Advanced Metrology for Ultrasound in Medicine
27–28 April 2004

AMUM 2004 proved to be a great success and provided a fantastic opportunity for the world's ultrasound experts from medicine, industry and academia to explore the measurement challenges presented by new and emerging clinical ultrasound equipment. There were a total of 88 attendees. Of these 39 were from the UK, 22 from the rest of Europe, and 27 from outside Europe. 31 of the delegates were from industry, 22 were university-based, 18 from hospitals, 10 from other National Metrology Institutes and regulatory bodies, and 7 from NPL. Test your knowledge of the ultrasound community by trying to name all the faces in the group photograph! It was especially gratifying to see so many major medical equipment manufacturers represented – including Siemens, Philips, Esaote, Kontron, Pie Medical, G.E., Hitachi, Aloka and Imasonic - since it is essential that there is a good dialogue between industry and the measurement community.

The presentations were split into 8 oral sessions – Hydrophones, Hydrophone measurements, Safety and thermal hazard, Measurement challenges for diagnostic ultrasound, Measurement of therapy fields, Tissue interaction, Novel measurement methods, and Measurement challenges for therapeutic ultrasound; and 3 poster sessions - Performance of diagnostic equipment, Measurement and safety, and Field modelling. It was always my hope that this conference would provide a framework for the development of measurement methods to meet the metrological challenges we face over the next decade. To this end, I have asked the Chairs of each oral and poster session to give their views of their own session and of the more general requirements in that topic area.

The feedback I received both during and subsequent to the meeting was almost uniformly good; this was borne out by the returned questionnaires, with most categories being scored excellent or good. I was delighted at the high standard of the presentations and to see delegates of such reputation and experience in the audience. This clearly shows that there is a need for such a conference.

The commercial exhibition, although small, gave delegates the opportunity to discuss their requirements with three of the most important suppliers of ultrasound measurement devices – Precision Acoustics, Onda Corporation, and Sonora Medical Systems – and to see the latest developments. It also gave the companies concentrated access to a large number of important customers and potential customers.

Socially, also, the event was a great success. The welcome reception (plus miniature 'Big Band') was sponsored by Precision Acoustics and held in Bushy House, site of the original NPL; the gala dinner in Hampton Court Palace was attended by more than 70 delegates who were treated to guided tours of the magnificent gardens and an address by Dr Bob McGuinness, the Director of NPL.

My thanks to everyone who attended or otherwise contributed to the success of AMUM2004. I would particularly like to acknowledge the contributions of the guest speakers, the scientific advisory board members, NPL colleagues and the AMUM secretariat, who made the whole thing run so smoothly.

Adam Shaw
Chair, AMUM Scientific Committee
**Hydrophones – Dr Christian Koch**

The hydrophone is one of the most important and critical parts of the ultrasound detection process. Although it already has a history of several tens of years, a series of novel technical methods and metrological aspects was presented in the first technical session of the conference. At the beginning, traceability was shown to be a key issue of metrology supporting research and development. Ultrasound measurements should concentrate on the determination of traceable quantities to make results objective and comparable. This leads to a clearer feed-through of research output and a more reliable quantitative characterisation of devices to the benefit of the user community.

In general, hydrophone sensitivity is a complex valued quantity. Although the determination of the sensitivity amplitude has been realised in calibration procedures in several laboratories around the world for many years, thorough techniques for a measurement of the phase response have been missing so far. During the session, two methods for phase calibration were presented providing results up to a frequency of 70 MHz. Heterodyne time-delay spectrometry (HTDS) extended the known technique of time-delay spectrometry to a coherent detection. As a phase standard, an optical multilayer hydrophone was exploited using a pulse calibration technique. In combination, both techniques can provide a calibration service for amplitude and phase for all common hydrophones. The data obtained form the basis of deconvolution procedures which significantly improve the uncertainty of hydrophone measurements. However, the accuracy of the phase determination that is necessary for an adequate correction calculation remains an open question.

Another focal point of the session was the extension of the application frequency range for hydrophones and the development of appropriate calibration techniques. Since some new medical ultrasound applications use frequencies in the range of tens and hundreds of kHz, the measurement techniques for this lower frequency range should be improved. Technical difficulties, e. g. the generation of a sufficiently strong and wideband ultrasound field and the quality of common hydrophones in this frequency range, have to be overcome for the development of calibration standards.

The increasing working frequencies in many diagnostic fields, the growing importance of nonlinear techniques with significantly wider pulse bandwidths and higher demands on the measurement accuracy require measurements at frequencies higher than 20 MHz. To realise adequate hydrophone calibration, several techniques were presented. Nonlinear techniques can be extended up to 100 MHz and time-delay spectrometry allows an efficient calibration service. Interferometry reliably provides absolute amplitude values with high signal-to-noise ratio, but careful design is necessary. In general, optical techniques were shown to have a very high potential to meet the required specifications in the high frequency range. Recently developed optical interference hydrophones and 2-dimensional sensors showed excellent high bandwidths and transfer characteristics, and further development steps are to be expected in future.

**Hydrophone Measurements – Adam Shaw**

It is all too easy to fall into the trap of thinking that when we make a measurement with a PVdF hydrophone in an ultrasonic field, we are actually measuring the pressure in the field. In point of fact, what we are actually measuring (ie observing and recording) is almost always the number generated by an analogue-to-digital converter in response to the voltage produced by the combination of the hydrophone and its preamplifier. Even if we can assume that all the electronics work perfectly and do not distort the electrical signal, the ADC reading depends on the voltage at the input to the ADC, which depends on the voltage at the input to the hydrophone preamplifier, which depends on the charge generated by the hydrophone, which depends on the changing thickness of the hydrophone element, which is a convolution of the mechanical response of the hydrophone material and the spatial- and temporal-variation of pressure amplitude and phase over the area of the hydrophone element. Considerable effort has gone into making smaller, less perturbing, wider bandwidth hydrophones so that there is a more straightforward relationship between the output of the ADC and the pressure at the point of interest. But, in the meantime, transducer manufacturers have built smaller,
higher frequency, broader bandwidth and higher power transducers which make the problem more complex once again.

Up to this time, written measurement Standards have essentially relied on measuring the output voltage of the hydrophone and these procedures are quite well established. However, to be able to make more accurate and more reproducible measurements of demanding ultrasound fields, it is essential that we develop more reliable methods for deriving the local pressure throughout the field. Most of the techniques under consideration are already used in other areas of science, so it shouldn’t be beyond the capacity of the world’s ultrasound experts to adapt them and come up with improved measurements Standards.

With the aim of minimising the perturbation caused by the hydrophone, Hurrell’s first paper in this session described a method for modelling the mechanical interaction of the hydrophone and the ultrasound field. The method used a finite difference approach with two staggered grids, which is borrowed from geophysics and was successful in designing out resonances within the needle hydrophone. The following three papers presented by Wilkens, Cooling and Hurrell all addressed deconvolution of the temporal waveform to remove the effects of the frequency response of the hydrophone. This is clearly now something which is technically feasible (at least for membrane hydrophones) and must surely find its way into Standards before long. The final paper presented by Humphrey dealt with the very complicated issue of nonlinear propagation and how it impacts on existing measurement standards which attempt to relate measurements in water to equivalent values in tissue. Essentially, this paper describes a method for identifying when a field becomes significantly nonlinear and recommends that measurements be made at a drive level below this threshold. These results are later normalised to give acoustic values which correspond to the maximum output conditions. This is an important topic, because high level ultrasound fields can become ‘saturated’ in water, leading potentially to a large underestimate of the values in tissue with consequential implications for safety thresholds.

In some cases the results based on deconvolution will be significantly different to the raw results. This may have implications, for instance, for manufacturers seeking to comply with FDA requirements. This is certainly something that must be addressed but it is not a consideration that should be allowed to hold back the adoption of more accurate methods.

A topic which I was disappointed not to see raised in this session is spatial-averaging (or, more generally, spatial-deconvolution of the hydrophone response). Existing measurement standards contain correction methods for spatial-averaging but further research is required, particularly into the effects of phase-averaging, which is potentially very significant in some fields and has not so far been addressed in Standards.

**Safety and Thermal Hazard – Prof. Francis A Duck**

The increase in tissue temperature caused by diagnostic ultrasound transducers is the most significant limitation to the power that may be used safely during a diagnostic ultrasound examination. The papers presented in the “Safety and Thermal Hazard” session explored issues related to the common question “how may thermal hazard be quantified?”. For the clinical user, the Thermal Index is at present the only indicator of thermal hazard, being a rough estimate of the worst-case tissue temperature rise. Independent measurement is a necessary component in establishing that the displayed index values have been properly calculated. This, as Tony Whittingham demonstrated, requires investment in an acoustic measurement system of some complexity. Until there is measurement traceability for displayed TI values, such independent measurement on behalf of users is an essential component, which may start to create some confidence in their significance and meaning. For a true assessment of thermal hazard, however, a measurement of the temperature rise in tissue is needed. The Thermal Test Objects (TTOs) described by Adam Shaw are the only standard experimental method available for this purpose. Given the increasing complexity of modern scanning modes, TTO measurement presents an increasingly attractive means for quantifying thermal hazard without depending on oversimplified assumptions of field structures. It is to be hoped that design developments can improve on their long-term stability. Infrared thermography also has considerable value in evaluating thermal effects. Used with a special tissue-equivalent test object which may be
abruptly opened, thermography has allowed temperature rise distributions with depth to be measured, as described by Rob Hekkenberg. Transducer self heating remains a key limitation on transducer design, and transducer surface temperature rise in air can also be measured with IR thermography both for diagnostic and therapy transducers (Christian Kollman). Such measurements need cross calibration against a thin film thermocouple to ensure that appropriate correction for surface emissivity is applied. Finite-element modelling is enabling improved understanding of the key design aspects controlling surface temperature. Oliver Saunders demonstrated how the addition of appropriate thermal management within a transducer design may limit the surface temperature whilst retaining acoustic output. The development of standard ways to quantify thermal hazard and to communicate this to the user is being done through the efforts of several overlapping international and national bodies, most notably WFUMB and IEC. An alternative way of debating some of the issues, the “Standards Incubator”, was offered by John Abbott. This builds on the work commenced in the USA with the publication of the AIUM/NEMA “Output Display Standard”, and the definition of the Thermal Index as a hazard indicator. Given the issues raised in this session, it is perhaps still premature to build an international consensus for indicating thermal hazard based on an index which lacks traceability and has yet to establish user confidence.

**Challenges for diagnostic ultrasound – Dr Gerald R Harris**

Although diagnostic ultrasound is a mature imaging modality, it is by no means a static one. In this session, advances in ultrasound imaging technology were described, along with the possible impact on current measurement practice. For example, as pointed out in the introductory lecture, encoded excitation pulses, newer broadband transducers, and the development of higher frequency applications (e.g., ophthalmic, dermatological, intravascular), all are contributing to the increased demands on measurement devices and techniques. From the following presentation on the modeling of ultrasound contrast agents, it was evident that the increasing use of these agents makes the accurate knowledge of in situ exposure levels in these applications more critical, both from safety and effectiveness standpoints. Next a method was presented to address the problem of identifying maximum system output conditions, in which field simulations could be used as an alternative to detailed hydrophone scans. Exploring such approaches is important, given the complexity of modern multimode scanning. Finally, the practical issues associated with real-world measurements in a manufacturing environment were described. Test procedures, no matter how accurate, will be of diminished value if they cannot be implemented in an industrial setting. In the ensuing discussion, which encompassed not only the current session but the preceding ones as well, several measurement challenges were enumerated, including:

- developing more accurate means to convert a hydrophone voltage waveform to pressure, such as impulse convolution, which would require that both the amplitude and phase of the hydrophone sensitivity be measurable over the range of relevant frequencies;
- extending the upper frequency range of operation of hydrophones;
- designing hydrophones with smaller effective active dimensions, or deriving reliable spatial averaging correction procedures;
- assessing the validity of the conventional definition of center frequency, given the effects of both non-linear propagation and complex pulsing regimes;
- establishing better methods to evaluate the temperature rise both in vivo and at the transducer surface;
- developing a dependable scheme to extrapolate low-amplitude hydrophone measurements made in water to higher levels, and thus avoid the problems associated with measurements in the presence of finite amplitude distortion.
It was noted that successful completion of this last challenge could alleviate some of the more stringent requirements on hydrophone bandwidth. Finding practical solutions to these challenges will be necessary to ensure the future safe and effective operation of medical ultrasound devices.

Measurement of therapy fields - Rob Hekkenberg
Although the whole conference was about (advanced) measurement methods the need to provide Traceability and Quality Assurance was most prominent in the presentations in this session. Roy Preston pointed out in the opening presentation of the conference the need for traceability of the performance of equipment. Adding to that, Stan Barnett summarised that there is presently no large awareness for Accreditation and Quality Assurance of ultrasound equipment including the practitioners. Even for some applications using ultrasound, the responsibility for a proper application is moving away from the ultrasound profession. It seems obvious that the practitioner using ultrasound, either for diagnostic or for therapeutic purposes, needs to be a skilled person. This however is not always the reality, which may lead to diagnostic misinterpretations, errors in treatment or even tissue damaging situations. Three areas were identified as needing essential improvements: first the traceability of test-objects to characterise performance, second the accurate interpretation of the application results, including supplementary and more invasive methods, and finally the development of standards of competence.

In the presentation of Rob Hekkenberg this last subject was clearly an important topic. The Portable Power Standard under development would be suitable for conducting in-the-field proficiency testing of small companies, hospitals and manufacturers undertaking routine ultrasound physical-therapy device testing. By using this new device the user can show traceability of the calibration, the calibration process and the qualification of the testing staff.

A detector to monitor the onset of cavitation (CD) during power measurements as discussed by Mark Hodnett is surely a welcome addition to the measurement method. It can be expected that the method used in the CD will have a broader use than just the fields produced by physical therapy devices. Increasing fields to be covered by measurement methods are High Intensity ultrasound, low frequency therapeutic ultrasound, low power therapy and very diverging ultrasonic beams.

Specific problems in the measurement of High Intensity ultrasound were very clearly identified by Lawrence Crum. Especially the measurement using a small, scattering target can be seen as an interesting development.

Pyroelectricity is the electrical potential created in certain materials when they are heated. The use of this effect for power measurements has been studied. Bajram Zeqiri presented results that for certain applications showed a challenging possibility for a cheap and simple measurement set-up.

In general the presentations showed a clear need not only to prepare instrument performance traceability but also the need to prepare worldwide accepted qualification tools to qualify testing staff. It was questioned whether the WFUMB could play here a leading role as a lot of the needs for measurements are based on the concern for the safe application of ultrasound. The presentations also showed the need to develop improved measurement methods mainly in the area of several applications of therapeutic ultrasound. One question raised during the conference was: is there a need for higher accuracy of the measurements carried out? For some people higher accuracy is important but for others it is not needed. It is my opinion that methods should not only be developed for the standard laboratory level, but also for the “in-the-field”environment. To maintain confidence, traceability will then always be important.

Interaction with tissue – Dr Marvin C. Ziskin
This session included three excellent papers relating to some aspect of the interaction of ultrasound with tissue. The first paper entitled, “A study on premature ventricular contractions caused by ultrasound exposure with microbubbles using cultured ventricular muscle cells”. It was presented by Dr. N. Kudo. Premature ventricular contractions (PVCs) are a type of cardiac arrhythmia in which irritable ventricular cells fire before the normal electrical excitatory pulse arrives from the SA node of the Atria. When the excitatory pulse arrives the ventricles are in a refractory state and do not contract until the following pulse. Overall, there is no change in the number of heart beats. PVCs frequently
occur spontaneously in normal individuals, and are not considered significant. However, if very frequent, PVCs are hallmarks of an irritable heart, and one must be cautious about unduly stimulating the heart.

PVCs are one of the very few bioeffects noted as a consequence of ultrasound examinations using contrast agents, and therefore of much interest. In a very elegant experimental setup, Dr. Kudo and his associates show the effect of insonation of microbubbles adjacent to neo-natal rat ventricular myocytes in culture. The observation chamber was exposed to 1 MHz pulsed ultrasound with negative peak pressures of 0.1 – 0.6 MPa. In the cases where there was no attachment of the microbubbles to the myocytes, reduction in pulsation rate was rarely observed at 0.6 MPa and never at lower pressure amplitudes. When the microbubbles were attached, pulsations were stopped for periods of about 10 seconds when the pressure amplitudes were in the 0.3 – 0.6 MPa range. At high peak pressures, the membranes of myocytes with attached microbubbles were lyzed. All of this is consistent with inertial cavitation becoming the mechanism of action. Also, because of the very short “range of influence” of cavitation, the further the microbubble was from the myocytes the smaller was the effect. The direct observation of the interaction of ventricular muscle cells and insonated microbubbles provides a dramatic demonstration of a bioeffect of much clinical interest. It also effectively shows that cavitation is the mechanism of action.

The second paper, “Measurement of temperature elevation in tissue for the optimum and safe use of scalpel-type ultrasonic surgery devices” was given by Dr. Christian Koch. He described ultrasonic scalpel-like devices that are commonly used for cutting and coagulating tissue in surgical procedures. He also described measurement techniques for measuring the temperature elevation in vitro and in vivo when using these devices. An important part of this study was the histological evaluation permitting the conclusion that tissues nearer than 3 mm could be damaged in routine applications. The pathology looked for was coagulation necrosis which occurs very rapidly (within the first hour) following the injury. However, cell death can occur at lower temperature elevations by a process of apoptosis. Apoptotic cell death may not show up for 24 hours, so the actual extent of tissue damage might be underestimated in the present study.

The third paper, “Ultrasonic measurement of the temperature distribution due to absorption of ultrasound: potential and limitations” was presented by Dr. N. R. Miller. This paper responds to the need for a more convenient and accurate method of measuring the in situ temperature rise due to absorption of ultrasound. The measurement of body surface temperature is well accomplished today with infrared thermography. It is capable of 5 mK temperature resolution, spatial resolution limited only by the optical lens and the size of the detector array employed, and frame rates as high as 60 per second and higher. However, there is no convenient and accurate method for measuring the in situ temperature and its distribution. Therefore, if successful, the proposed technique would be extremely important. The technique is based on the principle that the speed of sound in a medium changes as a function of temperature, and that the heat-induced sound speed changes can be observed as shifts in the locations of corresponding echoes. The authors demonstrated that they were able to detect temperature elevations as small as 1 K in ex vivo bovine liver. They also reviewed the limitations of this technique. The effectiveness of this technique ultimately depends on our knowledge of the relationship of sound speed and temperature elevation in the tissues of the body. For any given subject or patient, this knowledge will be limited, and the success of this approach is certainly not assured. Nevertheless, this technique is certainly worthy of further study.

Novel measurement methods – Dr Bajram Zeqiri

This session comprised a range of presentations dealing with new and emerging measurement technologies. A recurring theme encountered throughout AMUM was a plea, primarily originating from equipment manufacturers, to develop simpler, lower cost, more rapid methods of ultrasonic metrology. In principle, this would then allow metrological methods to move away from conventional, hydrophone-based, techniques. In this respect, optical techniques, due to their potential to provide rapid, non-perturbing, absolute measurements of high spatial and temporal resolution, have long held considerable promise. Three presentations covered disparate optical applications. In an elegant paper, Kudo et al. presented a newly developed schlieren method, whose novelty lay in the way optical
images derived with and without ultrasound on were subtracted. Tomographical ultrasonic characterisation of air-borne ultrasound in the frequency range 40 kHz - 2 MHz, was presented by Almqvist et al. Theobald et al. presented work using a commercially available optically scanned vibrometer, operating at frequencies up to 1 MHz, where the displacement of a thin membrane, positioned in the acoustic field, was monitored. Example applications were presented which enabled reflected and scattered waves from objects to be visualised. This theme of simpler measurement methods, appropriate for more routine use, was the rationale behind a thermo-acoustic sensor described by Wilken and Reimann. Such a sensor held promises, they claimed, as an alternative ultrasound exposure measurement technique.

It was clear from AMUM that surgical and therapeutic application of ultrasound had a significant future, through the growth of techniques such as HIFU. With this, came an increasing need to be able to control the exposure to the applied field, preferably using in-vivo techniques. The paper by Fedele et al. described a new sensor designed to monitor effect of shock-waves on stone destruction during treatments. The technique was based on a passive acoustic emission technique which used a sensor to detect emissions from the shock-wave striking the stone. The importance of cavitation in such fields was the theme of the paper by Ohl et al., who used an optical method to determine the spatial and temporal evolution of cavitation activity.

Conventional calibration of hydrophones can generally be carried out up to frequencies of 40 MHz, although the capability is still restricted to a few very specialised laboratories. It was clear from many of the AMUM hydrophone related presentations, that calibrations at increasingly higher frequencies up to 100 MHz would become an increasing issue in future. The presentation by Shung et al., described a comparison of pulse-echo and hydrophone determined beam-widths, up to 60 MHz.

Challenges for therapeutic ultrasound – Dr Gérard Fleury
The therapeutic use of ultrasound has developed over the last 15 years as a promising alternative to surgery and X-ray treatment techniques. Compared to other approaches, the particular technique known as "High Intensity Focused Ultrasound" (HIFU) appears to be more precise to involve fewer side effects, and to enable the treatment to be repeated.

Great advances in knowledge and techniques have been made in the design of these devices and their use in treating patients. However, further progress is still possible and in fact necessary to improve control of the desired effects.

The development of this technique still involves many challenges for the scientific and medical community. Among the major challenges are the control of the radiated ultrasonic power, and control of the various physical and biological effects produced in the tissue.

In the first place, further progress can be made in characterizing the ultrasonic power delivered by HIFU devices. The measurement of ultrasonic power that can reach several hundred Watts for periods ranging from a few seconds to some tens of seconds poses difficult instrumental problems of technical feasibility, traceability and accuracy of measurements.

Another major problem is to characterize the radiated fields. Some therapeutic devices use magnetic resonance imaging (MRI) to control in real time the rise in temperature in the tissue, and this gives greater security when using these devices. However, at the stage of qualifying or verifying the instruments, the ultrasonic characteristics of the radiated field in a reference environment such as a water-bath, for example, must be able to be measured in a way that can be reproduced and standardized. It must be noted here that the radiated field can reach a local intensity of more than 10 kW per sq. cm during operating time. At such levels, conventional measuring devices, such as hydrophones, for example, are frequently destroyed, and, in addition, the measurements can be distorted by non-linear effects.

Confronted with these constraints, users and researchers have come up with solutions using well known means and techniques, such as low-level measurements extrapolated to a high level, or measurements taken over a reduced time, but these measurements are made on the basis of various hypotheses which are difficult to control accurately. The result is that the conditions of control of these measurements are still far from truly satisfactory.
Several techniques that are better adapted to measuring power are currently being studied in public and private laboratories. Strong support for research and for the improvement of measurement techniques at high power levels is required for researchers, manufacturers and users to have reliable and accurate tools and methods at their disposal as quickly as possible.

As well as the means and techniques of measurement, another major challenge in the future involves the development of appropriate standards in the field of therapeutic ultrasound. It is absolutely necessary that manufacturers of transducers and systems, and the certification bodies can all have at their disposal a common terminology, common reference methods, and appropriate guidelines for analyzing the performance of devices and the risks associated with using systems. In particular, the management of the risks associated with accidental breakdown, the ageing of components and human error when operating the devices must be taken into account. Advances can still be made in limiting and, if possible, technically preventing any risk from serious breakdown, and in giving operators reliable and real time information on any abnormal change in the critical parameters of the system they are using.

Finally, the entire community involved must be made aware of the specific aspects of this technique and in particular the risks associated with using devices that generate high ultrasonic power levels.

In conclusion, the development of therapeutic ultrasound promises to advance progress compared to other treatment techniques. However this development involves many challenges, in particular in the field of instrumentation and methods for power measurement. Progress must also be made to ensure that systems are always used optimally, and that they are appropriately verified, calibrated and maintained.

**Measurement and safety – Dr Stanley B Barnett**

This meeting of Advanced Metrology for Ultrasound in Medicine was remarkably successful in attracting a rich mixture of presentations and posters that dealt with developing new therapeutic applications and associated biological effects underlying physical interactions with tissue in addition to safety of diagnostic applications and the needs for Quality Assurance. The fundamental need for traceability of measurement was stressed and should be an essential consideration of future technological developments in ultrasound application and metrology. This is essential for both acoustic field measurement and the precision of equipment biometric devices, e.g. diagnostic callipers, measure of Doppler flow. For example, measurement of fetal nuchal translucency is reliant on accurate measurement of a few millimetres. Accurate biometric information is essential to avoid clinical misdiagnosis; potentially the greatest risk of harm to the patient. Clearly, traceability of user accreditation is also of fundamental importance although its traceability is somewhat more difficult. There is no standard on which to assess benchmarking equivalents of the multitude of accrediting bodies. In other words; Who assesses the assessors? Proper Quality Assurance protocols would include quantifiable measure of accreditation and systems for regular testing of equipment, particularly after software updates when altered machine operating settings may introduce changes to output conditions or measurement facility.

In the case of equipment output measurement for safety assessment, proper metrological traceability requires the measurement of a defined physical quantity, not something mathematically derived or based on assumptions about tissue composition and attenuation parameters. It is recognised that the only currently available indicator of bioeffects, the on-screen Output Display, is not a traceable quantity. Furthermore, it is generally accepted that TI and MIs are generally ignored in clinical practice. The lack of universal standards based on traceable metrology is a serious omission for safety matters and has created the opportunity for research and development by National Measurement Institutes. There is an opportunity to develop international standards based on measurement of physical quantities.

Interesting *in vitro* studies demonstrated some spectacular effects at the cellular level due to interaction with free radicals or when gas encapsulated echo-contrast agents were introduced into the sound field. Such studies are essential for the understanding of interactive mechanisms. Most *in vivo* therapeutic applications use high power, low frequency so that the ablative action results from a
combination of shockwave interaction, streaming and substantial localised tissue heating. Production of free radicals inevitably accompanies such interactions. The challenges to advanced metrology involve the development of technology to accurately measure acoustic field strength without perturbing the field while avoiding rapid deterioration of the sensing hydrophone. This is particularly important for HIFU applications for tumour ablation or blood vessel coagulation through acoustic haemostasis. Ideally, diagnostic and therapeutic systems may be combined to develop ultrasound image-guided therapy.

Challenges to metrology arise from a number of areas. Some of those identified during this conference include:

- Technical complexity, including solving non-linearity problems,
- Robust measurement systems; not degraded by high intensity fields,
- Traceability of measurement,
- Traceability of accreditation for QA,
- Responsibility to calibrate and biometric devices and image quality,
- Publication of international standards based on traceable metric,
- Effective monitoring of therapeutic effects in tissue to ensure optimum treatment.

This AMUM 2004 conference has set the stage for the development of measurement methods to meet these challenges in future years.

**Performance of diagnostic equipment – Dr John Abbott**

Four presentations were prepared for this session. Three of the posters touch on the issue of the measurement of performance criteria of diagnostic ultrasound equipment. The fourth reports on an alternative to Doppler processing for detecting microvascular flow in high-noise/low-signal applications.

The definition of objective, universal, and widely accepted performance criteria for diagnostic ultrasound equipment has been and continues to be a highly sought after goal. A well defined set of standard performance criteria would allow meaningful side-by-side comparison of equipment and a consistent means for ensuring system quality over time – if only as a simply guidance for when to call for service. At present, there are no widely accepted means or standards available to either the manufacturer or the end user to define performance correlated to diagnostic image quality. As a result each site, manufacturer and user alike, tends to develop different procedures and parameters to establish an acceptable level of confidence that their system is operating within expected norms.

The three performance posters of this session discuss efforts to develop phantom based measurement tools and processes, each describing a different performance metric: Point Spread Function, Perfusion, and Vessel Wall Tracking. A common thread in these reports is the fundamental difficulty encountered in relating the results of their *in vitro* phantom measurements to *in vivo* conditions. The last sentence in the Ramnarine, Kanber & Paneri poster accurately summarizes the challenges before the metrology community in developing common performance measurement procedures for diagnostic ultrasound imaging equipment:

“This study highlights important considerations and limitations in the application of test phantoms for realistic measurement of … performance.”

The fourth poster by Chung, Prager, Gee & Treece differs from the first three in that it addresses a signal processing alternative to the classic Doppler shift technique for detecting flow. The authors describe their results and limitations in applying the use of image-based decorrelation techniques as an alternative means for measuring flow in high-frequency/high-resolution microvascular flow
applications. This poster reports results similar to those observed at lower frequency applications by earlier investigators\(^1\).

**Field modelling – Dr Andrew Hurell**

A range of analytical or numerical techniques are available to model acoustic fields and this poster session represented a range of diverse methods. The first two papers used two of the most popular numerical methods (finite/boundary elements and finite differences respectively) whilst the third followed an analytical approach. Although the contributions adopted different methods to achieve their goals, each clearly indicated the benefit that accurate field modelling offers.

Historically, modelling the complex nature of the generation of a stress wave within a complex piezoelectric device (such as a foetal heart monitor [FHM]), and the acoustic field it generates has not been accurate enough to permit optimisation of transducer design. This study by Gélat into *Prediction of the Acoustic Field Produced by a Foetal Heart Monitor using the Finite Element and Boundary Element Methods* started by developing a combined finite/boundary element model for a single crystal transducer. Differences between modelled and experimental data were observed, and an iterative modelling method was implemented to refine the estimates of material parameters used. Once good agreement between experimental and modelled data was obtained for a single element transducer, the principle of superposition was exploited to predict the field produced by a complex seven-element FHM. The results of this combined model were shown to be highly consistent with the pressure distribution obtained experimentally by hydrophone mapping the field of a real device. This is of significant metrological importance since the accuracy of the predictions obtained in these simulations offers the possibility for such models to cross-validate experimental measurements.

Pulsed ultrasound is gaining increased popularity as a therapy to encourage bone fracture healing however the optimal position for the ultrasonic source is unclear. This study by White of *Modelling the Propagation of Ultrasound in the Knee* aims to improve the understanding of the underlying physics governing ultrasonic propagation within the knee joint, but given the complex geometry of this structure, a simplifying geometry was used. Initially this simplified problem was modelled with a commercial finite difference package, then replicated experimentally and the results of the two processes were compared. A good agreement between experimental and modelled results was obtained when then “pseudo-receiver” (required by the finite difference model) was the same size as the receiving element of the hydrophone. The model clearly indicated a focussing effect caused by the curved inner surface of the knee joint. Further work is ongoing to determine whether the model is capable of accurate simulations when parameters more representative of biological tissue of the knee are used. If this proves to be the case it is hoped that this study may be able to optimise treatment position for pulsed ultrasound therapy.

Goldstein’s poster on *Unfocussed Beam Patterns in Non-Attenuating and Attenuating Fluids* undertook a fundamental re-evaluation of the underlying assumptions used in the derivation of the conventional circular plane piston model, and addresses an erroneous simplification that is present if the original solution. A single integral solution for corrected version of the field produced by a circular piston is presented. This new solution may present significant differences in the near field region but is found to converge with the more conventional solution in the far field. This new formulation is also extended to consider propagation within attenuating media. It is found that conventional scaling methods of the form \(e^{-\alpha z}\) are sometimes insufficient, and an alternative formulation to describe lossy propagation is presented. Given that many standards implicitly rely upon the circular plane piston model (e.g. in the determination of effective radius) or on simple exponential attenuation factors (e.g. derating of acoustic parameters), the implications of this poster need careful examination.

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\(^1\) L.N. Bohs, B.J. Geiman, M.E. Anderson, S.C. Gebhart and G.E. Trahey, *Speckle tracking for multi-dimensional flow estimation*, *Ultrasonics*, 38, pp. 369-375, 2000.