

# Metrological Evaluation and Traceability of Intravascular Pressure Guidewire Measurements in Interventional Cardiology

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## Abstract

Intravascular pressure guidewires are widely used in interventional cardiology to derive indices such as fractional flow reserve and instantaneous wave-free ratio, yet their metrological characterization and traceability are not fully established. This work presents a laboratory-based approach for the metrological evaluation of intravascular pressure guidewire measurements that is independent of clinical data. A complete measurement chain is analysed, from national or international pressure standards to the guidewire output, and static and dynamic measurement models are formulated. Traceable static calibration systems and a pulsatile fluidic simulation loop are developed to assess linearity, hysteresis, repeatability, dynamic response and stability. The influences of temperature, static drift, data acquisition parameters and signal-processing algorithms are systematically investigated. Based on these studies, a comprehensive uncertainty budget is constructed and combined standard and expanded uncertainties are obtained under representative operating conditions. A traceability framework and a practical laboratory calibration procedure are finally proposed, providing a technically sound basis for future guidelines and standardization activities related to intravascular pressure measurements in interventional cardiology.

**Keywords: intravascular pressure guidewire; fractional flow reserve (FFR); measurement uncertainty; metrological traceability; static and dynamic calibration; fluidic simulation loop**

## **I. Research Background and Significance**

### **1.1 Clinical background**

Fractional flow reserve and instantaneous wave free ratio have become central indices for the functional assessment of coronary artery stenosis[1-7]. They are now incorporated in many clinical decision pathways and are routinely used to determine whether a lesion requires stent implantation, which vessel segment should be treated, and whether an intervention has achieved a satisfactory functional result. Both indices are derived from simultaneous measurements of aortic pressure and distal coronary pressure and are expressed as ratios of these pressures over specific parts of the cardiac cycle[1-3,7]. In this context, the intravascular pressure guidewire is the primary device that acquires the distal coronary pressure signal. It sits at the very beginning of the information chain that leads from a physical haemodynamic state to a numerical decision index and, ultimately, to a therapeutic decision. Small systematic errors or instabilities in the pressure readings, especially when values are close to clinical decision thresholds, can directly translate into misclassification of lesion severity. This may lead to unnecessary stent implantation in functionally non significant lesions or, conversely, to under treatment of haemodynamically significant stenoses, with potential consequences for patient outcomes and healthcare costs.

### **1.2 Current status and problems**

In current practice, however, the metrological properties of intravascular pressure guidewires are only partially characterized and are not usually documented in a way that allows independent verification[9-12]. Most guidewires are delivered with a

manufacturer specific factory calibration that focuses on internal production tolerances and quality control. Such calibration is typically performed under static or quasi static conditions, at a limited number of pressure points and at a reference temperature close to room temperature. It is rarely designed to be reproduced in external laboratories, and the traceability route to national or international pressure standards is often not transparently described. There is at present no widely accepted, vendor independent laboratory procedure for the calibration of intravascular pressure guidewires, nor are there harmonized requirements for key performance parameters such as linearity, hysteresis, long term stability or dynamic response[12-14,19]. Furthermore, the influence of realistic dynamic pressure waveforms, temperature variation around body temperature, long term drift and specific signal processing choices is usually not assessed in a dedicated metrological framework[14-21,25]. Instead, their combined effect is often inferred indirectly from clinical outcome studies or registry data, which are not designed to isolate and quantify individual measurement influences. From the viewpoint of measurement science, this situation is not sufficient to guarantee comparability and long term stability of the pressure values used in interventional cardiology across different devices, laboratories and time periods.

### **1.3 Significance from the viewpoint of metrology**

Metrology offers a structured and well established framework to address these gaps. By explicitly treating the intravascular pressure guidewire as a measuring instrument, it becomes possible to define a complete measurement chain from primary standards to clinical readouts, to analyse the value transfer at each stage, and to formulate measurement models that link the measurand (the true pressure) to the observed output signals. Within this framework, uncertainty budgets can be constructed under clearly specified conditions, using recognized concepts such as type A and type B evaluation of uncertainty and the combination of standard uncertainties[22,23]. A laboratory based approach makes it feasible to establish full traceability to national or

international pressure standards through calibrated reference sensors and pressure generation systems[15,16,19,21,25]. It also enables systematic and controlled variation of influencing quantities, such as temperature, waveform shape and frequency content, static and dynamic range, sampling conditions and data processing parameters. These quantities can be varied one at a time or in defined combinations, and their influence can be quantified with repeatable experiments rather than inferred from complex clinical environments. In addition, the same framework allows a consistent comparison of different guidewire models and manufacturers using common reference conditions[12-14].

The present work adopts this metrological perspective and applies it specifically to intravascular pressure guidewire measurements. It aims to establish a technically sound basis for the calibration and traceability of these devices using only physical simulation systems that emulate the relevant pressure conditions. All tests are carried out in dedicated laboratory setups that include static pressure generation systems and pulsatile fluidic loops, without human or animal participation and without the use of clinical records or personal data. This strict focus on physical and instrumental aspects ensures that the study remains within the domain of engineering and measurement science, while still addressing questions that are directly relevant for the reliability and consistency of functional coronary indices in clinical use. By clarifying the measurement chain, quantifying uncertainty contributions and proposing a practical calibration and traceability framework, the work is expected to form a bridge between basic metrology and routine interventional cardiology, and to provide a foundation for future guidelines and standardization activities concerning intravascular pressure measurements.

## **II. Research Objectives**

### **2.1 Overall objective**

The overall objective of this study is to establish a rigorous metrological evaluation and traceability framework for intravascular pressure guidewires used in interventional cardiology. In this framework the guidewire is treated explicitly as a measuring instrument whose output must be linked, through a documented chain of comparisons, to national or international pressure standards. Both static and dynamic performance characteristics are evaluated, and the associated measurement uncertainties are quantified under operating conditions that reflect typical use in functional coronary assessment. The ultimate aim is to provide a solid technical basis that can support future standardization, inter laboratory comparability and long term quality control of intravascular pressure measurements.

## **2.2 Specific objectives**

To achieve this overall objective, several specific objectives are defined and pursued in a coordinated way.

First, the study seeks to construct traceable static pressure calibration systems and pulsatile fluidic simulation loops that can reproduce, in a controlled laboratory environment, the pressure levels and waveforms encountered in coronary arteries. The static calibration systems will be designed to generate stable pressure steps and plateaus over the relevant range, using devices such as piston gauges, precision pressure controllers and water column arrangements. The dynamic part will rely on closed fluidic loops with circulation pumps, compliant tubing and adjustable resistances to generate cardiac like pressure waveforms. In both cases, traceability to national or international standards will be ensured by integrating calibrated reference pressure sensors and by documenting the full chain of value transfer.

Second, the study aims to develop static and dynamic measurement models that are specifically tailored to intravascular pressure guidewires. For static conditions, the models will describe the relationship between the guidewire output signal and the applied pressure, while explicitly including the influence of ambient or medium

temperature, zero offsets and possible drift with time. For dynamic conditions, the models will represent the time dependent pressure in terms of the time varying guidewire output together with the overall system response, which includes the sensor, the fluidic loop and the data acquisition chain. These models will form the basis for quantitative evaluation of measurement errors and for the propagation of uncertainty in both the time domain and the frequency domain.

Third, the study will systematically analyse the influence of key factors on the measurement results, including temperature, drift, dynamic response, data acquisition and signal processing algorithms. Temperature dependence will be investigated by repeating calibrations at different controlled temperatures and extracting temperature coefficients for zero offset, sensitivity and other parameters. Drift and stability will be studied by long duration measurements at constant pressure. The dynamic response of the guidewire will be characterized by measuring amplitude and phase behaviour under different pulsatile conditions. The impact of data acquisition settings, such as sampling frequency, quantization resolution and synchronization, will be evaluated by controlled variation in both experiments and simulations. Signal processing steps, including filtering, averaging, peak detection and automatic baseline correction, will be examined to identify any systematic biases that they introduce.

Fourth, all relevant uncertainty contributions identified in the previous steps will be brought together into a comprehensive uncertainty model. This model will combine uncertainties from static calibration, dynamic behaviour, temperature effects, drift and the data processing chain in a consistent way, following the principles of the Guide to the Expression of Uncertainty in Measurement[22]. The result will be an overall uncertainty budget that can be used to calculate combined standard and expanded uncertainties for intravascular pressure guidewire measurements under clearly defined reference conditions. On this basis, a transparent and technically sound traceability chain will be formulated, showing how the pressure values displayed by the guidewire can be traced back to primary standards.

Finally, the study will propose a practical laboratory calibration procedure that can serve as a reference for hospitals, manufacturers, calibration laboratories and standardization bodies. This procedure will specify the recommended calibration setups, pressure points, environmental conditions and test sequences for both static and dynamic evaluations. It will also describe the required data analysis steps, the presentation of results and the minimum content of calibration reports and certificates, including uncertainty statements and traceability information. By doing so, the work intends not only to demonstrate a complete metrological approach for intravascular pressure guidewires, but also to provide a clear and reproducible methodology that can be adopted in future guidelines, technical documents and quality assurance schemes related to intravascular pressure measurements.

### **III. Research Contents and Methods**

#### **3.1 Measurement chain and metrological models**

The first step is to analyse the entire measurement chain from the primary pressure standard to the displayed guidewire pressure value in a structured and transparent way. The chain begins with a national or international pressure standard, for example a piston gauge or a calibrated pressure balance, which provides the highest level of accuracy and serves as the reference for traceability. Through comparison or calibration procedures, the pressure value from this primary standard is transferred to a laboratory reference system consisting of one or more calibrated pressure transducers and pressure generation devices such as precision pressure controllers or fluidic columns. These devices generate well defined pressure conditions in a test chamber or fluidic loop. The intravascular pressure guidewire is then exposed to the same pressure medium, ensuring that the reference sensor and the guidewire experience identical conditions. The guidewire converts the physical pressure into an electrical or digital signal, which is routed through the guidewire interface unit and

the data acquisition system. At this stage, amplification, filtering and digitization may already modify the signal. Finally, signal processing algorithms are applied to the acquired data to obtain the displayed pressure value or to compute derived indices, for example mean pressures over selected time windows or ratios of distal to proximal pressure.

Potential sources of error are identified and classified at each stage of this chain[15,19,21,25]. These include calibration uncertainties associated with the primary standard and the transfer standards in the laboratory reference system, which reflect both their limited accuracy and their long term stability. The guidewire sensor itself may introduce non linearity, hysteresis, zero offset and drift over time. Temperature variations can affect both the sensitivity and the baseline of the sensor and can also influence the mechanical properties of the fluidic setup. The dynamic behaviour of the guidewire and the fluidic loop introduces bandwidth limitations and possible resonances, which distort rapidly varying pressure signals. On the data acquisition and processing side, sampling frequency, quantization resolution, synchronization, digital filtering and interpolation can all contribute additional numerical errors. On the basis of this analysis, static and dynamic measurement models are formulated. Under static conditions, the pressure is expressed as a function of the guidewire output, temperature and time related drift, typically through a calibration relationship that may include correction terms for temperature and zero shift. Under dynamic conditions, the pressure as a function of time is described in terms of the time varying guidewire output together with the overall system response, including the sensor, the fluidic loop and the acquisition chain, and the subsequent processing steps such as filtering and averaging. These models provide the mathematical framework for propagating uncertainties from individual error sources to the final pressure readings and derived indices. The overall measurement chain and main influence quantities are summarized in Table 1 and illustrated in Figure 1.

Table 1 Measurement chain for intravascular pressure guidewire measurements and main influence quantities

Stage No.	Stage in measurement chain	Typical device(s)	Main influence quantities / potential error sources
1	Primary pressure standard	National / international piston gauge, pressure balance	Calibration uncertainty, stability, environmental conditions
2	Laboratory pressure reference system	Calibrated pressure transducers, precision controllers	Transfer standard calibration, resolution, drift, linearity, hysteresis
3	Fluidic test chamber / loop	Test chamber, tubing, connectors, working fluid	Hydrostatic effects, leaks, trapped air, dynamic behaviour, temperature
4	Intravascular pressure guidewire sensor	Guidewire pressure sensor element	Sensitivity, linearity, hysteresis, zero offset, drift, bandwidth
5	Guidewire interface and data acquisition (DAQ)	Interface unit, A/D converter, communication link	Sampling rate, quantization, latency, noise, synchronization
6	Signal processing and calculation of derived indices	Filtering, averaging, baseline correction, index algorithms	Filter characteristics, algorithm settings, numerical precision
7	Displayed pressure values and functional indices (e.g. FFR)	Clinical console, workstation	Rounding, display resolution, data export format

Figure 1. Measurement chain from pressure standards to displayed guidewire value

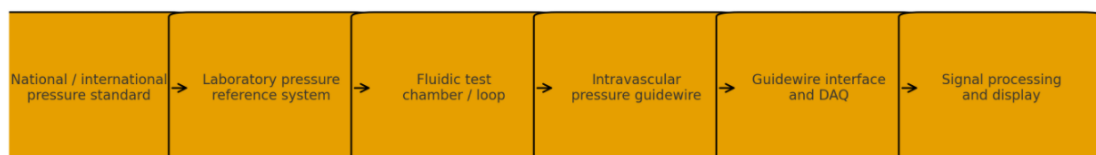


Figure 1. Measurement chain from national or international pressure standards to the displayed intravascular pressure guidewire values.

### **3.2 Static pressure calibration system and experiments**

A traceable static pressure calibration system is designed using combinations of a piston gauge, a precision pressure controller and water column devices[15,16]. These devices generate stable pressure levels over the range relevant for coronary applications, typically from atmospheric pressure to about two hundred millimetres of mercury, with the possibility to extend the range if needed. One or more high accuracy pressure transducers, previously calibrated against national standards, serve as reference instruments in the calibration bath or pressure chamber.

Static calibration of the pressure guidewire is performed by applying a series of pressure steps. Upward and downward sweeps are used to assess linearity and hysteresis. At selected points, the pressure is repeated several times to evaluate repeatability and reproducibility of the guidewire readings. Long duration holds at constant pressure allow the study of zero drift and medium term stability. For each condition, the guidewire output is recorded after suitable stabilization times. The relationship between reference pressure and guidewire output is then determined by regression or other fitting methods.

The uncertainty analysis in static calibration covers several components. The uncertainty of the pressure standard and reference transducers is obtained from their calibration certificates and stability data. The resolution and short term repeatability of the guidewire output are evaluated from repeated measurements. Environmental influences such as temperature variations, vibration or electrical noise are estimated based on monitoring data and dedicated tests. The effect of data processing methods, for example averaging time and fitting model, is examined by comparing alternative analysis strategies. All components are combined into a static calibration uncertainty

budget following accepted metrological practice. An example static calibration protocol is given in Table 2.

Table 2 Example static pressure calibration protocol for intravascular pressure guidewires

Item	Example setting / description
Pressure range	0 - 200 mmHg (extendable as required)
Reference standard	Piston gauge + calibrated pressure transducer
Medium	Water or physiological saline at controlled temperature
Temperature setpoint	$(23 \pm 1) ^\circ \text{C}$ for baseline static calibration
Pressure points (up-sweep)	0, 25, 50, 75, 100, 125, 150, 175, 200 mmHg
Pressure points (down-sweep)	200, 175, 150, 125, 100, 75, 50, 25, 0 mmHg
Repeats at key points	0, 100, 200 mmHg, at least 3 repeats each
Stabilization time	$\geq 30$ s after each pressure change before recording
Recorded quantity	Guidewire output signal and reference pressure
Evaluated characteristics	Sensitivity, linearity, hysteresis, repeatability, zero drift
Data analysis	Regression fit of P vs. output, residual analysis, GUM-based uncertainty budget

### 3.3 Dynamic fluidic loop and pressure response

To investigate the dynamic response of the guidewires in a controlled and repeatable way, a closed fluidic loop is constructed and tuned to reproduce a range of physiologically relevant pressure waveforms[15-21,25]. The loop consists of a circulation pump, compliant tubing and adjustable resistive elements that emulate vascular compliance and resistance. The choice of pump and tubing is made so that the loop can generate stable pulsatile flow without excessive mechanical noise or cavitation. By adjusting pump speed, downstream resistance and the stiffness or volume of compliant chambers, different combinations of mean pressure, pulse

amplitude and frequency content can be obtained. In this way, the system is able to generate quasi sinusoidal signals for fundamental frequency studies, step like transients for time domain characterisation, and cardiac like waveforms that resemble typical coronary pressure patterns in both amplitude and dominant frequency range. The working fluid is selected to have suitable viscosity and density, and its temperature is controlled to remain within a narrow band, so that fluid properties do not introduce additional uncontrolled variability in the dynamic response.

A high bandwidth reference pressure transducer is installed at the same location as the guidewire sensor, or as close as is practically achievable, in order to minimise spatial pressure gradients between the two measurement points. The transducer is chosen with a bandwidth significantly higher than the expected frequency content of the coronary like waveforms, so that it can be regarded as providing the true dynamic pressure signal for the purpose of comparison. Both the guidewire and the reference transducer are connected to synchronized acquisition channels that share a common time base. Synchronization ensures that any observed phase difference between the two signals is due to the devices and the fluidic system rather than to timing errors in the data acquisition unit. Dynamic tests are carried out over a range of fundamental frequencies and waveform shapes, from low frequency pulses to higher frequency components that approach the upper limit of the guidewire bandwidth. For each test condition, time series from the guidewire and the reference transducer are recorded over many cycles to allow averaging and reduce random noise. From these data, amplitude ratio and phase difference between the guidewire and the reference are calculated as functions of frequency, for example by using Fourier based methods or by fitting sinusoids in the time domain. Rise time and fall time are also evaluated using step or fast ramp signals, which provide additional insight into overshoot, damping and delay characteristics.

The uncertainty analysis for dynamic measurements takes into account several interacting factors. First, the limited bandwidth and potential resonances of the

guidewire sensor are considered. If the sensor response is not flat over the frequency range of interest, it will attenuate or amplify certain components of the pressure waveform. Second, the fluidic loop itself may introduce additional oscillations or damping due to reflections in the tubing, local compliance in connectors and small trapped gas volumes. These effects can alter the shape of the pressure waveform at the measurement location and must be characterised or bounded. Third, the influence of sampling frequency, quantization resolution and acquisition time window is evaluated. Too low a sampling frequency can cause aliasing and distort the reconstructed waveform, while an insufficient time window can lead to poor frequency resolution. Digital filtering and interpolation algorithms used to reconstruct pressure waveforms are therefore studied in a systematic way by applying different filter types and parameter settings and observing the resulting changes in amplitude, phase and derived metrics. The sensitivity of the measured amplitude ratio, phase delay and time domain parameters to these choices is quantified and translated into uncertainty components. Based on these investigations, frequency response correction strategies can be proposed, for example in the form of correction factors or deconvolution procedures applied to the guidewire signal[18-21,25]. Finally, the identified contributions are combined into an uncertainty budget for dynamic pressure measurements, which specifies the expected uncertainty as a function of frequency and operating condition and can be used when interpreting guidewire measurements in pulsatile environments. The dynamic fluidic loop is shown schematically in Figure 2, and an illustrative amplitude–frequency response is presented in Figure 3.

Figure 2. Schematic of the dynamic fluidic loop for pulsatile pressure generation

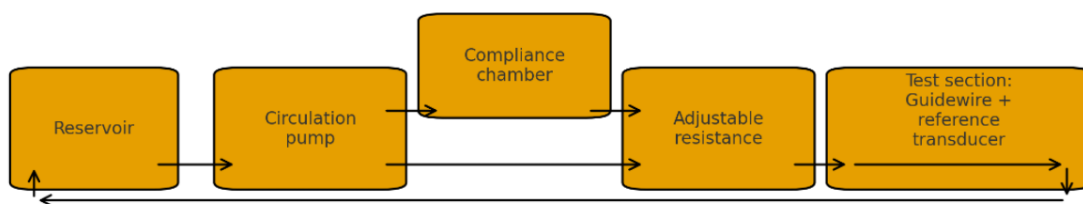


Figure 2. Schematic of the dynamic fluidic loop used to generate pulsatile pressure waveforms for guidewire testing.

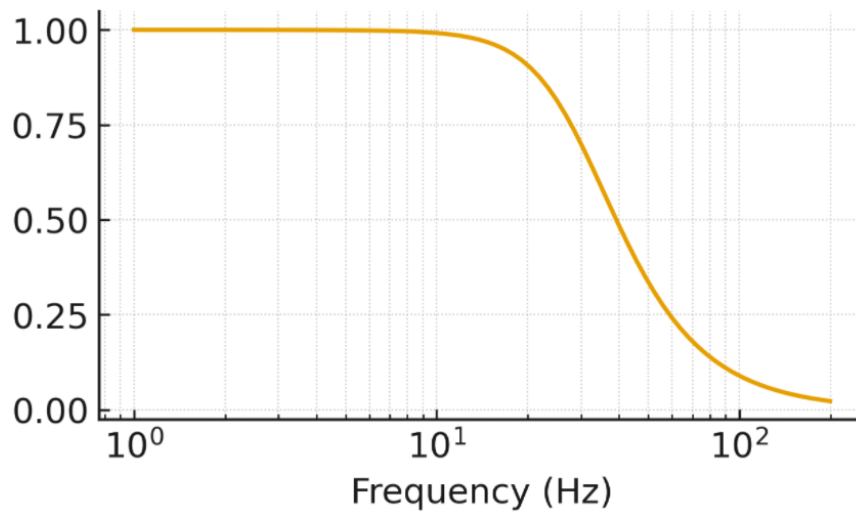


Figure 3. Example amplitude–frequency response of an intravascular pressure guidewire relative to a high-bandwidth reference transducer

### 3.4 Temperature effects and compensation

Temperature is a key influence quantity for intravascular pressure guidewires, since both the sensor element and the surrounding medium are temperature sensitive. Changes in temperature can affect the mechanical properties of the sensor diaphragm, the electrical characteristics of strain gauges or piezoresistive elements, and the viscosity and density of the fluid in which the sensor operates [18,20,21]. If these effects are not properly characterized and corrected, they can lead to temperature dependent shifts in zero offset, changes in sensitivity and subtle distortions of dynamic response. To quantify these effects in a controlled way, static and simple dynamic calibrations are repeated at several well defined temperatures. A thermostatic water bath is used as the primary means to stabilise the liquid environment in which both the guidewire sensor and the reference pressure transducer are immersed. When parts of the measurement chain, such as the guidewire interface or sections of the tubing, are exposed to air, an air temperature chamber can be used to control their

temperature as well. The system is allowed to reach thermal equilibrium at each set point, typically in the range of approximately twenty to forty degrees Celsius, which covers typical operating conditions for intravascular measurements and allows assessment of behaviour at temperatures slightly below and above nominal body temperature.

For each temperature set point, a complete static calibration sequence is performed. From these data, the zero offset at reference pressure, the sensitivity (slope of the pressure–output relationship) and indicators of linearity are determined for the guidewire. By comparing these parameters across temperatures, the dependence of zero offset and sensitivity on temperature is analysed, and approximate temperature coefficients are derived. In addition, residuals from the calibration fit are inspected to detect any temperature induced non linearities. Simple dynamic tests, for example low frequency pulsatile waveforms with stable mean pressure and amplitude, are also carried out at each temperature. These tests are used to identify whether dynamic response characteristics such as bandwidth, phase delay, rise time and damping are temperature dependent. For instance, an increase in fluid viscosity at lower temperatures may reduce effective bandwidth or alter phase characteristics, while changes in sensor material properties may modify damping and overshoot.

Based on the combined static and dynamic results, temperature dependent correction models are developed. In the simplest case, these models can take the form of linear or piecewise linear functions that relate pressure to the guidewire output and temperature, with separate terms for zero offset and sensitivity. For more complex behaviour, higher order or segmented functions may be used, or the corrections may be implemented as tables of correction factors for discrete temperature intervals, to be interpolated during use. The choice of model is guided by a balance between fidelity to the observed behaviour and ease of implementation in practical systems. Once candidate models have been established, their performance is evaluated by applying the corrections to independent test data and comparing the compensated pressure

values to the reference measurements. Measurement errors and associated uncertainties before and after applying temperature compensation are quantified, for example by examining residuals across the pressure range and by constructing uncertainty budgets that explicitly include temperature related components. This analysis demonstrates the extent to which the compensation models reduce systematic temperature effects and clarifies the residual temperature related uncertainty that must still be taken into account in the overall uncertainty evaluation for intravascular pressure guidewire measurements. An example of the temperature dependence of guidewire sensitivity is shown in Figure 4.

Figure 4. Example temperature dependence of guidewire sensitivity

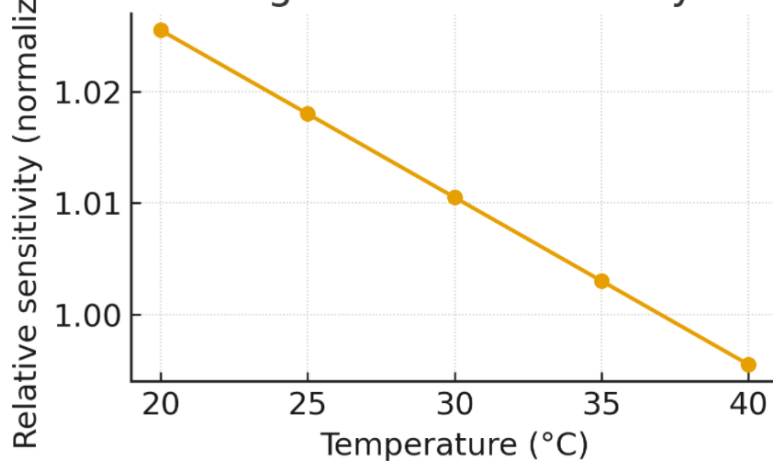


Figure 4. Example temperature dependence of the normalized sensitivity of an intravascular pressure guidewire

### 3.5 Data acquisition, algorithms and their uncertainty contribution

The data acquisition chain and associated algorithms form the final link between the physical pressure signal and the recorded numerical values. In this study, the analogue or digital interfaces of the guidewire interface unit are examined, together with the sampling frequency, quantization resolution and communication latency of the acquisition system. Typical signal processing modules, such as low pass filters,

moving average filters, peak detection routines, cycle averaging methods and automatic zero drift correction, are identified and characterized[14,19,21,23].

A combination of simulation and experiment is used to quantify the influence of these elements. Synthetic signals with known characteristics are generated and processed through different sampling and filtering configurations. The resulting deviations from the original signal are analysed as functions of sampling frequency, filter bandwidth and algorithm parameters. In parallel, experimental data from the static and dynamic tests are reprocessed using different analysis settings to evaluate the sensitivity of the derived pressure values and indices. The observed differences are expressed as additional uncertainty contributions. Depending on their nature, they are treated as type A contributions when derived from statistical analysis of repeated tests, or as type B contributions when based on theoretical or manufacturer information.

### **3.6 Comprehensive uncertainty model and traceability framework**

All identified uncertainty components are collected into a comprehensive model. Static calibration uncertainties, dynamic response related uncertainties, temperature effects and contributions from data acquisition and algorithms are combined using standard uncertainty propagation rules[19,21-23,25]. The combined standard uncertainty is obtained for typical operating conditions, for example for pressure levels and waveform characteristics resembling those used in fractional flow reserve measurements. Expanded uncertainties are then calculated using appropriate coverage factors.

On this basis, a clear traceability chain is described. It begins with national or international pressure standards, continues through the laboratory pressure generation and reference sensor systems, and reaches the intravascular pressure guidewire as the device under test[15,16,19,21,24,25]. The final link connects the calibrated guidewire to the clinical equipment in which it is used, although the present study does not perform clinical experiments. A practical laboratory calibration procedure is drafted,

including recommended test points, environmental conditions, data acquisition settings, analysis steps and the content of calibration certificates. Application examples under simulated fluidic conditions, such as normal, post stenosis and post vasodilator waveforms, are used to illustrate how calibrated guidewires with known uncertainties can support more reliable interpretation of functional coronary indices. A template for the combined uncertainty budget under representative conditions is summarized in Table 3.

Table 3 Example combined uncertainty budget for guidewire pressure measurements under representative conditions

Component ID	Source of uncertainty	Type (A/B)	Probability distribution	Sensitivity coefficient	Standard uncertainty (mmHg)	Contribution to u <sub>c</sub> (%)
U1	Primary standard calibration	B	Normal	1.0	0.11	5
U2	Laboratory reference transducer calibration	B	Normal	1.0	0.16	10
U3	Static non-linearity and hysteresis of guidewire	A	Normal	1.0	0.22	20
U4	Short-term repeatability of guidewire readings	A	Normal	1.0	0.16	10
U5	Temperature dependence (after compensation)	B	Rectangular / normal	1.0	0.19	15
U6	Dynamic response (amplitude vs. frequency)	B	Normal	1.0	0.22	20
U7	Data acquisition (sampling, quantization, synchronization)	B	Rectangular / normal	1.0	0.16	10

Component ID	Source of uncertainty	Type (A/B)	Probability distribution	Sensitivity coefficient	Standard uncertainty (mmHg)	Contribution to u <sub>c</sub> (%)
U8	Signal processing (filtering, averaging, baseline correction)	B	Normal	1.0	0.16	10

#### IV. Technical Roadmap

The technical roadmap of the study follows a stepwise and logically ordered sequence, in which each stage builds on the results of the previous one. The work begins with a detailed requirement analysis, in which the clinical use of intravascular pressure guidewires is translated into metrological specifications. In this first stage, the relevant pressure ranges, waveform characteristics, temperature conditions and accuracy needs are identified. On this basis, static and dynamic measurement models are formulated. These models describe how the true pressure is related to the guidewire output signal, the environmental and medium conditions, and the properties of the measurement chain. They provide the conceptual foundation for all subsequent experimental design and uncertainty evaluation.

In the second stage, static pressure calibration systems are designed and constructed. Appropriate pressure generation devices and reference pressure sensors are selected and integrated into a stable and controllable calibration setup. The focus in this phase is on achieving traceability to national or international pressure standards, ensuring sufficient resolution and stability, and defining standard operating procedures for applying pressure steps and plateaus. Once the setup has been validated, static experiments are carried out according to predefined test plans. These experiments supply the data needed to determine basic characteristics of the guidewires, such as

sensitivity, linearity, hysteresis, repeatability and zero drift, under well controlled conditions.

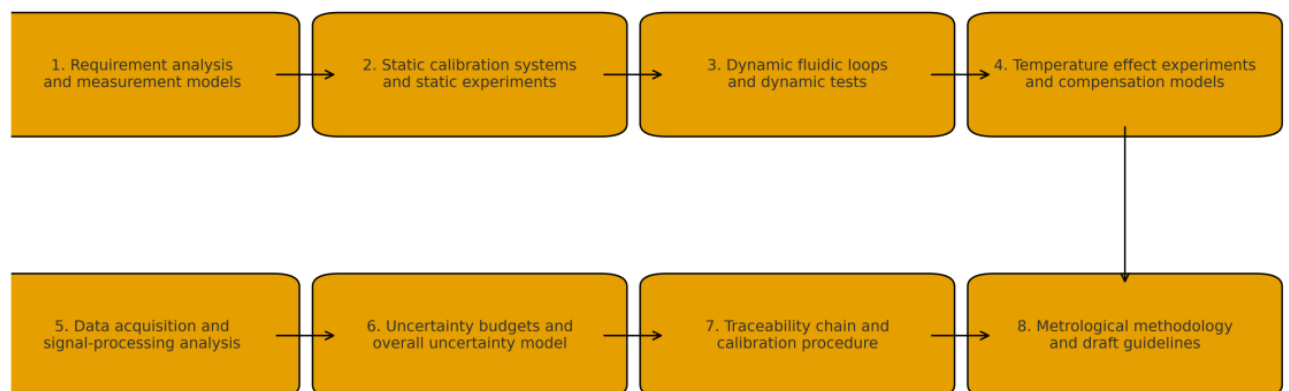
The third stage addresses the dynamic behaviour of the guidewires. Dynamic fluidic loops are designed to reproduce pulsatile pressures similar to those encountered in coronary circulation. This involves selecting suitable pumps, tubing, compliance elements and resistive components, as well as ensuring that the mechanical and hydraulic properties of the loop do not unduly distort the target pressure waveforms. After implementation and initial tuning, systematic dynamic tests are conducted. In these tests, the guidewire signals are compared with those of high bandwidth reference sensors in order to characterise amplitude response, phase delay and other dynamic parameters over a range of frequencies and waveform shapes.

In the fourth stage, temperature effect experiments are performed and compensation models are developed. The static and dynamic tests are repeated at several controlled temperatures that span the expected operating range. The resulting data sets are analysed to quantify how zero offset, sensitivity and dynamic response change with temperature. Based on these results, temperature correction functions or tables are derived, and their effectiveness is evaluated by comparing compensated and uncompensated measurement errors. In parallel, the fifth stage examines the contributions of the data acquisition chain and signal processing algorithms. By varying sampling frequency, quantization settings and filter parameters in both simulations and experiments, the study quantifies how these choices affect the recorded pressure values and the derived indices.

All findings from the previous stages are then integrated in the sixth stage into detailed uncertainty budgets and an overall uncertainty model. Each identified source of uncertainty, whether related to static calibration, dynamic response, temperature dependence, drift, data acquisition or signal processing, is expressed as a standard uncertainty and combined following accepted metrological rules. The result is a set of

combined standard and expanded uncertainties for typical use cases, together with clear assumptions and conditions of validity.

On this basis, the seventh stage focuses on establishing a complete traceability chain and formulating a practical calibration procedure. The traceability chain links the displayed guidewire pressure values back to national or international standards via the laboratory calibration systems and reference sensors. The calibration procedure specifies step by step how a laboratory should set up the equipment, choose test conditions, acquire and process data, and report calibration results, including uncertainty statements and traceability information. In the final stage, these elements are consolidated into a coherent metrological methodology specifically tailored to intravascular pressure guidewire calibration. This methodology is intended to be sufficiently detailed for implementation in calibration and testing laboratories, while also being clear enough to serve as a basis for future technical guidelines and standardization documents. Throughout all stages of the roadmap, all experiments and evaluations are carried out exclusively with laboratory physical simulation systems, without involving human or animal subjects or any clinical data.



All experiments are conducted using laboratory physical simulation systems; no human subjects or clinical data are involved.

## V. Expected Innovations

The work is expected to provide, for the first time, a systematic laboratory based analysis of intravascular pressure guidewires from the viewpoint of a complete measurement chain[9-12,15-21]. By explicitly linking the guidewire output to national and international pressure standards, it supports consistent and comparable pressure measurements across different laboratories and manufacturers. A dedicated methodology for evaluating dynamic response under pulsatile conditions will improve understanding of how bandwidth, phase delay and waveform distortion affect derived clinical indices.

Another innovation lies in the comprehensive uncertainty model, which includes not only static calibration and dynamic response, but also temperature effects and the influence of data acquisition and algorithms. This integrated view is essential for realistic uncertainty statements. The proposed traceability framework and calibration procedure can serve as a technical reference for future guidelines and standardization activities in the field of intravascular pressure measurements.

## **VI. Feasibility and Ethical Compliance**

From a practical viewpoint, the study is highly feasible. The required equipment consists of standard instruments commonly available in metrology and biomedical engineering laboratories, including pressure calibration devices, reference pressure transducers, fluidic loop components, temperature control systems and data acquisition hardware and software. No clinical infrastructure or patient recruitment is necessary, which reduces both time and administrative burden.

In terms of ethical aspects, the research focuses exclusively on intravascular pressure guidewires and physical simulation systems. No human participants or animals are involved, and no clinical or personal data are collected or processed. All measurement data are generated by standard instruments under controlled laboratory conditions. The study can therefore be regarded as an engineering and metrology investigation

that falls outside the scope of institutional medical ethics review, while still supporting safer and more reliable clinical use of intravascular pressure guidewires in future applications[24].

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