Wednesday, May 10

8:30–9:30	**Breakfast**	
9:30–9:40	**Welcome message**	
9:40–10:20	**Karl Jousten** PTB, Germany	Measurement standards for ultra- and extreme-high vacuum
10:20–10:40	**Coffee break**	
10:40–11:30	**Matthias Bernien** PTB, Germany	Comparison of a cold atom and a continuous expansion standard
11:30–12:00	**Panel discussion** Jousten, Bernien, Eckel, Barker	What is required to create an atomic standard and why is this important?
12:00–13:30	**Lunch**	
13:30–14:20	**Daniel Barker** NIST, USA	Progress toward field-deployable, cold-atom vacuum sensors
14:20–15:10	**Stephen Eckel** NIST, USA	Accurate, model-independent measurements of the loss rate coefficients for the cold atom vacuum standard
15:10–15:40	**Recap discussion**	
15:40–17:30	**Lab tour**	

Thursday, May 11

9:30–10:20	**Jacek Kłos** Univ. of Maryland, USA	Calculations of background gas collision-induced losses and their uncertainties in cold-atom trap sensors
10:20–10:40	**Coffee break**	
10:40–11:30	**Pinrui Shen** UBC, Canada	Development of a Cold Atom Pressure Standard
11:30–12:00	**Jim Booth** BCIT, Canada	Quantum Diffractive Collision Universality and its Limits
12:00–13:30	**Lunch**	

Friday, May 12

8:30–9:30	**Breakfast**	
9:30–9:45	**Katherine Herperger** UBC, Canada	Effects of Rb+H_2 Interaction Potential Uncertainty on Collision Observables

9:45–10:20	**Panel discussion** Kłos, Krems, Herperger, Barker, Bernien, Booth	What are the error bars for theory/calibration universality?
10:20–10:40	**Coffee break**	
10:40–11:05	**Riley Stewart** UBC, Canada	Measurement of Rb-Rb van der Waals coefficient via quantum diffractive universality
11:05–11:30	**Avinash Deshmukh** UBC, Canada	A Model of Quantum Diffractive Heating
11:30–12:00	**Erik Frieling** UBC, Canada	Cross-calibration of cold atom pressure sensors based ^{6}Li and ^{87}Rb atoms
12:00–13:30	**Lunch**	
13:30–13:55	**Perrin Waldock** UBC, Canada	Building a transportable cold atom pressure standard: Mistakes and lessons learned
13:55–14:20	**Jens Grosse** ZARM, Germany	Towards compact and ruggedized high-performance cold atom sensors
14:20–14:45	**Panel discussion** Eckel, Shen, Madison, Frieling, Stewart	What are sources of measurement error and uncertainty for the atom sensor?
14:45–15:20	**Tom Rubin** PTB, Germany	Cold-Atom-Standards and Refractometers - Challenges, Benefits, and potential Common Pressure Ranges
15:20–16:10	**Panel discussion** Rubin, Eckel, Krems, Madison	Roadmap paper discussion: what is the future of the CAVS?
16:10–16:30	**Closing remarks**	

Measurement standards for ultra- and extreme-high vacuum

Karl Jousten[1]

[1] *Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany*

When measuring a physical quantity such as vacuum pressure, it is important that the instrument's indication conforms to the International System of Units (SI). National measurement standards and a carefully managed calibration system ensure this through the traceability of the instrument to the national measurement standard. The quantity realized by a measurement standard must be described by a fully understood model equation. Each quantity in this equation must have a known value with a known uncertainty. The international "Guide to the expression of uncertainty in measurement" (GUM) describes how the uncertainties of these known quantities propagate into the final uncertainty of the realized quantity. Current vacuum pressure measurement standards, spanning 14 decades from 100 kPa down to 10^{-9} Pa, are based on measuring pressure as a force per area near 100 kPa and scaling it down by either the so-called static or continuous expansion method. In the past, the molecular beam method was also used for pressures below 10^{-7} Pa. All these methods rely on secondary standards calibrated at much higher pressures. In this sense, the current realization of vacuum pressure can be compared to climbing down a ladder. With each step down the uncertainty increases and a significant contribution to the uncertainty is the instability and calibration uncertainty of the secondary standard used. Atomic-based measurement standards for ultra-high and extreme high vacuum can break this logic through a model equation that does not require a quantity to be measured by a secondary standard. The talk will describe what is needed to qualify as a measurement standard as such, and describe current and past measurement standards for vacuum pressures, particularly for ultra- and extremely-high vacuum.

Comparison of a cold atom and a continuous expansion standard

Matthias Bernien[1], Kirk Madison[2], Perrin Waldock[2], Thomas Bock[1], Karl Jousten[1]

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Primary standards based on cold atoms promise a new route to the realization of the pascal in the ultra-high vacuum range by measuring the loss rate induced by collisions with gas molecules. To establish such standards comparisons to conventional standards must be carried out in order to validate their working principle. Currently, the University of British Columbia and the Physikalisch-Technische Bundesanstalt are carrying out a comparison of a mobile standard based on cold atoms and a continuous expansion system. The comparison will cover different gases like e.g., N_2, Ar, Ne, Kr, Xe and H_2 in the pressure range from 3×10^{-8} Pa to 1×10^{-6} Pa.

The presentation will detail the working principle of the continuous expansion method as well as the design of PTB's continuous expansion system and its fixed pressure, variable volume flowmeter. The uncertainty budget will be discussed as well as the practical implications that arise due to presence of the cold atom system. Unlike a secondary standard, like e.g., an ionization vacuum gauge, comparing the cold atom standard to a primary standard provides lower uncertainties and a higher flexibility on the gas species, as no gas type dependent calibration is needed for the continuous expansion system. The obtained values of the collision cross sections will serve as a means to validate the concept of universality of quantum diffractive collisions, but they may also be used just as input parameters for pressure measurements of the gas types investigated.

Progress toward field-deployable, cold-atom vacuum sensors

Daniel S. Barker[1], Stephen Eckel[1], James A. Fedchak[1], Julia Scherschligt[1], Jacek Klos[2], Eite Tiesinga[2,3]

[1] *Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, MD, USA*

[2] *Joint Quantum Institute, University of Maryland, College Park, MD, USA*

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We introduce the cold-atom-based vacuum metrology program at NIST. The experimental effort consists of two cold-atom vacuum standards (CAVS): a laboratory-scale standard (l-CAVS) and two portable standards (p-CAVS). Both l-CAVS and p-CAVS are quantum-based standards that use *a priori* scattering calculations to convert a measured loss rate of cold atoms from a conservative trap into a background gas pressure. We describe operation and initial tests of the l-CAVS and p-CAVS. In particular, we show that, when attached to the same vacuum chamber, the two p-CAVS measure the same pressure within their uncertainties. Finally, we compare compare the utility of p-CAVS to that of an ionization gauge and identify applications where quantum-based vacuum standards may be preferable to legacy gauges.

Towards compact and ruggedized high-performance cold atom sensors

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This talk will present an overview of the sensors under development at the University of Bremen, Germany. These include sensors for fundamental physics research as well as sensors for inertial sensing. Fundamental physics sensors are envisioned for the test of the weak equivalence principle on board the International Space Station or on board sounding rockets in the projects Bose-Einstein Condensates and Cold Atoms Laboratory (BECCAL) and Matterwave Interferometry in Microgravity (MAIUS). For inertial sensing a hybrid sensor is under development. For all projects an overview of the design and objectives will be given.

In addition, our current activities towards a cold atom vacuum sensor/standard will be presented. Here the focus will be on synergies with running and completed projects, to achieve ruggedized and transportable vacuum standards. This talk closes with a glimpse on future applications and possibilities of commercialization in Germany.

Accurate, model-independent measurements of the loss rate coefficients for the cold atom vacuum standard

Stephen Eckel[1], Daniel S. Barker[1], James A. Fedchak[1], Jacek Kłos[2], Julia Scherschligt[1], Abrar A. Sheikh[1], Eite Tiesinga[1], Stephen P. Eckel[1]

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We present measurements of thermalized collisional rate coefficients for ultra-cold ^{7}Li and ^{87}Rb colliding with room-temperature He, Ne, N_2, Ar, Kr, and Xe. In our experiments, a combined flowmeter and dynamic expansion system, a vacuum metrology standard, is used to set a known number density for the room-temperature background gas in the vicinity of the magnetically trapped ^{7}Li or ^{87}Rb clouds. Each collision with a background atom or molecule removes a ^{7}Li or ^{87}Rb atom from its trap and the change in the atom loss rate with background gas density is used to determine the thermalized loss rate coefficients with fractional standard uncertainties better than 1.6 % for ^{7}Li and 2.7 % for ^{87}Rb. We find consistency—a degree of equivalence of less than one—between the measurements and recent quantum-scattering calculations of the loss rate coefficients [J. Kłos and E. Tiesinga, *J. Chem. Phys.* **158**, 014308 (2023)], with the exception of the loss rate coefficient for both ^{7}Li and ^{87}Rb colliding with Ar. Nevertheless, the agreement between theory and experiment for all other studied systems provides validation that a quantum-based measurement of vacuum pressure using cold atoms also serves as a primary standard for vacuum pressure, which we refer to as the cold-atom vacuum standard.

Calculations of background gas collision-induced losses and their uncertainties in cold-atom trap sensors

Jacek Kłos[1], Eite Tiesinga[2]

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There is a need to establish a new pressure standard that is based on reproducible quantum phenomena. New apparatuses and portable devices are being developed by Cold-Atom-Vacuum-Standards (CAVS) group at the National Institute of Science and Technology[1]. These new devices rely on clouds of magneto-optically trapped and laser-cooled alkali atoms (Li(^{2}S) or Rb(^{2}S)) at micro-Kelvin temperatures. They will allow for measurements of extremely low Ultra-High-Vacuum pressures, for which current pressure sensors are not reliable. Trapped cold atoms come into contact with residual room-temperature atomic and molecular gases in the vacuum system, which results in cold atom losses. Therefore, one needs detailed knowledge of collisional rate coefficients. We present results of quantum scattering calculations using high-quality *ab initio* potentials computed with the current gold-standard coupled-cluster method. We computed total (elastic and inelastic) and glancing rate coefficients between cold ^{7}Li/^{87}Rb and room-temperature background gases such as: noble gases, molecular nitrogen and hydrogen[2]. The quantum scattering calculations are performed by solving quantum close-coupling scattering equations for collision energies necessary to converge rate coefficients up to a temperature of 400 K. For all molecular systems considered we compared the quantum rate coefficients to a semiclassical model. The computed loss-, and glancing rate coefficient are consistent with recent experimental results[3]. We also estimated uncertainties of the elastic rate coefficients associated with the error in the *ab initio* potentials and relativistic effects. We will also present comparisons to a Universal Quantum Diffraction Collision model and ongoing efforts to estimate loss-rates for new background gases, such as CO_2, $CO(^1\Sigma)$ and $O_2(^3\Sigma_g^-)$.

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[1] L. Ehinger, B. P. Acharya, D. S. Barker, J. A. Fedchak,J. Scherschligt, E, Tiesinga, S. Eckel, AVS Quantum Sci. **4**, 034403 (2022)

[2] J. Kłos and E. Tiesinga J. Chem. Phys. **158**, 014308 (2023)

[3] D. S. Barker, J. A. Fedchak, J. Kłos, J. Scherschligt, A. A. Sheikh, E. Tiesinga, S. P. Eckel, arXiv:2302.12143v1, submitted to AVS Quantum (2023)

Development of a Cold Atom Pressure Standard

Pinrui Shen[1], Riley A. Stewart[1], Avinash Deshmukh[1], Roman V. Krems[2],3 James L. Booth[4], Kirk W. Madison[1]

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In this talk, we report the developments of the cold atom based pressure standard for the high- and ultra-high vacuum (UHV) regimes, $< 10^{-6}$ Pa. This standard is a fundamentally new approach to vacuum metrology as it is based on a universal law governing quantum diffractive collisions between particles. We show that a measurement of trap loss rate versus trap depth provides the velocity averaged total collision cross-section, $\langle \sigma_{\text{tot}} v \rangle$, - the only parameter required to quantify the pressure of background particles given a measurement of the collision rate with a sensor atom. This new quantum measurement standard is fully empirical, based on unchanging and fundamental atomic constants. We demonstrate, using a sensor ensemble of ^{87}Rb atoms, that this new quantum pressure standard can be applied to gases of both atomic species (He, Ar, and Xe) and molecular species (N_2, CO_2, and H_2), surpassing the scope of existing orifice flow pressure standards. The accuracy of this new standard was also verified by comparing it with an N_2 calibrated ionization gauge traced back to an orifice flow standard. They agree within 0.5%. A complete uncertainty analysis of this cold atom pressure standard is provided here. Using this universal law, we can precisely measure the total collision cross-section $\langle \sigma_{\text{tot}} v \rangle$ for the collision system of interest. As an example, we show a precision measurement of $\langle \sigma_{\text{tot}} v \rangle$ for collisions between Rb and Ar. We also analyze the limitions of this universal law and outlook the work need to be done to improve this unversality method. Finally, We demonstrate the use of a magneto-optical trap (MOT) as a transfer pressure standard to extend the operational range of the cold atom pressure standard by a factor of 100, from $P < 10^{-7}$ Pa to include pressures up to $P < 10^{-5}$ Pa.

Quantum Diffractive Collision Universality and its Limits

James Booth[1], Pinrui Shen[2], Riley Stewart[2], Erik Frieling[2], Katherine Herperger[3], Avinash Deshmukh[2], Roman Krems[3], and Kirk Madison[2]

[1] *Physics Department, BCIT*

[2] *Department of Physics and Astonomy, UBC*

[3] *Department of Chemistry, UBC*

In our work to realize a cold atom-based pressure standard, we describe the elastic collision induced loss rate of atoms from a shallow magnetic trap as, $\Gamma_{\text{loss}} = n \langle \sigma_{\text{loss}} v \rangle$, where n is the density of the background gas impinging on the trapped atoms, and $\langle \sigma_{\text{loss}} v \rangle$, is the trap-depth dependent loss rate coefficient characterizing the collision process. The coefficient has to be determined *a priori*, usually through calibration against another standard, or by computation from first principles. We have found an alternative approach which is applicable to many collision partners: universality of the quantum diffractive collisions. These collisions, which transfer little energy and momentum to the trapped atoms, are primarily responsible for shallow trap loss and heating of the trapped ensemble. In this talk I will present a brief overview of the character of the universality we expect and have observed for losses of cold atoms from shallow magnetic traps. In particular I will outline the origin of this universality in the long range van der Waals interaction characterized as $V(R) = -C_6/R^6$, the role that averaging the over the Maxwell-Boltzmann distribution of the room temperature collision partner has on the observed loss rate coefficient, and how shallow interatomic potentials and low C_6 coefficients contribute to the break down of this universality.

Time permitting, I will discuss our trail of *ab initio* computations leading to the deduction of the universality, computations based on more realistic inter-species collision models, and the comparison with other work. Of note is the apparent persistence of the universal cumulative energy transfer distribution function, which we refer to as p_{QDU}, across computational models and how this might point to more refined descriptions of the collision-induced loss and heating processes for the trapped atoms.

Effects of Rb+H_2 Interaction Potential Uncertainty on Collision Observables

Katherine R. Herperger[1,3], Roman V. Krems[2,3]

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Quantum Diffraction Universality (QDU) is a law that allows the experimental determination of the velocity averaged total collision cross-section $\langle \sigma_{\mathrm{tot}} v \rangle$ between an impinging gas and a nearly stationary sensor gas in high vacuum. This law allows one to bypass time-intensive theoretical scattering calculations for $\langle \sigma_{\mathrm{tot}} v \rangle$. A key feature of QDU is the insensitivity of $\langle \sigma_{\mathrm{tot}} v \rangle$ to changes in the short-range interaction potential. Thus, the sensitivity of this collision observable to the underlying interaction potential can be employed as a quantitative measure of whether a system adheres to QDU. Here, we explore the non-universal system Rb+H_2. We detail how to represent the interaction potential of these collision partners, and describe a method to vary only the depth and position of the minimum of the interaction potential without affecting the long-range potential. Finally, we illustrate how $\langle \sigma_{\mathrm{tot}} v \rangle$ varies in response to these changes. By analyzing the trends in this system, we have the opportunity to provide an error estimate on the rate coefficient $\langle \sigma_{\mathrm{tot}} v \rangle$. We expect $\langle \sigma_{\mathrm{tot}} v \rangle$ to have a high amount of error for the Rb+H_2 system, while the rate coefficient of a Universal system should be relatively unaffected.

Measurement of Rb-Rb van der Waals coefficient via quantum diffractive universality

Riley A. Stewart[1], Pinrui Shen[1], James L. Booth[2], Kirk W. Madison[1]

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Collisions between trapped atoms or trapped molecules with room-temperature particles in the surrounding vacuum induce loss of the trapped population at a rate proportional to the density of the background gas particles. The total velocity-averaged loss-rate coefficient $\langle \sigma_{\mathrm{tot}} v \rangle$ for such collisions and the variation of the loss rate with trap depth has been shown to depend only on the long-range interaction potential between the collision partners. This collision universality was previously used to realize a self-calibrating, atom-based, primary pressure standard and was validated by indirect comparison with an orifice flow standard. Ensemble heating and intra-trap collisions modify the measured loss rate, and we elaborate on schemes to mitigate and correct for these effects to isolate losses due to background collisions. Doing so, we use collision universality to measure $\langle \sigma_{\mathrm{tot}} v \rangle = 6.44(11)(5) \times 10^{-15}$ m^3/s for Rb-Rb collisions and deduce the corresponding $C_6 = 4688(198)(95) E_h \mathrm{a}_0^6$, in agreement with predictions based upon *ab initio* calculated and previously measured C_6 values.

A Model of Quantum Diffractive Heating

Avinash Deshmukh[1], Pinrui Shen[1], Riley A. Stewart[1], Kirk W. Madison[1], and James L. Booth[2]

[1] *Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, B.C., V6T 1Z1, Canada*

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One of the major challenges in making measurements of trapped particles at nonzero trap depth is that collisions with the background cause the energy distribution of the trapped ensemble to change in time. We propose a model that describes the evolution of the energy distribution of trapped Rubidium atoms subject to a thermal Argon background, and we show that it agrees with experimental measurements. We then demonstrate that this law obeys Quantum Diffractive Universality for several species; by rescaling the energy, the model can be used to describe experimental energy distribution measurements for a Rubidium ensemble subject to other background gases. We use this energy scale to extract the velocity averaged cross-section $\langle \sigma(v) v \rangle$ and compare the results to those obtained from quantum scattering calculations.

Cross-calibration of cold atom pressure sensors based ^{6}Li and ^{87}Rb atoms

Erik Frieling[1], Riley A. Stewart[1], Denis Uhland[1], Kirk W. Madison[1], and James L. Booth[2]

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A pressure sensor based on quantum diffractive background gas collisions with trapped ultracold atomic ensembles has been proposed as a new primary pressure standard in the UHV and XHV regime. This sensor relies on converting the loss rate of atoms from the trap Γ into a measurement of the background gas density n using the relation $\Gamma = n\langle\sigma v\rangle_{\text{loss}}$,where $\langle\sigma v\rangle_{\text{loss}}$ is the velocity averaged loss cross section. The optimal choice of sensor atom for a particular application may vary, and since accurate knowlege of $\langle\sigma v\rangle_{\text{loss}}$ is a requirement for the operation of the sensor, cross-calibration of different sensor atom species is highly relevant for the future of a cold atom vacuum standard (CAVS).

We present the first cross-calibration measurements of $\langle\sigma v\rangle_{\text{loss}}$ for two different atomic species (^{6}Li and ^{87}Rb), and compare the results to quantum scattering calculations and previous measurements. Since we are able to trap both sensor atom species at at the same location, we can determine $R = \langle\sigma v\rangle^{\text{Li}}_{\text{loss}}/\langle\sigma v\rangle^{\text{Rb}}_{\text{loss}}$ without requiring any knowlege of the actual pressure.

We present preliminary results for collisions with Ar, Ne, and H_2 and compare them to quantum scattering calculations and a previous experimental determination of $\langle\sigma v\rangle_{\text{loss}}$ for ^{6}Li and ^{87}Rb by comparison to an orifice flow standard. We show deviations from both previous experiments and theory, highlighting the need for further work to more accurately determine $\langle\sigma v\rangle_{\text{loss}}$.

We also discuss limitations of the loss rate determination and the need for further work to better understand how inter-trap dynamics affect the loss rate measurement.

Building a transportable cold atom pressure standard: Mistakes and lessons learned

Perrin Waldock[1], James L. Booth[2], Kirk W. Madison[1]

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Ultra-high vacuum metrology is on the cusp of a revolution. For decades, ion gauges have been used to measure vacuum pressure, and they are calibrated for specific gases using dynamic expansion standards. Recently, methods of measuring pressure using quantum effects have been developed, such as measuring the loss rate of ultracold atoms from a conservative potential. This method hinges on understanding the velocity-averaged collision loss cross section between the trapped atoms and the background species.

This cross section can be found by (a) calculating it from a potential energy surface found using ab initio methods (b) measuring it for a known pressure of a known species generated using a pressure standard or (c) fitted for using quantum diffractive universality.

We developed a version of a cold atom pressure standard that can trap 85Rb or 87Rb. It can be transported to existing standards around the world. It will allow us to compare the cross sections we found using method (c) to cross sections we measure using (b).

This talk will explore the consequences of the design decisions made and outline our future plans for the apparatus.

Towards compact and ruggedized high-performance cold atom sensors

Jens Grosse[1], Jaspar Halbey[1]

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[2] *Center of Applied Space Technology and Microgravity (ZARM), University of Bremen*, Am Fallturm 2, 28359 Bremen, Germany

This talk will present an overview of the sensors under development at the University of Bremen, Germany. These include sensors for fundamental physics research as well as sensors for inertial sensing. Fundamental physics sensors are envisioned for the test of the weak equivalence principle on board the International Space Station or on board sounding rockets in the projects Bose-Einstein Condensates and Cold Atoms Laboratory (BECCAL) and Matterwave Interferometry in Microgravity (MAIUS). For inertial sensing a hybrid sensor is under development. For all projects an overview of the design and objectives will be given.

In addition, our current activities towards a cold atom vacuum sensor/standard will be presented. Here the focus will be on synergies with running and completed projects, to achieve ruggedized and transportable vacuum standards. This talk closes with a glimpse on future applications and possibilities of commercialization in Germany.

Cold-Atom-Standards and Refractometers - Challenges, Benefits, and potential Common Pressure Ranges

Tom Rubin[1]

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With the redefinition of the SI in 2019, density-based methods for the realization of the pascal came into focus vacuum metrology. Refractometry with ultra-pure helium, argon or nitrogen has proven to be particularly promising for this purpose for the pressure range from 1 Pa to 100 kPa. For example, in the QuantumPascal project, uncertainties of 10 ppm and 10 mPa (geometric sum, k=2) have already been achieved. In the follow-up project MQB-Pascal, the goal is, among other things, to further reduce the pressure-independent contribution to this uncertainty. Thus, the pressure range that can be meaningfully addressed with refractometry can be extended to smaller pressures.

In contrast, Cold-Atom-Vacuum-Standards (CAVSs) are optimal for much lower pressures, typically in the UHV range. This talk discusses the lower limit of pressures that still can be realistically measurable by refractometry according to the currently available state of the art to have an overlapping pressure range with respect to CAVSs. In addition, the potential main benefits, such as the possibility of comparing CAVS to another independent and 'noninvasive' technique (potentially even with some spatial resolution) will be pointed out.