham	
1230 – 1250	Multiphase flow in the lung	
	James B. Grotberg	
1250 – 1300	Group Photograph	
1300 – 1400	Lunch (CMS)	
	SESSION 3: CARDIOVASCULAR (Chair: S.L. Waters)	
1400 – 1420	Mechanics of red blood cell motion in the microcirculation	
	Timothy W. Secomb	
1420 – 1435	Pulse propagation in the pulmonary circulation	
	N.A. Hill, Mette S. Olufen and Gareth D.A. Vaughan	
1435 – 1450	Haemodynamics in the mouse aortic arch	
	C. Ross Ethier	
1450 – 1505	Vascular droplet and bubble dynamics in gas embolotherapy	
	J.L. Bull, A. Qamar, Z.Z. Wong, S. Samuel, O.D. Kripfgans and J.B. Fowlkes	
1505 – 1520	Wall shear stress and atherosclerosis: age related variations in a study of rabbit aortas	
	S.J. Sherwin, V. Peiffer and P.D. Weinberg	
1520 – 1540	Fluid mechanics of bileaflet mechanical heart valves	
	Ajit P. Yoganathan	
1540 – 1550	**POSTERS 1 – 6**	
1550 – 1620	Tea and Coffee (CMS)	
	SESSION 4: GENERAL (Chair: I.J. Sobey)	
1620 – 1640	From red cells to skiing to an airborne jet train that flies on a soft porous track at 700 km/hr	
	Sheldon Weinbaum	
1640 – 1655	Differential dynamic microscopy of swimming algae	
	O.A. Croze, V.A. Martinez, R. Besseling, M.A. Bees and Wilson C.K. Poon	
1655 – 1710	Symmetry breaking cilia-driven flow in the zebrafish embryo	
	A.A. Smith, T.D. Johnson, D.J. Smith and J.R. Blake	
1710 – 1725	Two new stagnation-point flows	
	P.D. Weidman	
1725 – 1740	Unsteady flow in a curved tube	
	A.L. Hazel, R.E. Hewitt, R.J. Clarke and J.P. Denier	
1740 – 1800	The shape of a ponytail and the statistical physics of hair fiber bundles	
	R.E. Goldstein	
1930 – 2000	Reception: all welcome (Old Courts, Gonville and Caius)	
2000 – late	Dinner: tickets required (Old Courts, Gonville and Caius)	

Tuesday 3^{rd} April

0830 – 9000	Registration
	SESSION 5: SUSPENSIONS (Chair: N. Hill)
0900 – 0920	Computational biomechanics of physiological flow *T. Yamaguchi, T. Ishikawa, Y. Imai, H. Ueno, K. Numayama-Tsuruta and T. Omori*
0920 – 0935	Division by fluid incision: biofilm patch development in porous media *W.M. Durham, O. Tranzer, A. Leombruni and R. Stocker*
0935 – 0950	Colonial chemotactic dynamics in the presence of microswimmer interactions *E. Lushi*
0950 – 1005	A tale of three taxes: photo-gyro-gravitactic bioconvection *M.A. Bees*
1005 – 1020	Microfluidic one-way streets for algae *J. Dunkel, V. Kantsler, M. Polin and R.E. Goldstein*
1020 – 1040	Copepodology for the ornithologist: how suspension feeding zooplankton optimize their fitness *T. Kiørboe and H. Jiang*
1040 – 1050	**POSTERS 7 – 11**
1050 – 1120	Tea and Coffee (CMS)
	SESSION 6: PHYSIOLOGICAL (Chair: T.W. Secomb)
1120 – 1140	The importance of arterial wall viscoelasticity in cardiovascular dynamics *M. Olufsen*
1140 – 1155	Fast waves in oscillatory channel flow *I. Sobey*
1155 – 1210	Leaky epithelia transport fluid by fluctuating paracellular electroosmosis *J. Fischbarg*
1210 – 1225	Long-distance mechanotransduction in vascular endothelial cells via two different pathways *Y. Hwang, C. Gouget, P. Kumar and A.I. Barakat*
1225 – 1240	Multicompartmental poroelasticity and the modelling of cerebral tissue *Y. Ventikos, J. Vardakis and B. Tully*
1240 – 1300	Lymphatic System Biomechanics and Pumping *J.E. Moore, Jr.*
1300 – 1400	Lunch (CMS)
	SESSION 7: LOCOMOTION (Chair: K. Singh)
1400 – 1420	Buckling to steer: an active flagellar instability in marine bacteria *R. Stocker, K. Son and J.S. Guasto*
1420 – 1435	Fluid mechanics of sperm swimming *D. Smith, P. Denissenko, V. Kantsler and J. Kirkman-Brown*
1435 – 1450	Swimming and feeding: optimal strokes of model ciliates *S. Michelin and E. Lauga*
1450 – 1505	The method of femlets: swimming in non-Newtonian fluid *T. Johnson*
1505 – 1520	2-D and 3-D analysis of swimming behaviour of copepods *E. Codling, M. Steinke, M. Breckels, N. Lewis and D. Wales*
1520 – 1540	Wakes and forces created by a flapping foil *A. Andersen, T. Bohr, T. Schnipper and J.H. Walther*
1540 – 1610	Tea and Coffee (CMS)
	SESSION 8: GENERAL (Chair: S.J. Cowley)
1610 – 1630	On two papers Professor Pedley should have read 40 years ago! *J. Blake*
1630 – 1645	How the nose knows *M. Borgas*
1645 – 1700	Paradigm of the oscillating in time flow: drifts and pseudo-diffusion *V.A.Vladimirov*
1700 – 1715	Modelling plankton dynamics in the north Indian Ocean *G. Jayaraman and R. Rani*
1715 – 1740	Suspensions of gyrotactic micro-organisms in uniform vorticity *T.J. Pedley*

Posters

Posters will be on display throughout the conference. Presenters will have about two minutes and a slide to highlight their posters at the following times.

Session 1: Monday 2nd April

1540 – 1550	**POSTERS 1 – 6**
	Helical swimming can provide robust upwards transport for gravitactic single-cell algae; a mechanistic model *R. Bearon*
	Some aspects of pollen tube growth in a creeping flow *I.L. Chernyavsky, V. Kantsler and R.E. Goldstein*
	Spontaneous synchronisation of eukaryotic flagella *M. Polin, I. Tuval, D.R. Brumley and R.E. Goldstein*
	Synchronizing eukaryotic flagella: in more forms than one *K.Y. Wan, K.C. Leptos, M. Polin and R.E. Goldstein*
	Human sperm cells swimming in micro-channels *P. Denissenko, V. Kantsler, D.J. Smith and J. Kirkman-Brown*
	Ferromagnetic microswimmers and micromixers *A. Gilbert, F. Ogrin, P. Petrov and P. Winlove*

Session 2: Tuesday 3rd April

1040 – 1050	**POSTERS 7 – 11**
	High-order simulations of flapping membrane airfoils in low Reynolds number flow *J.W. Jaworski*
	Edmond Halley's account of bird flight *T. Sugimoto*
	2-D coupled model of media flow, nutrient transport and cell growth in a perfusion bioreactor *P. Matthews, M. Shakeel, R. Graham and S. Waters*
	Mathematical modelling of high-frequency flow in curved, compliant arteries *S. Payvandi, J.H. Siggers and K.H. Parker*
	Stability of high-Reynolds-number flow in collapsible-channel *R.B. Kudenatti, N.M. Bujurke and T.J. Pedley*

Acknowledgement

We are grateful for financial support from the London Mathematical Society through its Conference Grant Scheme.

Information for Participants

Location and Timings

- The Scientific Conference will take place at the Centre for Mathematical Sciences (CMS), Wilberforce Road, Cambridge CB3 0WA, starting at 09:00 on Monday 2 April 2012, and finishing at 17:40 Tuesday 3 April 2012.
- On arrival at the CMS please report to our Registration Desk, which will be open each day from 08:30. All lectures will take place in Meeting Room 2 which will be signposted from the CMS Reception.
- The full address is: Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA. The phone number is: +44 (0)1223 765000.
- Eduroam is available at the CMS. If you do not have eduroam then there will be temporary wireless internet accounts available.

Travel

General instructions as to how to travel to the CMS are available at http://www.cms.cam.ac.uk/visiting/. On the map overleaf (Figure 1), the CMS is marked with a red circle; the accommodation at Harvey Court is marked with a red rectangle.

Arriving at the CMS

The CMS is located on Wilberforce Road (off Madingley Road). The Centre may also be reached on foot or bicycle from Clarkson Road (off Grange Road), or from Madingley Road. The architects had Fort Knox in mind when they designed access to the site, so please note the following.

- From Clarkson Road: follow the pathway to the east of the Isaac Newton Institute, turn left at the Gatehouse and the CMS main building (where the CMS Reception is located) is 50m in front of you.
- From Madingley Road: follow the pathway southward and turn right at the Gatehouse.
- From the Wilberforce Road Entrance, follow the signs for CMS Reception.

There are other entrances, but these are access-card protected.

Bus Services

The Uni4 and Citi4 bus services stop in Grange Road (close to the junction with Clarkson Road) and in Madingley Road (between Grange Road and Storeys Way). These bus stops are marked with a green star on the map; the stops near Harvey Court are also marked.

Taxis

Taxi drivers are generally familiar with the CMS. We recommend that you ask the driver to take you to Clarkson Road and drop you at the Isaac Newton Institute. Then follow access instructions from Clarkson Road (see above). If taking a taxi to Harvey Court make sure that you specify Harvey Court[1].

Parking

Parking on site is very limited. Please email TJP-Fest@biofluids.info with any specific requirements.

[1]CAUTION: If you request Gonville and Caius College then you may end up in the middle of town, which is not where you want to be.

Reception and Dinner on Monday

Both the Reception, starting at 19:30 in the Green Room, and the Dinner, starting at 20:00 in the Dining Room, will be held on Monday evening in Old Courts, Gonville and Caius College. There is no dress code for the dinner. There will be signs to the rooms from the Porters' Lodge. If walking to Old Courts from the CMS, proceed 'backwards' from B to A Figure 4 below.

At the dinner there will be an opportunity for guests to share brief memories of Tim. You might like to think about this in advance (and possibly forewarn one of the organizers). Any stories that you would prefer that a third party retold should be emailed to TJP-Fest@biofluids.info.

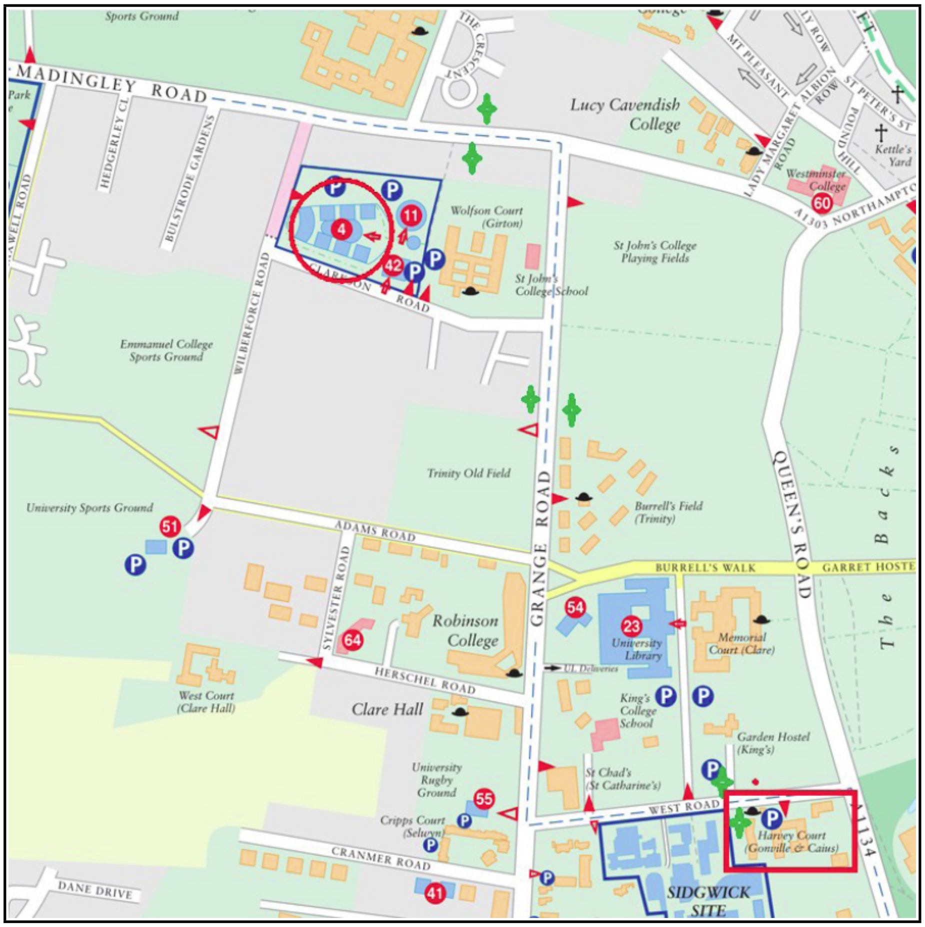


Figure 1: The CMS and Harvey Court

Accommodation

Bed and breakfast accommodation, for those who have booked in advance, is at the Stephen Hawking Building (part of Gonville and Caius College), Harvey Court, 5 West Road, Cambridge CB3 9DS (note the West Road site, not the Old Courts site). Harvey Court is marked with a red rectangle in Figure 1.

The rooms are en-suite, and contain tea and coffee making facilities, spa toiletries, work desk and wireless internet access. More information is available at www.caiusconference.com/conferences/.

Arrival

All visitors should report to the West Road Porters Lodge at 5 West Road, Cambridge which is staffed 24 hours a day; the telephone number is +44(0)1223 335400. Check in is from 14:30.

Breakfast

A full English breakfast with continental buffet is included. However, it is served in the Old Courts Dining Room, which is about a 11-minute walk via Garret Hostel Lane (as recommend by Caius), or a 9-minute walk through King's College (as suggested by Google, see Figure 2 below). Breakfast will be served from 08:00 (rather than the 08:15 advertised initially); even so some running shoes may be advisable if you are to register and make the first talk by 09:00.

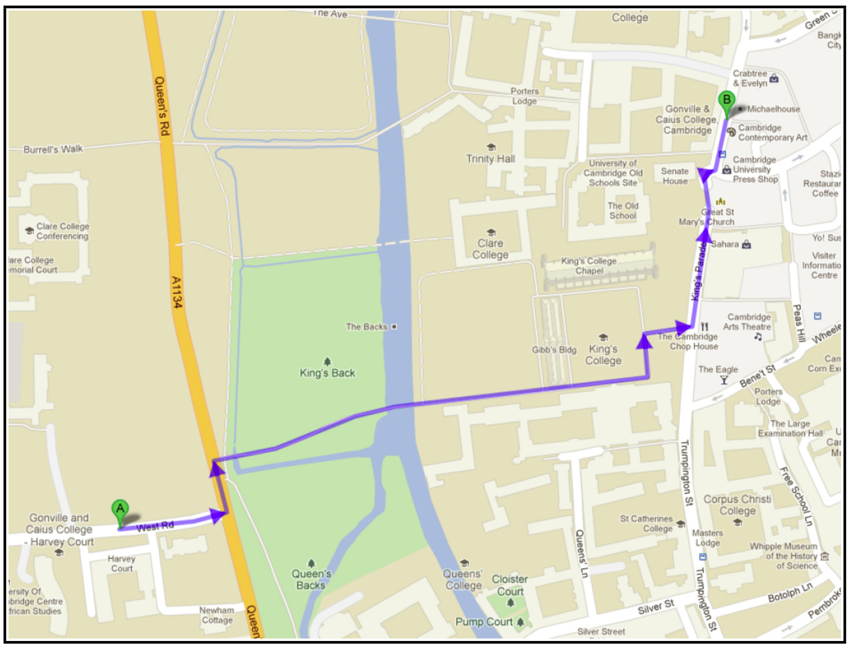


Figure 2: Harvey Court to Old Courts (9 Minutes)

Directions to the CMS

According to Google, the CMS is a 16 minute (or 0.8 mile or 1.3 km) walk from Harvey Court. Walk west down West Road, north up Grange Road, west down Clarkson Road, and then north along the pathway to the east of the Isaac Newton Institute (as illustrated in Figure 3 overleaf).

If you have had breakfast in the Old Courts Dining Room, you might want to walk direct to the CMS. According to Google maps, this is a 19 minute (or 1 mile or 1.5 km) walk: see Figure 4. Proceed west, successively down Senate House Passage, Garret Hostel Lane and Burrell's Walk, then north up Grange Road, west down Clarkson Road, and north along the pathway to the east of the Isaac Newton Institute.

Emergencies

In the case of an emergency, please phone or SMS one of the organizers on +44 (0)7500 883434.

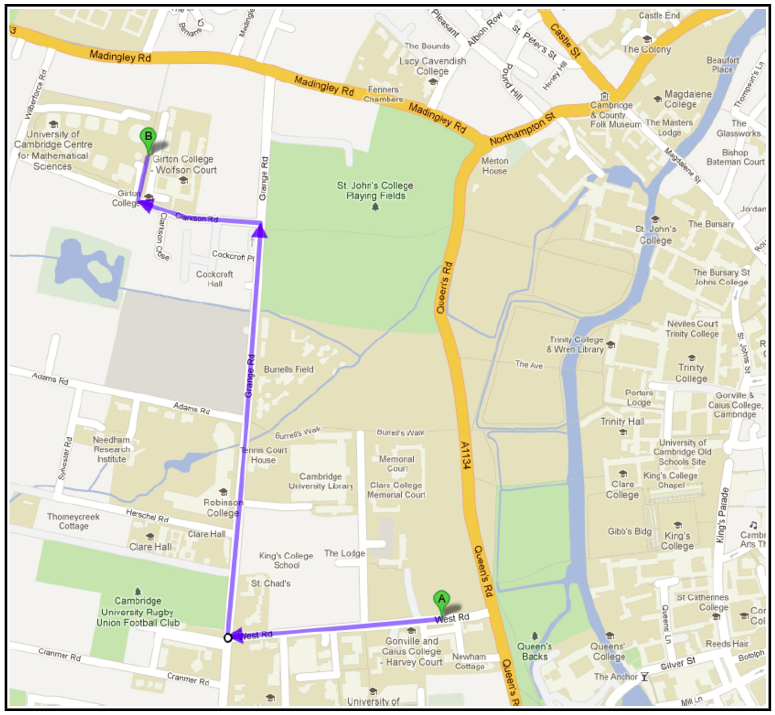


Figure 3: Harvey Court to the CMS (16 minutes)

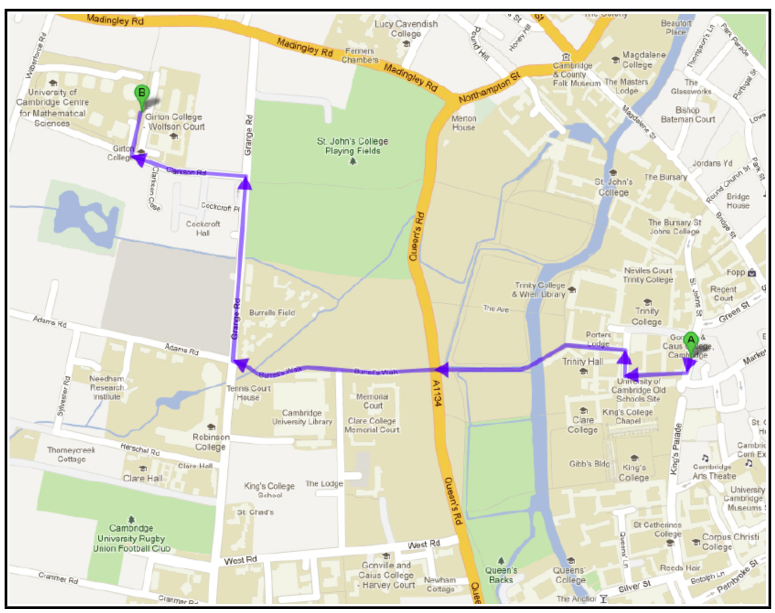


Figure 4: Old Courts to the CMS, or vice versa (19 minutes)

Financial Support

Some funding is available to cover transport costs of delegates, particularly those at an early stage in their careers. If you seek support for travel costs please contact Oliver Jensen (Oliver.Jensen@nottingham.ac.uk). Reimbursement of travel costs is impossible without original receipts.

ABSTRACTS

Wakes and forces created by a flapping foil

A. Andersen[1], T. Bohr[2], T. Schnipper[2], J. H. Walther[3] (Tue 15:20).

We present a combined experimental (soap film tunnel) and numerical study of a symmetric foil with pitching oscillations in a two-dimensional free stream. By varying frequency and amplitude of the oscillations we visualise a variety of wakes, including von Kármán vortex streets, inverted von Kármán vortex streets and 2P wakes in which two vortex pairs are shed per oscillation period. We map out the wake types in a phase diagram spanned by the width-based Strouhal number and the dimensionless amplitude. We follow the time evolution of the vortex formation near the round leading edge and the shedding process at the sharp trailing edge in detail. This allows us to identify the origins of the vortices in the 2P wake and to understand that two distinct 2P regions are present in the phase diagram due to the timing of the vortex shedding at the leading edge and the trailing edge. We find a close correspondence between the numerically determined vortex structures and the thickness variations that visualise the flow in the soap film. Finally, we consider the fluid forces, in particular the drag-thrust transition, and discuss the forces in relation to changes in wake structure.

How to measure the mechanical properties of artificial capsules

Dominique Barthès-Biesel[4] (Mon 10:20).

Encapsulation consists of protecting a substance with a solid envelope to avoid its dispersion in the ambient environment or its degradation in contact with it. The use of capsules (encapsulated liquid droplets) is common in nature (red blood cells, phospholipid vesicles) and in different applications such as pharmacology, cosmetics or biomedical engineering. For artificial capsules, the membrane properties play an essential role in the control of the capsule deformation or possible breakup (to be induced or prevented depending on the application). However, measuring the mechanical properties of the membrane is difficult because the capsules are small (from a few microns to a few millimetres), fragile and often highly deformable. Millimetre-size capsules can be squeezed between two plates, while relating the squeezing force to the compression ratio by means of a mechanical model of the process. Micron-size capsules require micro techniques to be measured. For example, it is possible to flow a capsule suspension in a small pore and measure the resulting deformed profiles of the particles. Then the experiments are analysed by means of a sophisticated model of the fluid structure interactions which lead to the deformation of a capsule in the pore. The aim of this presentation is to discuss the different techniques used to measure the elastic properties of a capsule membrane. This will be illustrated on pore flow experiments from which the shear elastic modulus of the membrane can be inferred and correlated with some fabrication parameters.

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[3]Swiss Federal Institute of Technology Zürich, Chair of Computational Science, ETH Zentrum, Universitätsstrasse 6, CH-8092 Zürich, Switzerland.
[4]Biomécanique Bioingénierie UMR CNRS 7338, Université de Technologie de Compiègne, BP 20529 60205 Compiègne France.

Helical swimming can provide robust upwards transport for gravitactic single-cell algae; a mechanistic model

Rachel Bearon (Poster, Mon).

In still fluid, many phytoplankton swim in helical paths with an average upwards motion. A new mechanistic model for gravitactic algae subject to an intrinsic torque is developed here, which results in upwards helical trajectories in still fluid. The resultant upwards swimming speed is calculated as a function of the gravitactic and intrinsic torques. Helical swimmers have a reduced upwards speed in still fluid compared to cells which swim straight upwards. However a novel result is obtained when the effect of fluid shear is considered. For intermediate values of shear and intrinsic torque, a new stable equilibrium solution for swimming direction is obtained for helical swimmers which results in positive upwards transport in vertical shear, which contrasts to the stable equilibrium solution for straight swimmers which results in downwards transport in vertical shear. Furthermore, for strong intrinsic torque, when there is no longer a stable orientation equilibrium, we show that the average downwards transport of helical swimmers in vertical shear is greatly suppressed compared to straight swimmers. We hypothesise that helical swimming provides robustness for upwards transport in the presence of fluid shearing motions.

A tale of three taxes: photo-gyro-gravitactic bioconvection

Martin A. Bees (Tue 09:50).

Accumulations of cells can occur in suspensions of swimming micro-organisms exhibiting taxes, biased motion relative to directional stimuli. For instance, phototactic swimming algae typically swim towards or away from light of weak or strong intensity, respectively. Also, many cells are bottom heavy and so, in the absence of flow, swim upwards on average, termed gravitaxis. Torques due to bottom-heaviness also act in concert with viscous torques and give rise to gyrotactic behaviour: in suspensions of gyrotactic swimming green algae, cells swim towards down-welling regions. For non-neutrally buoyant cells, the accumulations can give rise to bioconvection, hydrodynamic instabilities and intricate patterns in concentration. In the late 80s and early 90s, Tim Pedley and others developed and explored descriptions of gyrotactic swimming cells, culminating in a new continuum model incorporating stochastic aspects of individuals. In this talk, I shall present extensions of this model for the more natural situation where phototaxis, gyrotaxis and gravitaxis are all present, and contrast the theoretical results with some recent experimental results on the initial instability that occurs in suspensions of swimming algae illuminated with light of different intensities from above or below. The experiments attempt to unravel the mechanisms of the three not altogether separable taxes.

On two papers Professor Pedley should have read 40 years ago!

John Blake[1] (Tue 16:10).

The presentation will consist of several unreliable anecdotes, a potted history of the two papers, the influence of Sir James Lighthill on biofluiddynamics, implications for modern day research and, finally, why Professor Pedley should have read the papers.

[1] University of Birmingham.

How the nose knows

Michael Borgas[1] (Tue 16:30).

Animals including humans use smell to identify and track plumes to sources for food and sex. Smells are communicated by volatile organic compounds (VOCs) mixed into air or water. Noses detect these molecules by passing the ambient fluid over sensor cells with diffusion controlling the transfer of mass and information.

A mass transport theory of chemicals is a traditional bio-fluid approach, but smell is more closely related to information theory and probabilistic interpretations of sensing and cognition as well as turbulent characteristics of plumes.

In this talk, within the context of smell, simple models of signal extraction in the nose are described based on flow and molecular properties with idealised geometries of the human nose. The implications for sensing in water are significant and differences between fish and air breathing noses are described.

Finally, tracking implications are suggested including the interesting case of whales that retain a sense of atmospheric smell purportedly to track dimethyl sulphide plumes (cabbage smells) over the sea to patches of grazing zooplankton.

Vascular droplet and bubble dynamics in gas embolotherapy

Joseph L. Bull[2], Adnan Qamar[2], Zheng Zheng Wong[2], Stanley Samuel[2], Oliver D. Kripfgans[2], J. Brian Fowlkes[2] (Mon 14:50).

This work is motivated by a developmental gas embolotherapy technique for cancer treatment. In this methodology, infarction of tumors is induced by selectively formed vascular gas bubbles that arise from the acoustic vaporization of vascular microdroplets. Additionally, the microdroplets may be used as vehicles for localized drug delivery, with or without flow occlusion. The dynamics of acoustic droplet vaporization and bubble growth were examined by experiments with an ultra-high speed camera and by a combined theoretical and computational model. The ability of acoustic droplet vaporization to induce bioeffects was also observed in vivo. For the range of parameters investigated, the process of acoustic droplet vaporization was found to include an initial linear spherical growth, followed by a linear compressed oval shaped growth, and subsequently a slow asymptotic non-linear spherical growth. Close agreement between the model prediction of bubble evolution and the experimentally measured growth was noted. The tube wall affects the bubble evolution and the bubble does not remain spherical throughout its growth, even when the droplets are small compared to the tube diameter. The in vivo bioeffects depend on the size vessel in which the droplets are vaporized and may be either deleterious or advantageous, depending on their severity, location, and the goal of the treatment.

This work is supported by NIH grant R01EB006476.

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[2]University of Michigan, Ann Arbor, MI 48109 USA.

Natural drinking strategies

John W.M. Bush[1] and Wonjung Kim[1] (Mon 09:00).

We present the results of recent investigations of natural strategies for fluid imbibition. Particular attention is given to classifying the drinking strategies of all creatures according to their scale, and to exploring the relatively novel strategies employed by Nature's smallest denizens, which generally involve capillary effects. Nectar-feeding is also considered, and the dependence of optimal nectar concentration on drinking style reported in the biological literature is rationalized for a broad class of nectar-feeding birds and insects.

Some aspects of pollen tube growth in a creeping flow

Igor L. Chernyavsky[2], Vasily Kantsler[3], Raymond E. Goldstein[3] (Poster, Mon).

The growth of a pollen tube, a protuberance of the germinating pollen grain, is crucial for plant reproduction. This growth is extremely rapid and involves targeted intracellular cargo-transport, and the expansion of a pollen tube as a high-pressure vessel strongly depends on the mechanical properties of cell wall. Although the intracellular streaming in plant and animal cells is a common phenomenon, the understanding of intracellular flow dependence on cell geometry and the role of streaming in transport of solutes and suspended particles is incomplete. In addition, a growing pollen tube responds to a variety of environmental cues, and previous studies showed orientation response of pollen tubes growing in a medium of varying stiffness.

In this study, we address the response to the mechanical environment and some aspects of intracellular streaming in pollen tubes, as a representative model of cellular growth. To probe the impact of mechanical stresses - distributed over the pollen tube surface - on the growth of the cell, we have employed controlled perfusion in a microchannel. We have found some indication that the pollen tube can respond to the applied Hele-Shaw flow by reversibly slowing down the growth rate and aligning parallel to the flow streamlines. Due to high internal pressure relative to the created external viscous stress, the growth of the cell thus likely involves a combination of passive and active response mechanisms regulating its adaptation to the mechanical environment. We have also modelled drag-induced cytosol flow inside a pollen tube, using a superposition of distributed Stokeslets and higher-order multipoles. Our model indicates that the relative distance between counter-forcing cytoskeletal filaments as well as the forcing ratio can change both the direction and magnitude of net cytosol motion, which could be of significance for advective intracellular transport.

The study was supported by the David Crighton Fund.

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[1]MIT
[2]School of Mathematical Sciences, Nottingham.
[3]DAMTP, University of Cambridge, UK.

2-D and 3-D analysis of swimming behaviour of copepods

Edward Codling[1], Michael Steinke[1], Mark Breckels[1], Nicola Lewis[1], Danny Wales[1] (Tue 15:05).

Various measures of movement path tortuosity exist in 2-D and the link between tortuosity of paths and dispersal and behaviour is well understood. However, 3-D path analysis is less well studied in the movement path literature. In this talk I will suggest some ways of linking 2-D and 3-D path analysis and will illustrate the approach using experimental data from foraging copepods. I will also discuss the need for further developments in movement path analysis to properly deal with the 3-D helical movements observed in many species of swimming plankton.

Differential dynamic microscopy of swimming algae

Ottavio A. Croze[2], Vincent A. Martinez[3], Rut Besseling[3], Martin A. Bees[4], Wilson C. K. Poon[3] (Mon 16:40).

Populations of swimming microorganisms are usefully characterised in terms of statistical measures (e.g. mean swimming speed, diffusivity etc.). These measures are usually obtained from microscopic tracking, which however is limited to statistically small sample sizes (hundreds of cells). Here we apply the new method of differential dynamic microscopy (DDM) to obtain improved statistical measures of swimming cells. Instead of tracking individual cells, we analyse the spatio-temporal fluctuations of the local cell number density in the sample from acquired time-lapse images, obtaining a characteristic intermediate scattering function (as in light scattering studies). This function allows to extract the statistics of motile cells averaged over approximately 10000 organisms in a few minutes. We have applied the technique to swimming bacteria and algae, validating results with simulations and tracking. We present here our results for populations of the bi-flagellate alga Chlamydomonas reinhardtii for which we have measured mean swimming amplitude, frequency and swimming speed distribution with unprecedented accuracy. Implications for the continuum models which Tim has pioneered (where statistical measures are critical input parameters) will be briefly discussed.

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[2]School of Mathematics and Statistics, University of Glasgow, Glasgow G12 8QW, UK.
[3]SUPA, School of Physics and Astronomy, University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, UK.
[4]School of Mathematics and Statistics, University of Glasgow, Glasgow G12 8QW, UK.

Microfluidic one-way streets for algae

Jorn Dunkel[1], Vasily Kantsler[1], Marco Polin[1], Raymond Goldstein[1] (Tue 10:05).

Controlling locomotion and transport of microorganisms is a key challenge in the development of future biotechnological applications, ranging from drug testing devices to the harvesting of biofuels and microbial energy sources. Here, we demonstrate the use of optimized microfluidic ratchets to rectify the mean swimming direction in suspensions of the unicellular green alga Chlamydomonas reinhardtii, which is a promising candidate for the photosynthetic production of hydrogen. To assess the potential of microfluidic barriers for the manipulation of algal swimming, we studied first the scattering of individual C. reinhardtii from solid boundaries. High-speed imaging reveals the surprising result that these quasi-spherical 'puller'-type microswimmers primarily interact with surfaces via direct flagellar contact, whereas hydrodynamic effects play a subordinate role. A minimal theoretical model, based on run-and-turn motion and the experimentally measured surface-scattering law, predicts the existence of optimal wedge-shaped ratchets that maximize rectification of initially uniform suspensions. We confirm this prediction in experimental measurements with different geometries. Since the mechano-elastic properties of eukaryotic flagella are conserved across many genera, we expect that our results and methods are applicable to a broad class of swimming microorganisms.

Human sperm cells swimming in micro-channels

P. Denissenko[2 3], V. Kantsler[4], D.J. Smith[5 2 3], and J. Kirkman-Brown[3 6] (Poster, Mon).

The migratory abilities of motile human spermatozoa in vivo are essential for natural fertility, but it remains a mystery what properties distinguish the tens of cells which find an egg from the millions of cells ejaculated. To reach the site of fertilization, sperm must traverse narrow and convoluted channels, filled with viscous fluids. To elucidate individual and group behaviours that may occur in the complex three-dimensional female tract environment, we examine the behaviour of migrating sperm in assorted micro-channel geometries. Cells rarely swim in the central part of the channel cross-section, instead travelling along the intersection of the channel walls ('channel corners'). When the channel turns sharply, cells leave the corner, continuing ahead until hitting the opposite wall of the channel, with a distribution of departure angles, the latter being modulated by fluid viscosity. If the channel bend is smooth, cells depart from the inner wall when the curvature radius is less than a threshold value close to 150 micron. Specific wall shapes are able to preferentially direct motile cells. As a consequence of swimming along the corners, the domain occupied by cells becomes essentially 1-dimensional. This leads to frequent collisions and needs to be accounted for when modelling the behaviour of populations of migratory cells and considering how sperm populate and navigate the female tract. The combined effect of viscosity and three-dimensional architecture should be accounted for in future in vitro studies of sperm chemoattraction.

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Division by fluid incision: biofilm patch development in porous media

William M. Durham[1], Olivier Tranzer[2], Alberto Leombruni[3], Roman Stocker[4] (Tue 09:20).

Bacterial biofilms often occur in porous media, where they play pivotal roles in medicine, industry and the environment. Though flow is ubiquitous in porous media, its effects on biofilm growth have been largely ignored. Using patterned microfluidic devices that simulate unconsolidated soil, we find that the structure of Escherichia coli biofilms undergoes a self-organization mediated by the interaction of growth and flow. Intriguingly, we find that biofilm productivity peaks at intermediate flow rates, when the biofilm is irrigated by a minimum number of preferential flow channels. At larger and smaller flow rates, fluid flows more uniformly through the matrix, but productivity drops due to removal by shear and reduced nutrient transport, respectively. These dynamics are correctly predicted by a simple network model. The observed tradeoff between growth and flow may have important consequences on biofilm-mediated processes such as biochemical cycling, antibiotic resistance and water filtration.

Haemodynamics in the mouse aortic arch

C. Ross Ethier[5] (Mon 14:35).

Haemodynamics in the human aortic arch are a well-studied problem, having partially motivated much interesting fluid mechanical research on flow in curved tubes. With the wide-spread use of mice to study the pathogenesis of vascular disease, blood flow patterns in the mouse arch are now also of great interest. As first suggested from scaling arguments, and now experimentally confirmed, blood flow in the large arteries of the mouse occurs in a somewhat different fluid mechanical regime than in the human, with a lower characteristic Reynolds number (c. 100 for mouse vs c. 1500 for human), leading to correspondingly weaker secondary flows and reduced heterogeneity in wall shear stress (WSS) patterns. In order to better understand arch hemodynamics, we have recently used MR imaging to measure time-resolved blood velocity fields at the aortic root in C57BL/6 mice, and then used this data to drive numerical flow simulations in the mouse arch. In our mice, most of which had gradual arch curvature and a brachiocephalic trunk ostium located close to the aortic root, a transient separation zone formed proximal to the brachiocephalic trunk, creating a low WSS region on the outer curvature of the arch. Swirling present at the aortic root appeared to stabilise the flow and reduce WSS oscillations. Our predicted WSS patterns in mice are not entirely consistent with the belief that the formation of atherosclerotic-like lesions is promoted by low and oscillatory WSS, suggesting that other atherogenic factors may also be important in the mouse.

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Leaky epithelia transport fluid by fluctuating paracellular electroosmosis

Jorge Fischbarg[1] (Tue 11:55).

Leaky epithelial layers are generally assumed to transport fluid by local transcellular osmosis across the aquaporins in their plasma cell membranes. However, such assumption has come under strong challenge. Among many arguments, genetic deletion of aquaporins, supposed to be the main transport route, fails however to arrest fluid transport.

We have investigated this issue working with the corneal endothelium, a leaky epithelium which transports fluid. Modeling the secretory activity of this epithelium yields a surprise: no cellular transport of salt is apparent. Instead, anions are transported across the cell, and cations across the intercellular junctions, forming the limbs of an intense local electrical current. This suggested paracellular fluid transport by electroosmosis, with the junction being the site of the coupling. Experiments in which electrical currents were sent across the endothelium in either direction resulted in fluid moving in the same direction of the current. Both the direction of the fluid movement and the degree of coupling with the current are consistent with electroosmosis. Other experiments revealed that the cellular secretion of bicarbonate was oscillatory, with a period of $\approx$ 5s. This would allow a role for aquaporins, as in 5 s the cellular events, if continuous, would tend to run out of phase with the paracellular electroosmosis. Cyclic cellular secretion and fast compensatory water movements through aquaporins solve the problem. Transjunctional paracellular electroosmosis thus emerges as a likely explanation for fluid transport across leaky epithelia.

Statics and dynamics of planar shearable filaments in viscous fluid: a Cosserat rod approach

Hermes Gadêlha[2], Eamonn Gaffney[3], Alain Goriely[3] (Mon 09:50).

Cilia and flagella are ubiquitous in biology as a means of motility and constitute one of the most incredible engineering works of nature. Their inner core, namely the axoneme, consists of a remarkable phylogenetically conserved cytoskeletal structure formed by an assembly of semifexible filaments interconnected by crosslinking proteins. As a result, the flagellum or cilium is not only capable to flexure under the action of an external load, but also to shear. The latter is however a consequence from the intricate elastic crosslinking proteins which causes the elastic bending to couple with shearing deformations, modifying dramatically the effective mechanical response of these bundles of filamentous polymers. We consider deformations of nonlinearly elastic slender rods immersed in a fluid, and analyse the differences between the elastic cross-link shear response and pure material shear resistance under the action of viscous dissipation. We show that pure material shearing effects from Timoshenko's beam theory or, equivalently, Cosserat Rod Theory are fundamentally different from elastic crosslink induced shear found in filament bundles, such as the axoneme.

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Unsteady flows to induce endogenous surfactant therapy

Donald P. Gaver[1] (Mon 11:10).

The lung consists of many generations of bifurcating airways that terminate with alveoli, the site of gas exchange. Surfactant, a protein-phospholipid mixture, is released from alveolar type-II pneumocytes, and dynamically reduces the surface tension of the lining fluid. Without proper surfactant function the lung is micro-mechanically unstable, leading to airway closure and insufficient gas exchange. Airway reopening can result in large mechanical stresses being exerted onto the airway wall, which can damage airway epithelial cells. This atelectrauma is a component of ventilator-induced lung injury (VILI), and contributes to the high mortality (40%) of acute respiratory distress syndrome. We asked the question 'is it possible to enhance the surface activity of endogenous surfactant using unsteady flows?' If so, atelectrauma could be reduced through the judicious choice of mechanical ventilation waveform.

We investigate the fluid-structure and physicochemical interactions that lead to atelectrauma through theoretical and in-vitro experimental investigations of pulmonary airway reopening. Benchtop studies demonstrate a reduction of the macroscale pressure drop, and micro-PIV linked to Lagrangian methods establish the influence of dynamic surface tension on this system. Cell-based studies demonstrate the potential for unsteady flows with intermittent retrograde flow to reduce airway damage in cases of surfactant deficiency. The use of dynamic flow to enhance surfactant function therefore provides an opportunity for 'endogenous surfactant delivery' that may reduce the prevalence or magnitude of VILI.

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Ferromagnetic microswimmers and micromixers

Andrew Gilbert[2], Feodor Ogrin[2], Peter Petrov[2], Peter Winlove[2] (Poster, Mon).

A swimmer has recently been engineered based on ferromagnetic beads connected by an elastic link and driven by a time-dependent external magnetic field. One bead is magnetically 'hard' (having a fixed dipole direction) while the other is 'soft' (having a dipole direction that follows the external field). The time-dependent field imposes torques on the swimmer and leads to alternating attraction and repulsion between the two beads. This combined motion is sufficient to overcome the 'scallop' theorem and lead to swimming in the Stokes regime. Swimming and mixing regimes are demonstrated in terms of a mathematical model.

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The shape of a ponytail and the statistical physics of hair fiber bundles

Raymond E. Goldstein[1] (Mon 17:40).

From Leonardo to the Brothers Grimm our fascination with hair has endured in art and science. Yet, a quantitative understanding of the shapes of hair bundles has been lacking. In this talk I will describe work done in collaboration with Patrick B. Warren (Unilever Research) and Robin C. Ball (Warwick) that uses a combination of experiment and theory to propose an answer to the most basic question: What is the shape of a ponytail? A model for the shape of hair bundles is developed from the perspective of statistical physics, treating individual fibers as elastic filaments with random intrinsic curvatures. The combined effects of bending elasticity, gravity, and bundle compressibility are recast as a differential equation for the envelope of a bundle, in which the compressibility enters through an "equation of state." From this, we identify the balance of forces in various regions of the ponytail, extract a remarkably simple equation of state from laboratory measurements of human ponytails, and relate the pressure to the measured random curvatures of individual hairs.

Multiphase flow in the lung

James B. Grotberg[2] (Mon 12:30).

Our lab has been actively pursuing a number of problems involving multiphase flow in the lung. This talk will be a review of our efforts in surfactant and liquid delivery into the lung, airway closure, airway reopening, related aerosol deposition phenomena and alveolar dynamics. The disease settings are ARDS, asthma, cystic fibrosis, surfactant deficiency, and congestive heart failure. CFD is used extensively with comparisons to our own experiments and available literature. Computations give us a way of understanding critical fluid mechanical phenomena for Newtonian and non-Newtonian fluids such as: liquid plug splitting at airway bifurcations with the influence of gravity; initiation of plug motion from a critical yield pressure drop when it has a yield stress, as in mucus; the deposition of local aerosols during airway closure and reopening on the dynamic interface of that airway; the stability of a liquid film, or bilayer film, in an airway geometry to model the ser ous and mucus layers during airway closure; the combined effects of cyclic stretch and interface motion over alveolar cells. We are also gaining insight into the levels of stresses on the epithelial cells of airways and alveoli which may cause damage, provoke the release of bioactive molecules, and initiate and sustain inflammation.

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Unsteady flow in a curved tube

A. L. Hazel[1], R.E. Hewitt[1], R.J. Clarke[2], J.P. Denier[3] (Mon 17:25).

Flows in curved tubes are generic models for internal physiological flows. The associated meridional flows, induced by the interplay of viscous drag, centrifugal forcing and pressure gradients, can lead to 'collisional' boundary-layer structures that provoke singularities in the boundary-layer equations at finite times. Understanding the role and consequences of these types of singularity in the full Navier–Stokes equations is the motivation for this work.

Here, we present results for the temporal evolution of viscous, incompressible fluid in a rotating torus of finite curvature, after an impulsive change in rotation rate. (At a stretch, this could be considered as a model for the flow in inner ear when the body is subject to abrupt changes in external rotation.) In this case, analytic progress is facilitated by the simple form of the initial flow, instead of the more complex form associated with pressure-gradient-driven flows. We demonstrate that (rotationally symmetric) eruptive singularities of the boundary layer can occur at the inner and outer bend of the pipe for a decrease or increase in rotation rate, respectively. Comparison with finite (but large) Reynolds number computations indicate that the eruption is characterised by ejection of fluid from the boundary layer in to the core. We also find that the flow is subject to a non-axisymmetric inflectional instability induced by the developing eruptive instability and in qualitative agreement with the experimental observations of Madden & Mullin (1994).

On the liquid lining in fluid-conveying curved tubes

A.L. Hazel[4], M. Heil[4], S.L. Waters[5], J.M. Oliver[5] (Mon 10:05).

We consider axially-uniform, two-phase flow through a rigid curved tube in which a fluid (air) core is surrounded by a film of a second, immiscible fluid (water): a simplified model for flow in a conducting airway of the lung. Jensen (*J. Fluid Mech.* **331**, 373–403 (1997)) showed that, in the absence of a core flow, surface-tension drives the system towards a configuration in which the film thickness tends to zero on the inner wall of the bend. In the present work, we demonstrate that the presence of a core flow, driven by a steady axial pressure gradient, allows the existence of steady states in which the film thickness remains finite; a consequence of the fact that the tangential stresses at the interface, imposed by secondary flows in the core, can oppose the surface-tension-driven flow.

For sufficiently strong surface tension, the steady configurations are symmetric about the plane containing the tube's centreline, but as the surface tension decreases the symmetry is lost through a pitchfork bifurcation, which is closely followed by a limit point on the symmetric solution branch. This solution structure is found both in simulations of the Navier–Stokes equations and a thin-film model appropriate for weakly-curved tubes. Analysis of the thin-film model reveals that the bifurcation structure arises from a perturbation of the translational degeneracy of the interface location in a straight tube.

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Pulse propagation in the pulmonary circulation

N.A. Hill[1], Mette S. Olufen[2], Gareth D.A. Vaughan[1] (Mon 14:20).

We present a numerical model of periodic pulse propagation in the full pulmonary circulation. The arteries and veins are treated as two fully-coupled, bifurcating trees of compliant and tapering vessels. Given cardiac output data and pressure in the left atrium, we study the effects on the pressure pulse waveform of the number of generations of vessels, and of vascular compliance, and assess the possibilities for early detection of disease.

Long-distance mechanotransduction in vascular endothelial cells via two different pathways

Yongyun Hwang[3], Cécile Gouget[3], Praveen Kumar[3], Abdul I. Barakat[3] (Tue 12:10).

Flow shear stress applied to luminal surface of blood vessels plays a crucial role in regulating functions of vascular endothelial cells, a key factor in understanding the origin of atherosclerosis. One of the essential questions in this process is how the external mechanical stimuli (flow shear stress) translate into subcellular biochemical responses, the so-called cellular mechanotransduction. The pathways of the cellular mechanotransduction can be classified into two categories depending on the way of mechanical stimuli transmission in the cell: direct and indirect pathways. In the direct pathway, the mechanical stimuli are transmitted through the cytoskeleton and directly lead to biochemical responses at the nucleus. By contrast, in the indirect pathway, the mechanical stimuli deform signaling complexes at the cell membrane, which, in turn, activates biochemical signals at this location. The activated biochemical signals then propagate to the nucleus through reaction-diffusion cascades, resulting in biochemical responses at the nucleus. In this talk, we present two conceptual mathematical models which describe direct and indirect pathways of the mechanotransduction respectively, with particular emphasis on identifying the mechanisms of long-distance transduction of the mechanical stimuli. For the direct pathway, we develop a model for mechanical force transmission through actin-stress-fiber networks, and discuss important physiological factors for the long-distance transduction. For the indirect pathway, we consider a reaction-diffusion cascade model for signaling proteins, and show that the proper intracellular positioning of signal regulators, such as endosome and the Golgi apparatus, enables the biochemical signal to travel a long distance.

High-order simulations of flapping membrane airfoils in low Reynolds number flow

Justin W. Jaworski[4] (Poster, Tue).

The aerodynamics and aeroelastic response of a membrane wing under prescribed motion are investigated using a high-order, two-dimensional Navier-Stokes solver coupled to a geometrically-nonlinear membrane model. The impact of increasing Reynolds number on the vortex dynamics and unsteady aerodynamic loads is examined for moderate-amplitude plunge and combined pitch-plunge motions at low frequency. Simulation results are compared with classical thin airfoil theory and highlight the differences between rigid and flexible membrane airfoils undergoing small and moderate amplitude motions. The present study demonstrates the ability of lifting membrane surface flexibility to enhance thrust production and propulsive efficiency, which may inform the design of flapping wing membrane fliers.

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Modelling plankton dynamics in the north Indian Ocean

Girija Jayaraman[1] and Raj Rani[1] (Tue 17:00).

The difference in biological productivity between the two basins in the North Indian Ocean viz., the Arabian Sea (AS) and the Bay of Bengal (BOB) provides a study in contrast. Both the basins are situated in the same latitude and are controlled by the prevailing monsoon winds, which reverse semi-annually but the two basins exhibit distinct physical, chemical and biological features. The surface winds blow from the northeast during the winter monsoon (November to February) and from the southwest during summer monsoon (May to September). This semi-annual reversal of wind field influences the upper layers of both the basins. Bay of Bengal is influenced more by the variations of freshwater discharges to the coastal regions and the complex tidal oscillations, whereas, in the Arabian Sea, mostly, evaporation exceeds precipitation.

It is important to understand the seasonal cycles of biological response to different physical processes in the two basins. In the present study, a four compartment ecological model (NPZD) based on Nutrient (N), Phytoplankton (P), Zooplankton (Z) and Detritus (D) is used to investigate the plankton dynamics in two basins at the same latitude. The model is forced by the seasonally varying mixed layer depth (MLD), solar radiation and nutrients supply from below the mixed layer. Numerical experiments and sensitivity analysis show that the phytoplankton growth rate and nutrient input below the mixed layer are the main controlling factors whereas all other factors are of secondary importance. Simulated seasonal cycles of plankton at all locations are validated with monthly as well as eight day average sea-viewing wide field of view sensor (SeaWiFS) chlorophyll-a data during year-2006. The model simulation confirms that the higher biological productivity in the AS compared to BOB is due to deeper MLD and increased entrainment of nitrates from below the mixed layer.

Fluctuations of fixed-flux flow in the Pedley Resistor

Feng Xu[2], John Billingham[2], Oliver Jensen[2] (Mon 12:15).

A canonical problem in physiological fluid mechanics concerns the possible mechanisms of self-excited oscillation in the Starling Resistor, in which flow is driven through an externally pressurized elastic tube that is mounted between two rigid pipes. Its 2D analogue (a finite-length channel having a segment of one or both walls replaced by a membrane under tension), proposed by TJP in 1992, has provided a fruitful hunting ground for theoreticians, even though it has so far defied attempts to be realised experimentally. While considerable recent progress has been made in understanding the onset of instability when flows are driven by a prescribed pressure drop, less is understood about the case when the upstream flux is prescribed, despite long-standing numerical evidence being available (Luo & Pedley 1996). Through a stability analysis of a simplified 1D model, we have identified a set of organising centres in parameter space from which neutral curves emanate. We have used parametric and small-amplitude expansions to study the local dynamics around one such centre. We find that static eigenmodes can interact to generate a growing oscillation (leading to a system with approximately Hamiltonian dynamics), while oscillatory eigenmodes (strongly coupled to the downstream rigid segment) can interact to generate instabilities in a manner analogous to aerodynamic flutter.

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Impulsive generation of viscous vortex rings and propulsion at low Reynolds numbers

Houshuo Jiang[1], Thomas Kiørboe[2] (Mon 09:35).

Planktonic copepods (0.1-10 mm in body length) are abundant, evolutionarily successful, and ecologically important in the ocean and freshwater. They perform rapid jumps to relocate, to attack prey and to escape predators. The jump involves impulsively generated viscous vortex rings: the near impulsive (i.e. power stroke duration ¡ 10 ms) striking of the swimming legs exerts short-lasting localized momentum on the surrounding water, creating vortex rings that decay rapidly due to viscosity. Such viscous vortex rings can be approximated by a group of Stokes solutions called impulsive stokeslet and stresslet. Here, we compare the impulsive stokeslet and stresslet solutions to the steady stokeslet and stresslet solutions and to an inviscid vortex ring solution. We show that the impulsive generation of viscous vortex rings enables the jumping copepod to achieve a high Froude propulsion efficiency and simultaneously reduce predation risk by keeping the jump-imposed flow spatially limited and temporally ephemeral. Evidence suggests that the impulsive generation of viscous vortex rings is a widespread propulsion mode for aquatic organisms of body length around 1 mm.

The method of femlets: swimming in non-Newtonian fluid

Thomas Johnson[3] (Tue 14:50).

We present a new technique for modelling free-swimming problems in viscous flows with shear-dependent viscosity. The swimmer is represented by a set of regularised Dirac delta 'blob' volume forces (Femlets) of a priori unknown strength and direction, and the finite element projection of the governing fluid equations is taken over a body-conforming mesh. The force density on the swimmer surface is then calculated implicitly via the application of Dirichlet velocity conditions, given by the body-frame deformation of the swimmer, at the location of each Femlet. Swimming velocities are obtained through enforcing the zero net force and torque constraints. We hypothesise that this method may be of use in effectively coupling non-Newtonian fluid flow to structural mechanics of swimmers, potentially in viscoelastic rheologies. Here we give a brief summary of the methodology, followed by preliminary results in two-dimensions for a variety of swimmers in Newtonian and shear-thinning fluids.

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Copepodology for the ornithologist: how suspension feeding zooplankton optimize their fitness

Thomas Kiørboe[1], Houshou Jiang[2] (Tue 10:20).

Zooplankton feed on microscopic prey that they entrain in a feeding current or encounter as they cruise through the water. They generate fluid disturbances as they feed and move, thus elevating their risk of being detected and encountered by predators. Different feeding modes generate different hydrodynamic signals to predators but may also differ in their efficiency; the optimal behavior is that which maximizes the food intake over the predation risk. We use flow visualization (PIV) and simple hydrodynamic models to describe and generalize the fluid flow generated by the main zooplankton feeding behaviors. We show that the optimal feeding and motility behaviors, independent of the sensory mode of potential predators (tactic, rheotactic, or visual), lead to specific clearance rates corresponding to 1 million times the body volume of the zooplankter per day. This is the universally observed clearance rate of zooplankton irrespective of feeding mode, species, and size.

Stability of high-Reynolds-number flow in collapsible-channel

Ramesh B. Kudenatti[3,4], N.M. Bujurke[5], T.J. Pedley[4] (Poster, Tue).

We investigate the linear stability of the asymptotically high-Reynolds-number flow in a planar infinitely long collapsible channel of width a of which a part of the lower wall has been replaced by a flexible membrane under longitudinal tension and with and without wall inertia. Deformation of the membrane is assumed to have small amplitude and long wavelength. Far upstream the flow is the Poiseuille flow at high Reynolds number. In the study, we use unsteady interactive boundary layer theory to investigate the stability of the flow for zero external pressure. We observe that in the absence of wall inertia, the problem is ill-posed when the pressure is fixed upstream ($\tilde{P} = 0$ at $x = 0$). However, when it is fixed downstream ($x = 1$), the problem is well-posed and all observed solutions are stable. Now, addition of wall inertia to the membrane, we expect oscillations to arise in the model. The physical mechanisms underlying these phenomena are explored and studied in detail.

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An efficient eigensolver and its application in collapsible channel flows

Yujue Hao[1], Zongxi Cai[2], Steven Roper[1], Xiaoyu Luo[1] (Mon 12:00).

Large asymmetric eigenvalue problems occur in many nonlinear fluid-structure interaction applications. One such an example is the stability of collapsible channel flows, where identifying the neutral stability curves of the system poses a daunting and tedious computational task (Liu et al. in press). Traditionally such a problem is often solved using the so called QZ solver which is extremely computational time consuming and memory hungry. In this paper, we investigate an alternative approach for solving the asymmetric generalized eigenvalue problem using the Arnoldi method. This approach uses an iterative orthogonal projection method in the Krylov subspaces and seeks the first few eigenmodes, thereby greatly reduces the computational time. To overcome the drawback of a huge memory requirement, which exists equally in the Arnoldi and the QZ algorithms, we combine the Arnoldi method with the frontal solver, so that the computational efficiency is significantly enhanced. Comparison of the new approach with the conventional QZ solver is given, and pros and cons are discussed. This efficient eigensolver allows us to study the stability mechanism of the collapsible channel flows with affordable resources.

Colonial chemotactic dynamics in the presence of microswimmer interactions

Enkeleida Lushi[3] (Tue 09:35).

In suspensions of microswimmers like bacteria locomotion generates fluid motion, which can lead to collective behavior from unbiased swimming. I will present a model that couples bacterial run-and-tumble chemotaxis, which by itself leads to colony aggregation, with the flow fields generated by collective swimming. The stability of isotropic suspensions reveals separate branches of chemotactic and hydrodynamic instability, the first driving aggregation, and the second driving orientational ordering in 'Pusher' suspensions. Simulations of the long-time nonlinear dynamics show that including hydrodynamic interactions can limit and modify chemotaxis-driven aggregation dynamics. For Pusher suspensions chemotactic aggregation can lead to destabilizing time-dependent flows with fragmented regions of aggregation. In Puller suspensions the aggregation spots are mutually-repelling due to the non-trivial flows. In the end I will briefly describe how direct interactions between swimmers also alter and modify colonial dynamics in chemotactic suspensions.

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2-D coupled model of media flow, nutrient transport and cell growth in a perfusion bioreactor

Muhammad Shakeel[1], Paul Matthews[1], Richard Graham[1], Sarah Waters[2] (Poster, Tue).

A model is derived and solved numerically for a cell-seeded porous scaffold placed in a perfusion bioreactor in which fluid delivers nutrients to the cells. The model describes the key features, including fluid flow, nutrient delivery, cell proliferation and consequent variation of scaffold porosity. Fluid flow through the porous scaffold is modelled by Darcy's law, and nutrient delivery is described by a reaction-advection-diffusion equation. A reaction-diffusion equation describes the evolution of cell density, in which cell proliferation is modelled via logistic growth, and cell spreading via non-linear diffusion, which depends on cell density. The effect of shear stress on nutrient consumption and cell proliferation is also included in the model. The results reveal the dependence of the cell distribution and total cell yield on the initial cell density and scaffold porosity.

Swimming and feeding: optimal strokes of model ciliates

Sébastien Michelin[3], Eric Lauga[4] (Tue 14:35).

To swim at low Reynolds numbers, micro-organisms undergo periodic shape changes that break the temporal symmetry. In addition to creating a net motion of the organism, this stroke generates a flow around the organism that has two major consequences: (i) an energetic cost associated with viscous dissipation in the flow and (ii) a modification of the advective/diffusive transport of nutrients around the cell and therefore a modification of its feeding ability.

In this presentation, we will focus on the optimal strokes of model swimmers from two different points of view, swimming and feeding, by seeking the strokes that maximize either the net displacement or the feeding rate for a given energetic cost. Using adjoint-based optimization, we will show that, unlike the feeding rate, the optimal feeding stroke is independent of the relative importance of advection and diffusion (and therefore of the nutrient considered) and is essentially identical to the optimal swimming stroke.

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Lymphatic system biomechanics and pumping

James E. Moore, Jr.[1] (Tue 12:40).

The lymphatic system is an extensive vessel network featuring one-way valves and contractile walls that pump interstitial fluid, proteins, and immune cells through lymph nodes and then back to the blood circulation. This system is crucial in immune response, as well as being the pathway of distribution for metastatic tumor cells. Failure to drain and pump results in edema, or fluid retention and swelling.

We are developing multi-scale computational models of lymphatic function from the sub-cellular to the whole organ level in conjunction with a series of experiments. Models of vessel segments in series have been characterized through pump curves of steady pressure difference versus flow rate. These curves exhibit non-linear behaviors typical of mixed source pumps. These models also provide the opportunity to quantify the importance of various modeling parameters through sensitivity analysis. For example, the phase angle between successive lymphangion contractions is an important determinant of pumping efficiency, with out-of-phase behavior being the most efficient.

Experiments with rat mesentery lymphatics revealed that these vessels quickly adapted to increased volume loads by increasing lymph flow rate and contraction frequencies. Valves are biased toward the open position, with that bias increasing with transmural pressure.

Unlike the arterial and venous systems, the lymphatic system has not been the subject of extensive modeling efforts. Our work is aimed at constructing models that strike a delicate balance between the need to represent complex physiological phenomena and the desire to keep the modeling feasible computationally.

The importance of arterial wall viscoelasticity in cardiovascular dynamics

Mette Olufsen (Tue 11:20).

It has long been known that to understand cardiovascular dynamics all aspects of the system must be considered including the transport of fluid, the impact of the arterial wall, and the control of the system. One aspect that has recently received significant attention is arterial wall viscoelasticity (also an area of interest previously for T.J. Pedley). When predicting flow and pressure using fluid dynamics methodologies, it is important to account for the fluid interaction with the viscoelastic wall – failure to do so leads to inaccurate predictions of blood pressure, one of the most important quantities assessed in clinical studies. Another important influence of viscoelasticity is related to baroreflex regulation. When the arterial baroreceptors detect changes in stretch of the arterial wall in response to changes in blood pressure, the associated change in the firing rate of the afferent baroreceptor neurons is directly impacted by the viscoelasticity of the wall. If this effect is not taken into account, it is difficult to develop models that accurately predict heart rate regulation. Models in isolation can provide some understanding of dynamics, but to examine in detail the role of viscoelasticity, models should be integrated with data and adapted to responses recorded from individual experiments. This presentation will focus on how viscoelastic models can be developed from pressure area measurements using sheep arteries. These models will be combined with a one-dimensional fluid dynamics model and an ordinary differential equations model developed to predict baroreflex regulation of heart rate during head-up tilt.

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Mathematical modelling of high-frequency flow in curved, compliant arteries

Sevil Payvandi[1], Jennifer H. Siggers[2], Kim H. Parker[2] (Poster, Tue).

Cardiovascular disease, and in particular atherosclerosis, remain the leading cause of death in the western world. Despite the systemic nature of the risk factors, the distribution of atherosclerotic plaques in the cardiovascular system is highly focal, typically occurring in areas of disturbed flow such as curved arteries. The causative mechanisms of atherosclerosis remain unknown, but a correlation between atherosclerosis and wall shear stress has been identified by Caro et al (1971).

Vessel compliance has usually been omitted from previous studies, but could influence the haemodynamics in the near-wall region and hence the shear stress. The aim of this research is to understand the effect of compliance on flow in idealized curved arteries at high frequency and small steady-streaming Reynolds number using asymptotic analysis.

For high-frequency flow in a rigid pipe, Lyne (1971) found that the interaction of the oscillatory pressure gradient with the curvature of the pipe leads to the generation of a steady term in the streamfunction – a phenomenon known as steady streaming. We will show that for a compliant pipe, an additional mechanism for steady streaming exists, whereby the oscillatory pressure gradient also interacts with the compliance of the pipe and leads to a steady term in the axial velocity. The steady streaming terms are important as they represent a sustained effect during the cycle, and hence on the endothelial cells of the arterial walls, which may be pertinent in the development of atherosclerosis.

Suspensions of gyrotactic micro-organisms in uniform vorticity

T.J. Pedley[3] (Tue 17:15).

Analysis of bioconvection in dilute suspensions of bottom-heavy but randomly-swimming micro-organisms is commonly based on a model introduced in 1990[4]. This couples the Navier-Stokes equations, the cell conservation equation and the Fokker-Planck equation (FPE) for the probability density function (pdf) for a cell's swimming direction, **p**, which balances rotational diffusion against viscous and gravitational torques. The results have shown qualitative agreement with observation, but the model has not been subjected to quantitative testing in a controlled experiment.

Here we consider a simple configuration in which the suspension is contained in a circular cylinder of radius R, which rotates at angular velocity Ω about a horizontal axis. We solve the FPE and calculate the cells' mean swimming velocity, which proves to be horizontal when $B\Omega \gg 1$, where B is the gyrotactic reorientation time scale. Then we compute the cell concentration distribution, which is non-uniform only in a thin boundary layer near the cylinder wall when $\beta^2 = \Omega R^2/D \gg 1$, where D is the cells' translational diffusivity. The fact that cells are denser than water means that this concentration distribution drives a perturbation to the underlying solid-body rotational flow which can be calculated analytically when the Reynolds number is small. The predictions of the theory will be compared with observations in an experimental realisation of the proposed configuration, using a suspension of the alga *Chlamydomonas nivalis*.

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[4]Pedley, T.J. & Kessler, J.O. J. Fluid Mech. 212: 155-182 (1990)

Suppression of viscous fingering by elastic membranes

D. Pihler-Puzovic[1], P. Illien[1], M. Heil[1], A. Juel[1] (Mon 11:45).

Growth of complex dendritic fingers at the interface of air and a viscous fluid in the narrow gap between two parallel plates is an archetypical problem of pattern formation. We find a surprisingly effective means of suppressing this instability by replacing one of the plates with an elastic membrane. The resulting fluid-structure interaction fundamentally alters the interfacial patterns that develop and considerably delays the onset of fingering. We analyze the dependence of the instability on the parameters of the system and present scaling arguments to explain the experimentally observed behaviour.

How to win the 2012 Beverley Triathlon

Jon Pitchford (Mon 09:20).

Models of animal movement need to be understood in a sensible ecological and evolutionary context. I will try to illustrate this important and useful fact with reference to the dynamics of fish, butterflies, plant roots, and sweaty bipeds in special lycra costumes.

Spontaneous synchronisation of eukaryotic flagella

Marco Polin[2], Idan Tuval[3], Douglas R. Brumley[2], Raymond E. Goldstein[2] (Poster, Mon).

Cilia and flagella perform essential tasks in eukaryotes, from locomotion to sensing and development. They are usually part of large groups, which can display strikingly coordinated dynamics known as metachronal waves. The remarkable similarity in their underlying molecular structure across the whole eukaryotic world leads naturally to the hypothesis that a similarly universal mechanism might be responsible for synchronisation. One appealing hypothesis, still to be tested experimentally, is that synchronisation results from interflagellar hydrodynamic coupling.

We present our recent experimental studies of interflagellar coordination and its dependence on flagellar length in the biflagellate green alga *Chlamydomonas reinhardtii*. Our results support quantitatively the hypothesis of a purely mechanical origin of synchronisation, which develops as a result of an interplay between hydrodynamic coupling and flagellar elasticity. We also report some preliminary results suggesting that the same elastohydrodynamic mechanism can generate robust symplectic metachronal waves similar to those found in the multicellular alga *Volvox carteri*.

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Mechanics of red blood cell motion in the microcirculation

Timothy W. Secomb[1] (Mon 14:00).

Blood is a concentrated suspension of highly deformable red blood cells (RBCs), whose dimensions are comparable to the diameters of the small blood vessels that comprise the microcirculation. While the resulting non-continuum flow phenomena have important physiological consequences, their theoretical understanding presents many challenges. Early work, starting in the 1960s, focused on narrow capillaries, where RBCs often move in single file. Lubrication theory can then be used to describe the flow of the suspending fluid around the cells, yielding theoretical predictions of flow resistance in agreement with experimental results obtained using capillary-sized glass tubes. In larger microvessels, radial migration due to wall effects results in the formation of cell-depleted layers near the walls, which strongly affect resistance to blood flow. In diverging microvessel branch points, the distribution of RBCs between the branches is generally not in proportion to the flow rates, leading to wide local variations in RBC volume fraction. Living microvessels differ from glass tubes in that they are lined with a dilute layer of macromolecules, the endothelial surface layer, which strongly affects fluid flow. We have used a simplified two-dimensional representation of RBC mechanics to investigate a number of these phenomena, including effects of the endothelial surface layer on radial migration. In recent years, increasing computational capabilities have allowed three-dimensional simulations of multiple RBCs in microvascular flow geometries. The combination of detailed simulations and simplified analyses is providing new insights into microcirculatory blood flow phenomena.

Wall shear stress and atherosclerosis: age related variations in a study of rabbit aortas

V. Peiffer[2 3], P.D. Weinberg[3], S.J. Sherwin[2] (Mon 15:05).

Atherosclerosis is characterised in its early stages by focal accumulations of lipid within the arterial wall. The lesion distribution changes with age: atherosclerosis moves from downstream to the lateral sides and upstream of aortic branch ostia, and longitudinal streaks of disease in the descending aorta become more pronounced. These age-related differences may be a consequence of changes in blood flow. We simulated flow in five immature and mature rabbit aortas to investigate this hypothesis.

A key observation from our geometric analysis was that the aorta arch was more tapered in mature than in immature rabbits. However there were no clear age-related changes in the curvature and torsion of the aortic centreline. Dean-type vortical structures developed in all geometries; whilst these were confined to the aortic arch in the immature geometries, they extended into the descending aorta in the mature geometries. The wall shear stress (WSS) was higher on the dorsal side of the descending thoracic aorta than on the ventral side. This streak of high WSS was more pronounced in mature rabbits. WSS was increased downstream and to a lesser extent upstream of the origins of intercostals arteries.

Our simulations showed differences in the flow characteristics in immature and mature rabbit aortas. The change in the extent of the vortical structures can be explained by an increase in tapering with age. Although the results cannot account for changes in lesion patterns around intercostal ostia, the changes in the pattern of longitudinal fatty streaks may be associated to the difference in the large-scale WSS distribution although they do not obviously correlate to a low WSS hypothesis.

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Symmetry breaking cilia-driven flow in the zebrafish embryo

Andrew A. Smith [1 2], Thomas D. Johnson [1 2], David J. Smith [1 2 3], John R. Blake [1 2] (Mon 16:55).

Fluid mechanics plays a vital role in early vertebrate embryo development, an example being the establishment of left-right asymmetry. Following the dorsal-ventral and anterior-posterior axes, the left-right axis is the last of the three axes to be established; in several species it has been shown that an important process involved with this is the production of a left-right asymmetric flow driven by 'whirling' cilia. It has previously been established in experimental and mathematical models of the mouse ventral node that the combination of a consistent rotational direction and posterior tilt creates left-right asymmetric flow. The zebrafish organizing structure, Kupffer's vesicle, has a more complex internal arrangement of cilia than the mouse ventral node; experimental studies show that the flow exhibits an anticlockwise rotational motion when viewing the embryo from the roof, looking towards the floor. Reports of the arrangement and configuration of cilia suggest two possible mechanisms for the generation of this flow from existing axis information: (a) posterior tilt combined with increased cilia density on the roof; and (b) dorsal tilt of 'equatorial' cilia. We develop a mathematical model of symmetry breaking cilia-driven flow in Kupffer's vesicle using the regularized Stokeslet boundary element method. Computations of the flow produced by tilted whirling cilia in an enclosed domain suggest that a possible mechanism capable of producing the flow field with qualitative and quantitative features closest to those observed experimentally is a combination of posteriorly tilted roof and floor cilia, and dorsally tilted equatorial cilia.

Fluid mechanics of sperm swimming

David Smith [1 2] Petr Denissenko [4 2], Vasily Kantsler [5], Jackson Kirkman-Brown [2 6] (Tue 14:20).

Sperm are the archetypal microscopic swimmers, inspiring applied mathematicians from Lighthill to the present day, in addition to playing an essential role in fertility. In this talk we shall review some of the classic findings on sperm motility, including their method of self-propulsion and their behaviour near surfaces, before moving on to consider some surprises in sperm mechanics. In particular, we will focus on (1) how the fluid flow generated by sperm differs from the overwhelming majority of swimming cells, and (2) the related problem of how sperm are attracted to boundaries. For the latter problem, we will discuss strengths and weaknesses of generic models of boundary accumulation, including our own attempts and some recent theoretical advances in this area. Finally we shall present imaging experiments of sperm in fabricated microchannels that show how sperm motility can be controlled by relatively simple boundary features, and how boundary attraction is modulated by viscosity.

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Fast waves in oscillatory channel flow

Ian Sobey[1] (Tue 11:40).

In 1983 Stephanoff, Pedley, Lawrence and Secomb published in *Nature* observation of a new fluid phenomenon, the development of a travelling wave of vortices in a steady channel flow. The wave developed downstream of steady oncoming flow past a transversely moving wall indentation. These experiments were followed by a number of studies on separation and particularly the new wave. In 1985 I showed from experiments, that if the channel walls were fixed but the flow oscillatory, then a standing wave of vortices formed downstream of an asymmetric channel expansion. This seemed to be yet another type of flow development: in the case of steady flow past a moving wall, a travelling wave of vortices developed, in this case there was a standing wave of vortices. Much later, some accidental calculations I did with Hwu showed that in a restricted region of paramenter space, as well as the standing wave of vortices, a very fast travelling wave might occur during oscillatory flow through a channel with fixed walls. This has now been characterised much better in work with Kachuma. In this talk I will give a very brief historical outline of the problem before moving on to describe recent work. This uses both numerical solution of the Navier–Stokes equations and stability analysis in an Orr-Sommerfeld framework but with an asymmetric unperturbed flow. My conclusion is that a focus on instability of symmetric flows may be asking the wrong question about transition in channel flow.

Inhomogeneity promotes damage in reopening airway networks

Peter S. Stewart[2], Oliver E. Jensen[3] (Mon 11:30).

In respiratory distress, lung airways can collapse due to surface-tension-driven instabilities in their liquid lining, inhibiting gas exchange, with severe and possibly fatal consequences if not treated efficiently. We construct a model for the mechanical ventilation of a large network of collapsed flexible airways, where a bubble of gas is injected into the system to separate the airway walls (using either a prescribed flow rate or a ramped inflation pressure). This model follows from a previous lumped parameter model for reopening a single airway [Halpern *et al.*, *J. Fluid Mech.*, vol. **528**, 2005, p.53], which has been well validated by higher-dimensional studies. We allow for spatial variability in the elastic properties of the network and incorporate a threshold opening pressure for each airway (dependent on the local properties), non-linear reopening dynamics and a non-local coupling between all the reopening airways. We explore how each of these features (non-linearity, non-locality and inhomogeneity) influence the overall recruitment, as well as strategies that should be adopted to promote safe, efficient reopening, yet minimize damage to the airways themselves.

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Buckling to steer: an active flagellar instability in marine bacteria

Kwangmin Son, Jeffery S. Guasto, Roman Stocker (Tue 14:00).

Many marine bacteria are monotrichous, i.e. they have only one flagellum. Consequently, they lack Escherichia coli's mechanism for changing direction (the tumble) and have long been described as simply swimming back-and-forth, plus Brownian rotational diffusion. Recent work has shown this not to be the case and that instead a large-amplitude deformation (a 'flick') of the flagellum produces a large reorientation, with the same net result as E. coli's tumble. The mechanical origin of the flick has remained elusive. Using high-speed videomicroscopy we have discovered a previously overlooked component of this strategy, a millisecond forward swimming burst that directly precedes the flick and provides a clue to its mechanism: a buckling instability of the hook, the flexible structure that connects the flagellum to the motor. Buckling occurs when the viscous drag on the cell, proportional to the swimming speed, exceeds the critical buckling load. We tested this hypothesis by varying the cells' swimming speed, which for marine bacteria can be conveniently done by modulating the medium's salinity, since their motor is driven by sodium gradients. We find a sharp transition in the buckling probability as a function of the Sperm number, the ratio of the destabilizing, viscous force and the stabilizing, elastic force. These results lend support to the view that buckling is under the active control of the bacteria, which over evolutionary time have tuned the material properties of their hook to their swimming speed, so as to be able to turn with only a single flagellum.

Edmond Halley's account of bird flight

Takeshi Sugimoto[1] (Poster, Tue).

Daniel Bernoulli (1700-1782) unified hydrostatics and dynamic theory of fluids by publishing 'Hydrodynamica (1738),' in which there appears Bernoulli's Theorem. Almost half a century before this publication Edmond Halley (1656-1742) had read a series of unpublished papers at the Royal Society meetings and tried to account for physics behind bird flight in a modern sense for the first time in the history of sciences. Halley proposed a method to estimate the dynamic pressure by use of the idea of 'hydraulic head.' He extended this idea to estimate the wing-beat of the pigeon. Although he made a mistake in his computation, we validate his method by the corrected procedure.

[1]Kanagawa University.

Multicompartmental poroelasticity and the modelling of cerebral tissue

J. Vardakis, B. Tully, Y. Ventikos[1] (Tue 12:25).

Cerebral tissue and related transport phenomena in the brain combine a number of characteristics that make their theoretical and computational representation and analysis particularly challenging: the brain has extreme metabolic and oxygenation needs but with minimal capacity to store glucose and oxygen, it is perfused by a markedly complex vascular system, it produces and floats in cerebrospinal fluid which is in continuous exchange with vascular plasma and – enclosed in the cranium – is probably the most inaccessible organ in the human body. If, furthermore, we consider that the brain is the centre of all cognitive functions; the most important and irreplaceable organ, the intense research attention it concentrates is easily justified. We propose a novel mutliscale approach for addressing these modelling challenges, that involves the representation of cerebral tissue as a porous elastic medium permeated by a multiplicity of passages – each with its own features (porosity, permeability etc.) These networks have the potential to communicate with each other, according to predefined transport laws; for example the cerebrospinal fluid compartment can receive liquid from the arterioles/capillaries compartment and can drain in the venal compartment. We apply this new modelling framework to the case of Normal Pressure Hydrocephalus (NPH) – a disease that is equally important and paradoxical. We show, for the first time, that NPH may be a two-hit disease, where microscale variations in vascular and tissue properties can have macroscopic manifestations in ventricular dilatation and intracranial pressure – manifestations that match (and possibly explain) clinical observations.

Paradigm of the oscillating in time flow: drifts and pseudo-diffusion

V.A.Vladimirov[2] (Tue 16:45).

- The oscillating in time flows are the most used by Tim Pedley.
- The inviscid incompressible oscillating in time flows are studied with the use of inverse frequency as a small parameter ε. We classify such flows and build general and uniformly valid asymptotic solutions. The classes include strongly oscillating flows, moderately oscillating flows, *etc.*
- We show that all nonlinear averaged terms can be reduced to the variety of drifts and pseudo-diffusion, which can have different orders in ε.
- Our analytical approach combines the Eulerian averaging, the distinguished limits, a new analytical method for calculation of successive approximations, and the explicit estimations of errors.
- Our results do not contain any physical assumptions.
- Navier-Stokes, MHD, *etc.* equations can be treated similarly.

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Synchronizing eukaryotic flagella: in more forms than one

Kirsty Y. Wan[1], Kyriacos C. Leptos[1], Marco Polin[1], Raymond E. Goldstein[1] (Poster, Mon).

Ranging from sensory transduction to provision of cellular motility, the remarkably conserved group of organelles known as cilia and flagella are implicated in a variety of important life processes. These appendages display a fascinating multitude of individual as well as collective motions. Probing the generic phenomenon of how synchrony of beating can emerge between neighbouring weakly-coupled flagella through their immersion in a shared fluid environment, and the circumstances in which such synchrony can fail, or take unusual forms, may prove insightful for the deciphering of mammalian ciliopathies. Using high-speed video capture, micro-manipulation, and analytical image-processing, we examine three forms of flagellar synchronization in the motile biflagellated unicellular alga *Chlamydomonas*, whose flagella typify the model eukaryotic flagellum. Cells of the *wildtype* pull themselves through the fluid via a synchronized breaststroke beat-pattern interrupted by brief episodes of phase-asynchrony termed slips, which arise stochastically from subtle differences in the intrinsic frequencies of the two flagella. In addition to this form of synchronized breaststroke, we reveal coexistence of an alternative metastable state of flagella synchrony in a phototaxis *mutant* of *Chlamydomonas*, whose two flagella can at times be seen to switch to beating alternately in so-called *anti-phase*. Finally, we exploit the phobic behavioural response of *Chlamdyomonas* whereupon the waveform of both flagella transiently depart from their usual lateral asymmetric ciliary beat, to exhibit a frontal undulatory beat that may be well-characterized by synchronized waving filaments in 2D.

Two new stagnation-point flows

P. D. Weidman[2] (Mon 17:10).

Stagnation flows are ubiquitous in fluid mechanics, the three most famous of which are the planar stagnation-point flow of Hiemenz (1911), the axisymmetric stagnation-point flow of Homann (1936), and the non-axisymmetric three-dimensional stagnation-point flow of Howarth (1951). The Hiemenz and Homann flows are characterized by strain rate a whilst the Howarth flow depends on two strain rates a and b. Howarth's flow respresents the orthogonal intersection of two Hiemenz stagnation-point flows.

In this talk we generalize the Homann solution by adding a horizontal shear component of shear rate b to the axisymmetric stagnation flow of strain rate a to obtain a one-parameter family of non-axisymmetric solutions depending on the *shear-to-strain rate* ratio $\gamma = b/a$. Numerical solutions of the similarity equations, valid for $-\infty < \gamma < \infty$, are presented and compared with the asymptotic behavior of solutions for large γ.

The Howarth solution may be generalized by considering the nonlinear *oblique* intersection of two Hiemenz stagnation-point flows. This leads to a two-parameter family of solutions dependng on the *strain-rate* ratio $\sigma = b/a$ and the oblique intersection angle ϕ. In the limit $\phi = 0°$ one obtains two Hiemenz flows superposed one on top of the other, while in the limit $\phi = 90°$ the classic Howarth problem is recovered. Numerical solutions of the similarity equations, valid for $-1 \leq \sigma \leq \infty$, are presented and compared with the asymptotic behavior of solutions for large σ.

Both of these non-aixsymmetric stagnation-point flows are found as exact solutions of the Navier-Stokes equations.

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From red cells to skiing to an airborne jet train that flies on a soft porous track at 700 km/hr

Sheldon Weinbaum[1] (Mon 16:20).

It was first recognized more than a decade ago that red cells ski on a highly compressible soft, porous, water filled glycocalyx layer that coats inner surface of our blood vessels. This magical layer not only prevents adhesive interaction of proteins in the red cell and endothelial membranes, acts as a molecular sieve in determining the Starling forces that act across capillary endothelium, but also serves as a mechanotransducer of fluid shear stress into the cytoskeleton of the cell in initiating cellular responses. Quite remarkably the the parameter $h/\sqrt{k_p}$, where h is the layer thickness and k_p the Darcy permeability, is nearly the same for a red cell and a human skiing. This concept is first illustrated for the rapid compression of snow where it is shown that lift forces four orders of magnitude greater than classical lubrication theory can be generated. This concept is then extended to a giant ski which is capable of lifting a jet train car carrying 200 passengers on a soft porous bed of inexpensive fiber fill materials where the lift enhancement is of order 10^7. This futuristic vehicle is capable of reaching 700 km/hr using jet engines with about 1/5 the thrust of a jet plane with the same passenger load and 1/4 the energy expenditure of a much heavier bullet train in current use in Europe if it could travel at the same speed.

Computational biomechanics of physiological flow

Takami Yamaguchi[2], Takuji Ishikawa[3], Yohsuke Imai[3], Hironori Ueno[4], Keiko Numayama-Tsuruta[2], Toshihiro Omori[2] (Tue 09:00).

Biological systems of the human body are always under an integrated nervous and humoral control, i.e., in homeostasis. Multiple feedback mechanisms with mutual interactions among systems, organs, and even tissues provide integrated control of the entire body. These control mechanisms have different spatial coverage, from the micro-scale to the macro-scale, and time constants, from nanoseconds to decades. We think that these variations in spatial and temporal scales should be taken into account in discussing human physiology and pathology.

With this in mind, we have been investigating the biomechanics of the human body, particularly the biomechanics of physiological flows over micro to macro levels, by using conjugated computational mechanics to analyze fluid, solid and bio-chemical mechanics.

Recent studies on cardiovascular system have focused more on pathological conditions. At micro-scale, we have developed a particle-based modelling of microcirculation to simulate thrombosis and malaria infection. At macro-scale, we proposed a novel hemodynamic index predicting aneurysmal initiation, the gradient oscillatory number (GON). In addition, we have extensively studied respiratory and digestive systems, for example, pulmonary airflow, mucociliary clearance, swallowing and gastric mixing. Biomechanics of microorganism suspension has also been a recent topic. We have revealed collective swimming of bacteria, which is the most energy-efficient way of moving and of absorbing oxygen and nutrients in nature.

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Fluid mechanics of bileaflet mechanical heart valves

Ajit P. Yoganathan[1] (Mon 15:20).

Heart valve diseases are associated with high mortality and morbidity. In severe stages, valve replacement therapies are required. For replacement, mechanical heart valves are preferred over bioprosthetic valves due to their structural durability, and the bileaflet mechanical valve (BMHV) is the valve of choice (¿90%). However, BMHVs are associated with thrombo-embolic complications, due to coagulation caused by exposure of blood to elevated shear stresses, necessitating lifelong anti-coagulation therapy which has harmful side-effects.

Our laboratory utilizes a combination of in vitro experiments and computational fluid dynamic (CFD) simulations to understand BMHV fluid mechanics at various scales. We first characterized flow structures downstream of the BMHVs on a global scale using 2D and 3D Digital Particle Image Velocimetry (DPIV) and Laser Doppler Velocimetry (LDV). Next, micro-scale velocity measurements using LDV were conducted in the hinge regions. CFD simulations were performed on both regions to obtain fluid shear stresses over the cardiac cycle. We have observed that in the current BMHV hinge designs, blood elements can undergo multiple passes through the hinge and experience elevated shear stresses, creating a 'hostile' environment for blood. Our corresponding CFD computations of shear stresses on blood cells, compare well with our in vitro experimental observations. To further understand the blood coagulative potential of BMHV hinges, fresh human blood was circulated through hinge like orifices and platelet activation was gauged using TAT assays.

The fundamental understanding of the relationship between bileaflet mechanical valve designs and blood damage, should allow us to improve their flow characteristics and eventually overcome long term thromboembolic complications.

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