Smart Invasive Catheters: From Passive Conduits to Active Biosensing Platforms for Nursing Care

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Abstract

Invasive medical catheters serve as critical conduits for fluid drainage, drug administration, nutritional support, airway management, and physiological monitoring. Conventional models, however, function largely as passive devices with limited ability to provide information regarding their surrounding tissue conditions or local biological environment. The absence of *in situ* feedback delays the recognition of catheter-associated infections, obstruction, extravasation, malposition, and pressure-related injury, increasing the burden on patients and healthcare professionals. In this critical narrative review, we focus on representative advances in smart catheter and catheter-associated sensing technologies. Diverging from existing literature around engineering sensor modalities, we adopt a clinical nursing-focused perspective by anchoring the analysis in application scenarios. We link the clinical nursing challenges associated with each catheter category to relevant sensing targets, including impedance, biochemical markers, pressure, flow, and positioning information. Current technologies may support earlier risk recognition and more structured clinical reassessment; however, most remain at the laboratory, preclinical, or early clinical validation stage and should not be regarded as established autonomous care systems. This highlights the potential of smart catheters to complement bedside assessment and support timely and individualized catheter management. Finally, we outline future priorities for clinical translation and the responsible application of artificial intelligence and advanced materials.

Keywords: smart catheters; biosensors; clinical nursing; physiological monitoring; catheter-related complications; medical-engineering integration

Received: 13 June 2026; **Accepted:** 10 September 2026
DOI: 10.15302/IN.2026.000007
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Introduction

Healthcare systems rely heavily on the widespread use of medical catheters. Serving as the primary physical interface between a patient's internal physiological environment and external medical infrastructure, these devices are essential for numerous emergency and therapeutic procedures. They provide access for enteral nutrition, airway support, medication and fluid administration, physiological monitoring, and the drainage of urine or other bodily fluids. In both intensive care units (ICUs) and general wards, catheter placement, surveillance, maintenance, and complication prevention account for a substantial proportion of daily nursing activities. Driven by the rapid development of precision nursing and digital health, clinical decision-making is gradually shifting from experience-based routines toward earlier, individualized, and data-informed interventions supported by continuous and objective physiological information[1].

Medical catheters are used on a substantial scale worldwide. It has been estimated that more than 1.2 billion peripheral intravenous catheters (PIVCs) are inserted annually[2]. In critical care and other inpatient settings, central venous catheters (CVCs), endotracheal tubes (ETTs), urinary catheters, and gastrointestinal feeding tubes are also routinely used to support treatment delivery, organ function, nutritional support, and fluid drainage. Despite their clinical necessity, the insertion of foreign materials disrupts mucosal and endothelial barriers, predisposing patients to various complications. Device-associated infections, such as catheter-associated urinary tract infections (CAUTIs), central line-associated bloodstream infections (CLABSIs), and ventilator-associated pneumonia (VAP), constitute an important component of healthcare-associated infections (HAIs)[3]. A recent multicenter retrospective observational study further indicated that CAUTI was associated with increased hospital length of stay and additional healthcare costs[4], while HAIs more broadly impose a substantial economic burden on healthcare systems[5]. Furthermore, noninfectious complications, including catheter occlusion, thrombosis, pressure-related tissue injury, extravasation, leakage, and unintended malposition, may interrupt treatment and increase patient morbidity, nursing workload, and healthcare costs.

The occurrence of catheter-related complications is multifactorial and cannot be attributed solely to device design. Nevertheless, a major limitation of conventional catheters is that they generally function as passive conduits and provide little or no information regarding their position, patency, surrounding tissue condition, or local biological environment. The distal end of the catheter and the tissue-catheter interface are often not directly observable, limiting the nursing staff's ability to monitor early mechanical, physiological, or microbiological changes. Currently, clinical practice typically relies on external symptoms, scheduled flushing, or delayed laboratory cultures to identify complications. When healthcare providers observe sluggish flow, fever, localized swelling, or external leakage, the underlying obstruction, tissue injury, malposition, or infection may already have progressed. This limitation creates a temporal gap between the initiation of a complication and its recognition at the bedside.

Smart invasive catheters represent a class of indwelling catheter systems that incorporates catheter-integrated or catheter-associated sensing, data acquisition, signal processing, and, in some cases, responsive or actuating functions to provide time-resolved information concerning catheter placement, function, or related complications. Sensing refers to the acquisition of a physical, chemical, or biological signal, whereas monitoring involves the longitudinal interpretation of these signals. Actuation refers to a device response, such as pressure adjustment or controlled release, and a closed-loop system further links detected abnormalities with an automated or semi-automated intervention. These functions represent different levels of technological capability and should not be treated as interchangeable concepts. Accordingly, endowing catheters with smart sensing capabilities may support earlier risk recognition and more targeted clinical reassessment, although most current systems remain at the prototype, preclinical, or early clinical validation stage. The development of such systems therefore represents an emerging direction in medical engineering and nursing decision support rather than an already established model of automated catheter care.

Recently, advancements in flexible electronics, biocompatible hydrogels, and miniaturized biosensors have facilitated the development of smart catheters. However,

many existing technology-focused reviews organize these developments primarily according to sensor modality, such as electrochemical, piezoresistive, capacitive, or optical sensing. Although this classification is useful for understanding device design and sensing mechanisms, it does not always clarify which bedside problem a technology is intended to address or how the resulting information could be incorporated into nursing practice. Importantly, nursing staff are frequently involved in catheter insertion or assistance, position verification, routine surveillance, maintenance, complication recognition, documentation, and escalation of care, rather than the direct operation of individual sensor components. Each type of catheter presents distinct anatomical challenges and sensing requirements in clinical application, as well as different failure modes, assessment priorities, and potential nursing responses.

In this critical narrative review, we adopt clinical application scenarios as its primary organizational framework. Rather than attempting to exhaustively identify all publications or quantitatively compare device effectiveness, we critically examine representative sensing, monitoring, positioning, and responsive technologies associated with urinary, intravascular, respiratory, gastrointestinal, and surgical drainage catheters. By linking catheter-specific clinical blind spots with relevant sensing targets and technological approaches, this review aims to clarify the potential nursing relevance, current development stage, and translational limitations of smart catheter systems. Particular attention is also given to clinical workflow integration, alarm management, patient safety, and the evidence required before these technologies can support routine nursing decision-making.

Review scope and literature identification

To support this critical narrative review, targeted literature searches were conducted in PubMed/MEDLINE and IEEE Xplore without a lower publication-date restriction and were updated through July 2026. Relevant regulatory-agency websites were also searched through July 2026. Search terms combined catheter-related terms, including "smart catheter," "urinary catheter," "vascular catheter," "endotracheal tube," "nasogastric tube," "external ventricular drain," and "surgical drain," with technology-related terms, including "sensor," "biosensor," "bioimpedance," "pressure," "flow," "pH," "electrochemical," "optical," "flexible electronics," "robotic navigation," "responsive coating," and "closed loop." Clinically oriented terms, including "nursing," "monitoring," "complication," "alarm," "workflow," and "patient safety," were also used.

English-language peer-reviewed original studies, reviews, conference papers, and authoritative guidance documents were considered when they addressed catheter-integrated, catheter-associated, positioning, monitoring, or responsive technologies relevant to urinary, intravascular, respiratory, gastrointestinal, or surgical drainage systems. Original studies were prioritized when they described device design, sensing targets, validation methods, clinical context, or potential nursing relevance. Reviews were used to contextualize clinical complications and enabling technologies, whereas regulatory guidance documents were included to address cybersecurity, interoperability, and artificial-intelligence lifecycle considerations. Adjacent-field robotic or catheter technologies were included only when they provided clearly transferable engineering principles and were explicitly identified as indirect evidence. Technology-focused publications were excluded when they did not address an invasive or indwelling catheter system, a catheter-associated monitoring platform, or a clearly transferable adjacent-field concept, or when they provided insufficient information on device design, sensing function, or validation. Publications not available in English were also excluded.

Because this was a critical narrative rather than a systematic review, study identification and selection were purposive and non-exhaustive, and no formal risk-of-bias assessment or quantitative synthesis was undertaken. Technology maturity was categorized as laboratory prototype, preclinical validation, clinical feasibility/pilot, implemented clinical device, or adjacent-field concept.

Representative smart catheter technologies and their author-assigned maturity classifications are summarized in Table 1. None of the representative technologies was classified as an implemented clinical device because routine clinical deployment and evidence of improved patient outcomes were not demonstrated in the cited studies.

Table 1: Representative smart catheter technologies: clinical targets, evidence maturity, nursing relevance, and translational barriers.

Catheter category	Representative technology/ reference	Clinical problem	Sensing target	Sensor modality	Device relationship	Development stage	Evidence basis	Potential nursing relevance	Main limitations and translational barriers
Urinary catheters									
Urinary	STARS urine-bag monitoring system (Gopalakrishnan et al.[6])	Delayed recognition of reduced drainage and changes potentially associated with CAUTI risk	Urine volume/flow and conductivity	Wireless resonant/RF sensing sticker	Catheter-associated (urine bag)	Laboratory prototype	Bench testing with simulated healthy and infected urine under hospital-like conditions	May support remote surveillance and prompt assessment of drainage patency, urine characteristics, and patient symptoms	Conductivity is nonspecific; no prospective patient validation; thresholds, bag dependence, wireless reliability, and false-alert rates remain uncertain
Urinary	Flexible distributed urethral-catheter pressure strip (Ahmadi et al.[7])	Unrecognized pressure variation, impaired drainage, or catheter-related mechanical dysfunction	Distributed pressure along the catheter	Flexible capacitive pressure-sensor array (PI/PDMS)	Catheter-integrated	Laboratory prototype	In vitro bench-top pressure-chamber testing	Could provide objective pressure trends that prompt checks for patency, tubing position, and obstruction	No in vivo or patient validation; calibration, tissue effects, packaging, sterilization, long-term durability, and clinically actionable thresholds are unresolved
Urinary	Spectroscopic urinary-output monitoring prototype (Kuenert et al.[8])	Intermittent urine assessment and delayed recognition of biochemical changes	Bilirubin, erythrocytes, pH, protein, specific gravity, and urobilinogen	Optical spectroscopy with automated classification	Catheter-associated (urinary output line)	Clinical feasibility/ pilot	Prototype testing with 401 urine samples from 168 patients	May provide objective urinary trends that trigger bedside reassessment and confirmatory testing	Sample-based validation rather than continuous bedside use; urine-matrix variability, calibration, specificity, and clinical thresholds require study
Urinary	Real-time impedance biofilm biosensor (McGlennen et al.[9])	Delayed recognition of biofilm growth and dispersal	Impedance changes associated with biofilm development	Impedance biosensing	Catheter-associated laboratory platform	Laboratory prototype	In vitro biofilm model	May support earlier recognition of biofilm-related risk and prompt catheter and microbiological assessment	Indirect evidence for long-term urinary catheterization; organism and medium dependence, biofouling, calibration, and patient validation remain unresolved
Urinary	Mobile bioimpedance toolkit for biofilm monitoring (Wong et al.[10])	Limited portable assessment of biofilm formation	Bioimpedance signatures of biofilm growth	Portable bioimpedance analysis	Catheter-associated laboratory platform	Laboratory prototype	Bench/in vitro biofilm testing	Could enable portable trend monitoring and support targeted reassessment	Not validated during indwelling catheter use; signal interpretation, specificity, sensor placement, and workflow integration require evaluation

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Catheter category	Representative technology/ reference	Clinical problem	Sensing target	Sensor modality	Device relationship	Development stage	Evidence basis	Potential nursing relevance	Main limitations and translational barriers
Urinary	Modular microfluidic biofilm-analysis platform (Islayem et al.[11])	Need for multimodal assessment of biofilm formation and antimicrobial response	Biofilm growth and treatment-response signals	Modular microfluidics with multimodal sensing	Laboratory platform	Laboratory prototype	Microfluidic model	May inform development of catheter-associated biofilm monitoring and antimicrobial-testing strategies	Not a clinical catheter system; transferability to urine flow, long-term catheterization, sterilization, and bedside use is unproven
Urinary	Infection-responsive drainage-bag blockage sensor (Milo et al.[12])	Impending crystalline encrustation and catheter blockage	Urease-driven alkaline change associated with *P. mirabilis*	pH-responsive fluorescent/ visual sensor	Catheter-associated (drainage bag)	Laboratory prototype	Laboratory model of the catheterized urinary tract	A visible warning could prompt early patency assessment, urine review, and escalation before complete blockage	Primarily organism/ mechanism specific; urine color and composition may interfere; warning lead time, false alerts, and patient performance are unknown
Urinary	Zwitterionic antifouling hydrogel coating (Yao et al.[13])	Protein deposition, bacterial adhesion, biofilm coverage, and bacterial swarming	Surface fouling rather than a measured physiological signal	Hydrated zwitterionic copolymer hydrogel coating	Catheter-integrated coating	Laboratory prototype	In vitro fibrinogen, bacterial-biofilm, swarming, and cytocompatibility testing	If integrated with sensors, may help preserve surface function and reduce fouling-related maintenance burden	No direct sensing output or clinical validation; coating durability, mechanical integrity, sterilization, scale-up, and long-term safety require study
Urinary	pH-responsive antimicrobial hydrogel coating (Miao et al.[14])	Bacterial colonization, encrustation, and catheter-associated infection	Alkaline pH associated with infection/ encrustation	Stimuli-responsive antimicrobial hydrogel coating	Catheter-integrated sensing-actuation coating	Preclinical validation	In vitro and in vivo preclinical testing	May provide localized responsive antimicrobial activity while nursing staff continue routine surveillance and clinical reassessment	Not a clinically established closed loop; release control, toxicity, resistance, durability, sterilization, manufacturing, and patient outcomes remain unresolved
Intravascular catheters									
Intravascular	Bioimpedance and skin-strain infiltration detection (Bicen et al.[15])	Delayed recognition of peripheral IV infiltration	Tissue bioimpedance and skin deformation	Electrical bioimpedance plus strain sensing	External/ wearable	Preclinical validation	Anesthetized porcine model	Could provide an earlier alert prompting insertion-site assessment and interruption of infusion when clinically indicated	Animal-model evidence; motion, skin and tissue variability, device placement, infiltration-versus-extravasation generalizability, and thresholds require clinical validation

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Table 1

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Catheter category	Representative technology/ reference	Clinical problem	Sensing target	Sensor modality	Device relationship	Development stage	Evidence basis	Potential nursing relevance	Main limitations and translational barriers
Intravascular	Open-source multimodal wearable extravasation system (Lee and Lin[16])	Delayed recognition of tissue changes around an IV site	Local pressure, temperature, and optical tissue changes	Wearable pressure, temperature, and optical sensors	External/ wearable	Laboratory prototype	Experimental prototype evaluation	May prompt earlier inspection for pain, swelling, erythema, leakage, resistance, and altered blood return	Not catheter-integrated; skin contact, positioning, motion artifacts, false alarms, sterilization/ reuse, and clinical outcome benefit remain uncertain
Intravascular	Flexible on-catheter arterial-pressure sensor (Ye et al.[17])	Need for continuous local intravascular pressure monitoring	Arterial pressure and pressure-waveform changes	Flexible piezoresistive on-catheter pressure sensor	Catheter-integrated	Preclinical validation	In vitro liquid testing and acute in vivo rat arterial testing	Could provide continuous pressure information and support verification of catheter and hemodynamic status	Acute small-animal evidence; thrombogenicity, drift, biofouling, wiring/ readout, long-term vessel safety, sterilization, and clinical utility require evaluation
Intravascular	Smart implanted access-port pH/lactate biosensors (Gil et al.[18])	Intermittent biochemical monitoring through implanted vascular access	pH and lactate	Needle-type electrochemical biosensors with NFC wireless readout	Catheter-integrated/ implanted access port	Laboratory prototype	Bench/in vitro device testing	May support targeted metabolic reassessment and reduce selected manual sampling tasks if clinically validated	No patient validation; analytical stability in blood, biofouling, calibration, wireless range, infection risk, sterilization, and actionable thresholds remain unresolved
Respiratory catheters									
Respiratory	Carbon-nanotube ETT-cuff strain sensor (Wang et al.[19])	Unrecognized cuff underinflation, overinflation, or changing cuff-tracheal contact	Cuff deformation/strain related to pressure	Stretchable piezoresistive carbon-nanotube network	Catheter-integrated	Laboratory prototype	Bench/model testing	Continuous trends could prompt verification of tube position, cuff pressure, leakage, tidal volume, and mucosal risk	Strain-to-pressure calibration, coughing and suction artifacts, long-term airway exposure, sterilization, device integration, and clinical outcome evidence are lacking

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Catheter category	Representative technology/ reference	Clinical problem	Sensing target	Sensor modality	Device relationship	Development stage	Evidence basis	Potential nursing relevance	Main limitations and translational barriers
Respiratory	Long-period-grating optical biofilm sensor (Kurmoo et al.[20])	Delayed recognition of airway-device colonization and biofilm formation	Optical changes associated with progressive biofilm growth	Long-period-grating fiber-optic sensing	Catheter-integrated experimental ETT/ device sensor	Laboratory prototype	In vitro biofilm testing in an airway-relevant model	May prompt closer respiratory assessment and microbiological evaluation	Not specific for infection or VAP; clinical thresholds, fiber integration, mechanical robustness, biofouling baseline, sterilization, and patient validation remain unresolved
Gastrointestinal catheters									
Gastrointestinal	Integrated pH and strain sensors for NG placement (Lim et al.[21])	Nonvisual placement and risk of malposition	Local pH and tube strain during insertion	Electrochemical pH plus strain sensing	Catheter-integrated placement system	Laboratory prototype	Engineering/ bench prototype testing	Could provide supplementary positioning cues and prompt cessation of advancement when readings are abnormal	Conference-stage prototype; no patient diagnostic accuracy; pH confounders, calibration, sensor location, sterilization, and failure modes require evaluation
Gastrointestinal	Six-degree-of-freedom magnetic NG-tube tracking (Li et al.[22])	NG-tube malposition and delayed confirmation	Tube-tip position and orientation	Magnetic tracking with localization algorithms	Placement-assistance system	Clinical feasibility/ pilot	First-in-human prospective feasibility study (10 patients; feasible localization in 5)	May provide objective path information during insertion while established position confirmation remains mandatory	Limited feasibility and sample size; body depth and anatomy, magnetic interference, setup complexity, training, and inability to replace approved confirmation methods
Gastrointestinal	Ultrathin-endoscope-assisted visual NJ placement (Chen et al.[23])	Failure and complications of nonvisual nasojejunal placement	Direct visualization of the insertion pathway	Ultrathin endoscopic imaging	Placement-assistance system	Clinical feasibility/ pilot	Comparative patient study in mechanically ventilated ICU patients	May support first-pass placement and provide direct visual feedback during difficult procedures	Not a sensor-integrated feeding tube; equipment, training, cost, infection control, operator dependence, and generalizability require consideration

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Catheter category	Representative technology/ reference	Clinical problem	Sensing target	Sensor modality	Device relationship	Development stage	Evidence basis	Potential nursing relevance	Main limitations and translational barriers
Gastrointestinal	Automated impedance-based reflux and gastric-residual monitoring (Hellerman Itzhaki et al.[24])	Feeding intolerance, reflux events, and aspiration-risk assessment	Reflux events and gastric residual volume	Automated multichannel impedance-based monitoring	Catheter-associated enteral monitoring system	Clinical feasibility/ pilot	Patient study comparing mechanical ventilation with high-flow nasal cannula	Could provide trends that prompt assessment of positioning, feeding tolerance, abdominal distension, and respiratory symptoms	Reflux is not equivalent to aspiration; sample size, device-specific thresholds, alarm burden, and impact on management and outcomes require validation
Gastrointestinal	REALITI visual-servo robotic endoscope (Boehler et al.[25])	Operator-dependent navigation through complex anatomy	Airway images and anatomical landmarks	Camera-based visual servoing and robotic control	Adjacent-field concept	Adjacent-field concept	Experimental robotic tracheal-intubation evaluation	Provides transferable principles for image-guided steering, training, and human oversight in future enteral placement systems	Developed for tracheal intubation, not NG/NJ placement; anatomical transferability, autonomous safety, cost, regulation, and workflow implications are unproven
Gastrointestinal	Haptic-vision autonomous intracardiac catheter navigation (Fagogenis et al.[26])	Navigation and tissue-contact injury during catheter steering	Visual and force/contact information	Robotic catheter control with haptic vision	Adjacent-field concept	Adjacent-field concept	Preclinical intracardiac animal evaluation	Provides transferable engineering concepts for obstacle recognition, force-aware navigation, and supervisory control	Intracardiac rather than gastrointestinal application; major anatomical, procedural, safety, infrastructure, and regulatory differences limit direct translation
Surgical drainage catheters									
Surgical drainage	Naked-eye macromolecular-network leak sensor (Jessernig et al.[27])	Delayed recognition of gastrointestinal anastomotic leakage	Digestive-enzyme activity in postoperative drainage fluid	Non-electronic macromolecular network/ colorimetric sensing	Catheter-associated drainage-fluid sensor	Clinical feasibility/ pilot	Translational testing including postoperative patient drainage samples	A visible biochemical cue may prompt earlier abdominal/ wound assessment, imaging consideration, and escalation	Marker specificity, timing and cutoffs, subjective visual interpretation, sampling conditions, device placement, and evidence of improved outcomes remain limited

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Catheter category	Representative technology/ reference	Clinical problem	Sensing target	Sensor modality	Device relationship	Development stage	Evidence basis	Potential nursing relevance	Main limitations and translational barriers
Surgical drainage	Portable droplet-based pancreatic α-amylase monitor (Zhao et al.[28])	Delayed biochemical recognition of postoperative pancreatic leakage/fistula	α-Amylase activity in drainage fluid	Portable droplet-based microfluidic biosensing	Catheter-associated portable analyzer	Clinical feasibility/ pilot	Postoperative patient drainage samples	May enable more frequent biochemical reassessment and earlier protocol-based clinical review	An isolated marker is not diagnostic; sampling workflow, cutoff standardization, interferences, calibration, cost, and outcome benefit require evaluation
Surgical drainage	Flexible IDE blood-detection and AI-classification system (Xu et al.[29])	Delayed recognition of postoperative bleeding and difficulty classifying drainage fluid	Blood-related dielectric/ capacitive changes	Laser-induced-graphene capacitive interdigital electrode plus AI classification	Catheter-associated	Laboratory prototype	Bench/experimental fluid testing	An alert could prompt immediate review of drainage volume, vital signs, pain, wound findings, and escalation	No patient validation; complex fluid mixtures, sensor attachment, calibration, algorithm generalizability, false alarms, sterilization, and clinical thresholds remain unresolved
Surgical drainage	Multiplexed CSF biomarker and flow platform (Keyvani et al.[30])	Delayed recognition of metabolic change, possible infection, or impaired EVD drainage	CSF glucose, lactate, pH, and flow	Aptamer electrochemical biosensors, polydopamine pH sensing, and impedance flow sensing	Catheter-associated/ integrated drainage system	Clinical feasibility/ pilot	Patient CSF and early clinical-workflow validation	May support near-real-time trending and prompt checks of EVD level, patency, system integrity, neurological status, and confirmatory testing	Limited clinical validation; biomarker nonspecificity, sensor drift and biofouling, sterility, calibration, integration, false alerts, and patient-outcome benefit require further study

Development-stage assignments were made by the authors according to the highest validation level reported in each representative study.

Note. Development stage definitions: laboratory prototype = bench, simulated-fluid, in vitro, or microfluidic validation only; preclinical validation = animal, ex vivo tissue, or complex biological-model validation; clinical feasibility/ pilot = patient samples or small-scale use in patients/clinical environments without established effectiveness; implemented clinical device = routine clinical deployment or robust prospective clinical-outcome evidence; adjacent-field concept = technology developed for another catheter, anatomy, or procedure and included only for transferable engineering principles. Evidence basis indicates the highest reported validation setting and is distinct from the development stage. No representative technology in this table was classified as an implemented clinical device because routine deployment and patient-outcome evidence were not demonstrated in the cited studies. Abbreviations: AI, artificial intelligence; CAUTI, catheter-associated urinary tract infection; CSF, cerebrospinal fluid; ETT, endotracheal tube; EVD, external ventricular drain; IDE, interdigital electrode; ICU, intensive care unit; IV, intravenous; NFC, near-field communication; NG, nasogastric; NJ, nasojejunal; PI, polyimide; PDMS, polydimethylsiloxane; RF, radiofrequency; STARS, Sticker Type Antenna for Remote Sensing; VAP, ventilator-associated pneumonia; REALITI, Robotic Endoscope Automated via Laryngeal Imaging for Tracheal Intubation.

Urinary catheters: monitoring the urological interface

Urinary catheters are among the most frequently utilized medical devices in hospitalized patients. While essential for continuous urinary drainage, they are highly susceptible to bacterial invasion. CAUTI remains an important device-associated HAI, and one relevant pathogenic mechanism is the formation of crystalline bacterial biofilms on the catheter surface, a process predominantly driven by urease-producing pathogens such as *Proteus mirabilis*. At the microscopic level, *Proteus mirabilis* secretes urease to hydrolyze urea in the urine into ammonia, causing a localized elevation in pH. This alkaline environment triggers the precipitation of calcium and magnesium phosphates, which are subsequently encased in bacterially secreted extracellular polymeric substances (EPS), forming hard encrustations[31,32]. This progression can lead to urinary obstruction, urine reflux, and pyelonephritis, potentially contributing to prolonged hospitalization. Most clinical signs appear only after encrustation is well established, creating a window for early biochemical and biophysical detection.

From a nursing perspective, the preventive care of urinary catheters currently depends largely on intermittent bedside assessment, including visual inspection of urine output, drainage tubing, and collection bags, as well as evaluation of catheter patency and patient symptoms. To prevent CAUTI and obstruction, early identification of abnormal changes associated with infection, encrustation, or reduced drainage is required. Key parameters include variations in urine flow and conductivity[6], as well as catheter-associated pressure changes[7], which may provide early indications of altered urine characteristics or impaired catheter drainage before visible leakage or complete obstruction occurs. A catheter-associated spectroscopic prototype has also demonstrated the feasibility of automated assessment of urinary parameters, including bilirubin, erythrocytes, pH, protein, specific gravity, and urobilinogen[8]. The system was evaluated using 401 urine samples obtained from 168 patients; therefore, prospective bedside studies are still required to confirm its performance during continuous catheter use and its ability to identify clinically actionable complications. These parameters are generally nonspecific and should be interpreted together with clinical symptoms, bedside assessment, and microbiological findings.

To address these challenges, a Sticker Type Antenna for Remote Sensing (STARS) system was developed to monitor infection risk markers. Attached to the urine bag, this system was designed to measure urine flow rate and conductivity for remote monitoring in ICU settings, enabling non-contact monitoring of changes potentially associated with reduced urine drainage or catheter-related complications[6]. Recent advancements have also explored the integration of flexible and stretchable sensor arrays into the catheter lumen[7]. For instance, a miniaturized distributed capacitive pressure sensing array, fabricated using polyimide (PI) and flexible polydimethylsiloxane (PDMS) substrates, enables continuous mapping of pressure variations along the urethral catheter. Additionally, impedance-based sensing platforms have been investigated for the real-time monitoring of biofilm formation and dispersal[9–11]. An infection-responsive fluorescent sensor placed within the catheter drainage bag has also been developed to provide a visual early warning of *Proteus mirabilis*-associated encrustation and impending urinary catheter blockage[12]. However, these approaches have largely been evaluated under in vitro or experimental conditions. Their performance during long-term catheterization, including detection accuracy, warning lead time, and false-alert rates, remains to be established in patients. These technologies may provide supplementary information for nursing assessment and catheter maintenance, but sensor alerts should not independently determine antimicrobial treatment or catheter replacement. Instead, abnormal signals should prompt further assessment of catheter patency, tubing position, urine characteristics, patient symptoms, and the need for microbiological testing according to clinical protocols.

Current research on smart urinary catheters demonstrates a trend toward combining sensing with antifouling and responsive material strategies. Exposed microelectronic sensors are prone to biofouling in complex urinary environments, which may result in signal drift or distortion. This challenge has motivated interest in combining sensor-integrated catheter platforms with antifouling interface materials. For example, zwitterionic hydrogel coatings can form highly hydrated antifouling interfaces

that reduce fibrinogen deposition, biofilm coverage, and bacterial swarming on urinary catheter materials[13]. Multifunctional hydrogel coatings may additionally support antimicrobial loading and pH-responsive behavior[14]. If incorporated into sensor-integrated catheter systems, such antifouling interfaces may help preserve sensing performance during prolonged exposure to urine and may also support the development of responsive material systems. Future responsive catheter systems may use endogenous triggers, such as changes in pH or reactive oxygen species, or exogenous stimuli, such as photothermal activation, to trigger localized antimicrobial responses[33]. Nevertheless, most sensing–actuation systems remain at the material, in vitro, or preclinical stage. They should therefore be regarded as potential platforms for future sensing–actuation or closed-loop intervention rather than clinically established smart urinary catheter therapies.

For nursing implementation, future studies should determine clinically actionable thresholds, false-alarm rates, documentation requirements, and standardized response pathways. Sensor-generated information should complement rather than replace routine bedside observation, clinical judgment, and established CAUTI prevention and catheter-maintenance protocols.

Intravascular catheters: supporting intravenous infusion safety

Vascular access devices, including PIVCs, CVCs, and peripherally inserted central catheters (PICCs), establish temporary or long-term channels for chemotherapy, vasopressors, blood products, and hemodynamic monitoring. However, the venous access environment is dynamic and clinically complex. Associated complications are common. A subset of PIVCs fails prior to treatment completion due to phlebitis, thrombosis, or extravasation. Given the potentially severe consequences of CLABSI, vascular catheters represent a high-risk interface in intensive care.

The clinical challenge of extravasation detection lies in its subclinical onset. When infusate leaks into the subcutaneous interstitium, it first alters local tissue hydration, electrolyte concentration, and interstitial pressure without producing visible swelling or erythema. As fluid accumulation progresses, it compresses surrounding tissues and disrupts local microcirculation, eventually causing the macroscopic signs detected by visual inspection. Continuous physical and biochemical sensing can capture the earlier biophysical changes in tissue properties, narrowing the gap between extravasation onset and clinical recognition.

Current management of vascular access complications has important limitations. According to the Infusion Therapy Standards of Practice published by the Infusion Nurses Society (INS), clinical assessment of extravasation and phlebitis includes regular visual inspection and palpation by nursing staff, often supported by standardized assessment tools such as the INS Phlebitis Scale[34]. However, this intermittent and partly subjective approach may not capture early changes occurring between assessments. When nursing staff observe erythema or palpate localized edema at the insertion site, medication may already have entered the surrounding tissue, potentially causing severe tissue necrosis or nerve damage and, in some cases, requiring surgical debridement[35]. Although bedside assessment remains essential, it may be complemented by smart sensing technologies capable of continuously and objectively detecting subcutaneous or intraluminal changes. Potential sensing targets include extravasation-related tissue changes, intravascular or intraluminal pressure, catheter patency, and biochemical parameters. Bioimpedance and skin-strain measurements have been evaluated for the early detection of intravenous infiltration in a preclinical porcine model[15]. Pressure, temperature, and optical sensors have also been incorporated into wearable systems for detecting tissue changes around intravenous access sites[16]. Catheter-integrated pressure sensing may provide continuous information about intravascular pressure and pressure-waveform changes, although its value for specifically identifying fibrin sheath formation or thrombosis remains to be established[17]. Considering the catheter's direct contact with blood, integrating biochemical sensors may also enable continuous tracking of blood parameters, such as glucose and lactate, and potentially reduce the frequency of blood sampling.

Relevant research is advancing toward smart devices that integrate monitoring and clinical decision support. Studies have explored wearable sensor systems integrating

pressure, temperature, and optical sensors capable of detecting subtle tissue changes associated with fluid extravasation and generating early alerts in experimental or pilot settings[16]. These wearable systems should be distinguished from catheter-integrated devices because their sensing components are generally positioned on the skin surrounding the vascular access site rather than within the catheter itself. Furthermore, electrochemical biosensors have been explored in implanted vascular access devices for continuous molecular monitoring. One study reported a functionalized needle-type electrochemical sensor achieving dual-parameter detection of pH and lactate, utilizing a smartphone near-field communication (NFC) interface for near-field wireless energy harvesting and data reading, thereby demonstrating the feasibility of continuous metabolic monitoring through an implanted vascular access platform[18]. This approach could potentially reduce the need for repeated blood sampling and selected manual monitoring tasks, although its effects on nursing workload, infection risk, and clinical outcomes require prospective evaluation. More broadly, graphene-based electrochemical sensors and biosensors have been extensively investigated for antibiotic detection, illustrating advances in electrode functionalization, analytical sensitivity, selectivity, and portable signal readout[36]. However, these platforms have generally been evaluated outside indwelling catheter systems, and their integration into catheter-based continuous monitoring and performance in complex, continuously flowing biological fluids remain to be established. Overall, current evidence remains dominated by engineering proof-of-concept and early feasibility studies. Further clinical validation is needed to establish long-term stability, analytical accuracy in blood, sterilization compatibility, false-alarm rates, and clinically actionable thresholds.

For nursing practice, sensor-generated alerts should be incorporated into a structured assessment and escalation pathway rather than interpreted as stand-alone diagnoses. An alert indicating possible extravasation or altered catheter function should prompt inspection of the insertion site, assessment for pain, swelling, erythema, leakage, resistance to infusion, and changes in blood return. When clinically indicated, the infusion should be interrupted and the responsible clinical team notified according to institutional protocols. Biochemical measurements should likewise be interpreted alongside laboratory testing and the patient's overall clinical condition. Future implementation studies should clarify alert priorities, documentation requirements, response responsibilities, and whether these systems improve patient safety without introducing additional alarm burden.

Respiratory catheters: airway monitoring and management

ETTs and tracheostomy tubes are essential instruments for airway management in patients requiring mechanical ventilation. The use of an ETT bypasses the upper airway's natural defense mechanisms, potentially leading to clinical issues including airway injury and infection. The inflatable cuff is designed to seal the trachea and prevent air leakage; however, excessive cuff pressure can compromise tracheal mucosal perfusion and contribute to ischemia, ulceration, and other pressure-related injuries. Conversely, insufficient cuff pressure may permit leakage of bacteria-containing oropharyngeal secretions around the cuff, thereby increasing the risk of microaspiration[37,38]. These cuff-related complications may contribute to airway injury and adverse respiratory outcomes.

Tracheal mucosal injury from cuff pressure is a dose-dependent pathological process. The normal perfusion pressure of tracheal mucosal capillaries is approximately 25–30 cmH_2O; cuff pressures exceeding this threshold compress mucosal vessels and reduce blood flow, while underinflated cuffs fail to form an adequate seal. Furthermore, cuff pressure fluctuates dynamically with coughing, swallowing, and patient repositioning, making it challenging to maintain optimal pressure continuously.

Current nursing protocols typically include periodic manual measurement of ETT cuff pressure using a handheld manometer. Nevertheless, cuff pressure may vary with coughing, swallowing, ventilator-related pressure changes, nursing procedures, and patient repositioning; therefore, intermittent measurements may fail to identify clinically relevant underinflation or overinflation occurring between assessments[37]. Research into smart respiratory catheters focuses on achieving continuous sensing by integrating flexible pressure or strain sensors with the cuff to monitor cuff–tracheal contact conditions, alongside the potential use of sensing technologies to

detect subglottic secretion accumulation, airflow abnormalities, or early biofilm formation. Continuous sensing may complement routine nursing assessment, but clinically appropriate pressure ranges and intervention thresholds must be established before sensor readings can guide automated adjustment.

Technological advancements have supported experimental approaches toward sensor-integrated ETTs. Researchers have engineered trace polymer-bonded carbon nanotube sensors with stretchable piezoresistive strain properties. These sensors retain electrical conductivity while maintaining mechanical stability and stretchability, allowing conformal adhesion to the ETT cuff and demonstrating the potential for continuous deformation or pressure-related monitoring[19]. However, their ability to prevent airway injury or leakage has not yet been established through clinical outcome studies. Another study reported an optical sensing approach using long-period grating (LPG) fiber sensors to monitor changes associated with biofilm formation on medical-device surfaces[20]. Such optical signals may provide a means of estimating progressive biofouling, although the relationship between sensor output, clinically significant airway colonization, and VAP risk requires further validation. Sensor-derived biofilm information should not independently determine antibiotic administration or ETT replacement, because these decisions require integration with respiratory symptoms, secretion characteristics, microbiological findings, ventilation status, and the overall clinical condition.

For nursing practice, abnormal cuff-pressure signals should prompt verification of the monitoring system, reassessment of tube position and fixation, repeat cuff-pressure measurement using an established method, evaluation for audible air leakage or changes in delivered tidal volume, and inspection for signs of mucosal injury or secretion accumulation. Persistent abnormalities should be escalated according to institutional airway-management protocols. Similarly, secretion- or biofilm-related alerts should support closer respiratory assessment and microbiological evaluation rather than serve as stand-alone diagnostic signals. Future studies should determine sensor accuracy during coughing, suctioning, repositioning, and prolonged ventilation, as well as false-alarm rates, sterilization compatibility, device durability, and the effects of continuous monitoring on nursing workload and patient outcomes.

Gastrointestinal catheters: placement monitoring and localization

Nasogastric and nasojejunal tubes are medical catheters inserted through the nasal cavity into the digestive tract to provide enteral nutrition and administer medication for patients unable to meet their nutritional requirements orally. Insertion of these tubes is commonly performed without direct visualization. Serious complications may occur when a tube is inadvertently advanced into the tracheobronchial tree or, in rare cases, the pleural space rather than the gastrointestinal tract; administration of enteral formula through a misplaced tube may result in severe pulmonary or pleural injury[39,40]. Tube occlusion may also result from formula-related factors, inadequate flushing, or improperly prepared or administered medications[40].

Current clinical practice commonly includes confirmation of tube position using institutionally approved methods, including radiographic confirmation when indicated and pH testing of aspirated contents where feasible[41]. To facilitate more rapid localization, researchers have explored smart feeding tubes equipped with positioning-related sensing capabilities. One engineering prototype integrated pH and strain sensors into a nasogastric tube placement system[21]. However, this technology remains at the engineering prototype stage, and its diagnostic accuracy in patients has not yet been established. Catheter-associated or external monitoring systems have also been investigated for detecting gastroesophageal reflux, which may support the assessment of aspiration risk. Research has demonstrated the application of magnet tracking devices for nasogastric (NG) tube insertion, with a clinical feasibility study reporting six-degree-of-freedom localization through algorithmic optimization[22]. Another study reported a visual nasojejunal tube placement system based on an ultrathin endoscope, aiding the tube's passage through the pylorus into the duodenum under direct visualization[23]. This system represents a visualization-assisted placement technique rather than a sensor integrated into the feeding tube itself. Furthermore, automated impedance-based monitoring technologies have been used to continuously detect reflux events and evaluate

potential aspiration risk[24]. However, such monitoring systems should be distinguished from catheter-integrated smart feeding tubes unless the sensing components are incorporated directly into the enteral tube. These technologies may supplement conventional placement and reflux assessment by providing additional objective information, but they should not replace established position-confirmation procedures without adequate clinical validation.

To mitigate the safety risks associated with blind insertion, medical robotics research has also provided potential technological concepts for future sensor-assisted enteral tube placement. By integrating micro-actuators and multimodal sensors at the distal tip of flexible catheters, such systems may potentially support active steering, obstacle recognition, and navigation within complex anatomical pathways. Studies have developed visual servoing robotic endoscope systems, such as Robotic Endoscope Automated via Laryngeal Imaging for Tracheal Intubation (REALITI), based on anatomical image recognition. Such systems utilize cavity features captured by micro-cameras to algorithmically maneuver the flexible catheter tip, achieving autonomous steering and path navigation. Although REALITI was developed for tracheal intubation rather than nasogastric or nasojejunal tube placement, it demonstrates how image-guided robotic control may reduce dependence on operator experience in anatomically complex procedures[25]. Additionally, interdisciplinary research has developed flexible robotic catheters capable of navigation within internal anatomical structures using multimodal haptic vision. By employing force-feedback control and algorithms, these systems assist in avoiding mechanical injury to fragile tissues, although the reported system was developed for intracardiac catheter navigation rather than gastrointestinal intubation[26]. These studies should therefore be interpreted as examples from adjacent robotic-catheter fields that provide transferable engineering principles, rather than as direct clinical evidence for autonomous gastrointestinal tube placement. The integration of soft robotic control with multimodal sensing represents a potential future direction for transforming nonvisual tube insertion into a more standardized and data-assisted procedure, but fully autonomous or closed-loop gastrointestinal placement has not yet been clinically established.

For nursing practice, sensor- or navigation-generated information should complement rather than replace established tube-position verification and patient assessment. During placement, unexpected resistance, coughing, respiratory distress, abnormal sensor readings, or an inconsistent tracking path should prompt immediate cessation of tube advancement and further verification. Enteral feeding or medication administration should be withheld until the tube position has been confirmed according to institutional protocols. After placement, reflux-related alerts should prompt assessment of patient positioning, feeding tolerance, abdominal distension, respiratory symptoms, and aspiration risk. Suspected tube occlusion should first prompt inspection for external kinking and adherence to approved flushing protocols, rather than forceful irrigation. Future studies should establish positioning accuracy, clinically actionable thresholds, failure modes, false-alarm rates, training requirements, and whether these systems reduce placement-related complications without increasing procedural complexity or nursing workload.

Surgical drainage catheters: high-risk microenvironments

In surgical and neurocritical care, catheters are employed to drain postoperative or pathological fluids, such as cerebrospinal fluid (CSF) via external ventricular drain (EVD) or wound exudate via postoperative surgical drains. These catheters operate within high-risk and sensitive microenvironments. EVDs are used to divert CSF and monitor intracranial pressure, and impaired drainage caused by obstruction, clot formation, tubing kinks, or catheter malposition may result in inadequate CSF diversion and contribute to uncontrolled intracranial hypertension and neurological deterioration[42]. Similarly, changes in the volume, rate, or characteristics of postoperative drainage may provide important indications of ongoing bleeding, anastomotic leakage, or impaired drain patency.

Currently, clinical monitoring of these drains primarily involves manual measurement of fluid volume and observation of color changes, methods that may be intermittent and provide limited information regarding early biochemical or flow-related changes. Consequently, research into smart drainage systems has explored biochemical sensing of postoperative drainage fluid[27,28],

artificial intelligence (AI)-assisted blood detection and fluid classification[29], and multiplexed CSF biomarker and flow monitoring[30]. To address postoperative bleeding, a capacitive interdigital electrode (IDE) biosensor was designed to attach to postoperative drainage tubes using medical-grade nonwoven fabric. Rather than being incorporated into the drainage catheter itself, this catheter-adjacent device demonstrated rapid blood detection in experimental testing and used AI-based data processing to support drainage-fluid classification[29]. However, its diagnostic accuracy, false-alarm rate, and clinical performance in complex postoperative drainage fluids require further prospective validation.

Another study reported a portable device for real-time sensing of α-amylase activity in postoperative pancreatic drainage for patient monitoring[28]. Such a platform may facilitate more frequent biochemical assessment of pancreatic drainage and support earlier clinical reassessment when abnormal enzyme activity is detected. Nevertheless, an isolated α-amylase measurement should be interpreted together with drainage volume, patient symptoms, imaging findings, and established postoperative diagnostic criteria. For CSF monitoring, a multiplexed sensing platform was reported, integrating glucose and lactate aptamer-based electrochemical biosensors, a polydopamine pH sensor, and an impedance-based flow sensor into the drainage system. This platform enabled near-real-time measurement of CSF biomarkers, including glucose, lactate, pH, and flow[30]. These measurements may provide supplementary information regarding metabolic changes, possible infection, or impaired drainage; however, their ability to improve clinical outcomes or reliably distinguish infection from other neurological or systemic conditions remains to be established.

Collectively, these studies demonstrate the potential to transform postoperative and neurocritical drainage systems from passive fluid conduits into platforms capable of continuous or near-real-time monitoring. However, the existing evidence includes experimental prototypes and early clinical validation studies, and these technologies should not yet be regarded as established diagnostic systems. Sensor-generated abnormalities should prompt structured clinical reassessment rather than independently determine treatment.

For nursing practice, an abnormal flow, pressure, blood-detection, or biochemical signal should first prompt verification of the drainage system, including inspection for tubing kinks, dependent loops, disconnection, clot formation, inappropriate drain positioning, or changes in collection-device level. Nurses should concurrently assess drainage volume and appearance, wound or insertion-site condition, vital signs, pain, abdominal findings, and neurological status where relevant. For EVD systems, sensor information must be interpreted together with prescribed drainage height, accurate leveling and zeroing, clamping status, intracranial pressure data, system integrity, and the patient's neurological examination[42]. Persistent or clinically significant abnormalities should be documented and escalated according to institutional protocols. Future studies should evaluate sensor accuracy, device compatibility with drainage procedures, false-alarm rates, infection-control requirements, and whether continuous monitoring improves the timeliness of nursing intervention without increasing alarm burden.

Summary, challenges, and future priorities

The transition of medical catheters from passive conduits to active, smart physiological interfaces represents an emerging developmental direction in clinical nursing and medical engineering. Utilizing the clinical application of catheters as a framework, this critical narrative review summarizes representative developments in sensing technologies across different catheter categories. By embedding biochemical and physiological monitoring capabilities at the tissue-catheter interface, smart catheter systems may support earlier recognition of catheter-related abnormalities and more individualized clinical reassessment. However, they should be regarded as decision-support technologies rather than replacements for bedside assessment and clinical judgment. The path to widespread clinical translation continues to face substantial engineering and implementation challenges. Exposed microelectronic sensors are susceptible to biofouling and signal degradation post-insertion due to protein adsorption, bacterial colonization, mineral deposition, mechanical deformation, and prolonged exposure to complex biological fluids. Maintaining sensing sensitivity while minimizing tissue trauma requires not only antifouling surface modification but also reliable encapsulation, mechanical durability, long-term biocompatibility, and

stable sensor performance under physiologically relevant conditions[43]. Relevant materials science advancements indicate that developing fully implantable, battery-free soft platforms and employing biocompatible elastomer encapsulation may support more stable continuous monitoring in complex in vivo fluidic environments[44]. Scalable fabrication of multifunctional coatings and reliable integration of flexible sensors with catheter materials also remain important manufacturing challenges. Nevertheless, at the level of process implementation, integrating electronic components into flexible tubing necessitates sustained interdisciplinary efforts regarding large-scale manufacturing, medical sterilization protocols that may alter sensor materials or electronic performance, and cost-effectiveness.

To clarify how smart catheter outputs may be incorporated into clinical practice, Figure 1 presents a generalized workflow for signal verification, bedside assessment, protocol-based action, documentation, escalation, and outcome reassessment.

As illustrated in Figure 1, smart catheter signals should be interpreted within a structured nursing workflow rather than acted upon as isolated diagnostic outputs. Signal quality, the magnitude and persistence of an abnormality, and its consistency with the patient's clinical condition should be assessed before an alert leads to intervention. Bedside verification may include evaluation of tube position, the insertion site, catheter patency, drainage characteristics, pressure measurements, patient symptoms, and relevant neurological or respiratory findings. When an abnormal signal is clinically confirmed, nurses should initiate the appropriate protocol-based response, document the findings and actions taken, and escalate care according to institutional procedures. When the signal is not confirmed, enhanced observation and reassessment remain necessary because an apparent discrepancy may reflect either a technical artifact or an evolving clinical event. This workflow therefore positions smart catheter systems as decision-support tools that complement, rather than replace, nursing assessment, clinical judgment, and established emergency-response procedures.

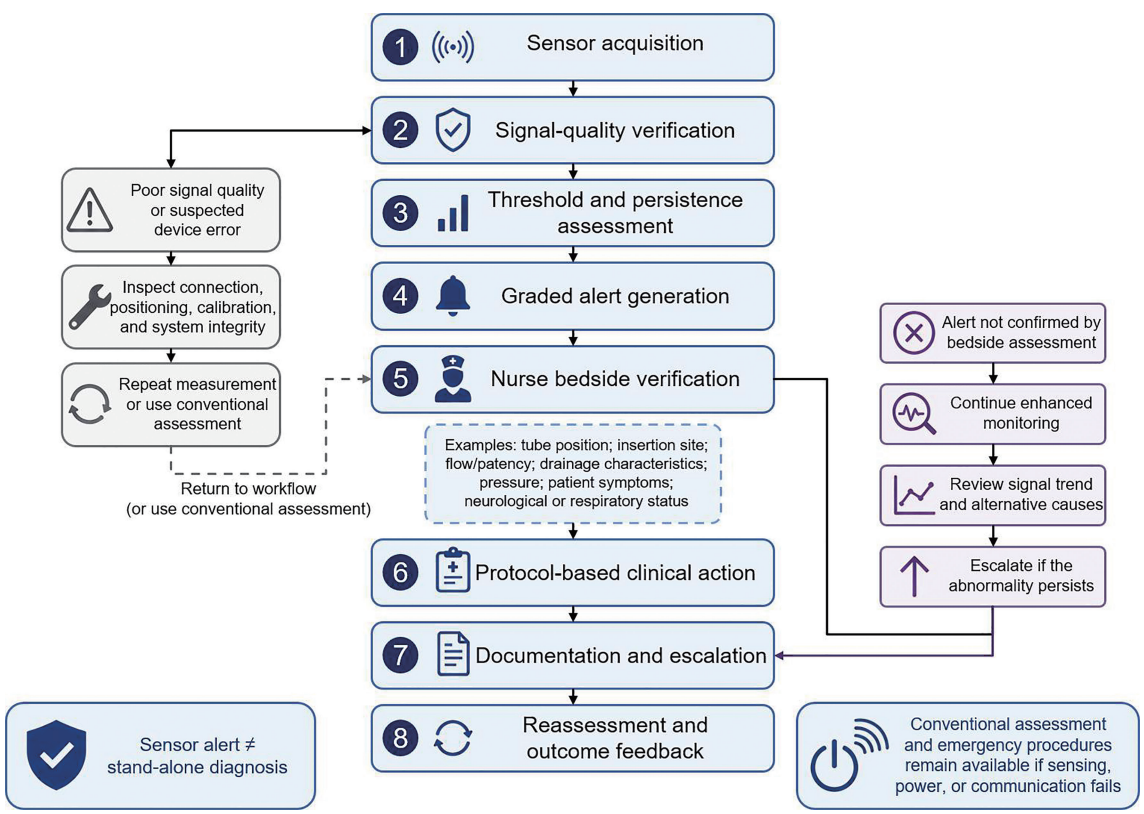

Figure 1: Proposed integration of smart catheter signals into nursing assessment and escalation workflows.

Simultaneously, the vast volume of data generated by smart sensing presents a challenge requiring attention. Without adequate filtering, continuously transmitting real-time impedance, pH, and micro-pressure data streams to nursing workstations may exacerbate information overload. Clinical research indicates that in intensive care environments, many medical-device alarms may be technically generated or clinically non-actionable. Over time, repeated non-actionable alarms can contribute to alarm fatigue, increased cognitive burden, and delayed responses to clinically important signals[45,46]. Therefore, the development of smart catheters should not simply add independent alarm streams to existing nursing workstations. Instead, alarm systems should incorporate signal-quality assessment, persistence criteria, multimodal confirmation, patient-specific baselines, graded alert priorities, and clearly defined escalation pathways.

AI and edge computing may assist in filtering raw sensor data, identifying clinically meaningful patterns, and reducing unnecessary data transmission. However, their application must be prospectively validated because poorly calibrated algorithms may also generate false alarms, miss clinically significant events, or introduce automation bias. The immediate objective should therefore be the development of transparent and clinically interpretable decision-support systems rather than fully autonomous catheter care. Alerts concerning possible extravasation, catheter occlusion, abnormal pressure, or infection-related changes should prompt nurse verification and protocol-based reassessment before clinical action is taken. Relevant clinical studies should report not only sensor sensitivity and specificity but also alarms per patient-day, false-positive rates, missed-event rates, response times, and effects on nursing workload.

Clinical translation also requires rigorous consideration of safety, regulation, cybersecurity, and data governance. Smart catheter systems must be evaluated for biocompatibility, electrical and thermal safety, sterilization compatibility, mechanical failure, sensor drift, wireless-power reliability, and the consequences of false-negative or false-positive results. Wireless and network-connected monitoring systems require lifecycle-based cybersecurity risk management, including device authentication, access control, data integrity and confidentiality, secure software updating, vulnerability monitoring, and incident-response planning[47]. Interoperability with electronic health records, nursing documentation systems, and hospital alarm platforms should be designed and validated to ensure that exchanged information is accurate, timely, correctly interpreted, and used only for its intended purpose[48]. For AI-enabled systems, algorithm versions, model updates, performance changes, and post-deployment monitoring should be documented, traceable, and auditable, and clinically meaningful information should be communicated transparently to users[49]. In addition, responsibility for reviewing sensor alerts and acting on automated recommendations must be clearly defined. Conventional catheter-assessment and emergency-response procedures should remain available whenever sensing or communication functions fail.

Future research should prioritize prospective and multicenter clinical validation rather than analytical performance alone. Studies should determine clinically actionable thresholds, evaluate long-term performance under realistic catheter-use conditions, and establish whether smart catheter systems reduce complications, improve response times, or meaningfully alter nursing workload. Future implementation studies should also assess staffing implications, responsibility allocation, and whether continuous sensor surveillance redistributes workload or alters nurse-to-patient monitoring demands across different care settings. Human-factors research is also needed to assess device usability, training requirements, alert interpretation, documentation burden, and the risk of overreliance on automated recommendations. Cost-effectiveness, regulatory pathways, compatibility with existing clinical infrastructure, and equitable implementation across different healthcare settings should be evaluated before widespread adoption. Nurses, patients, engineers, infection-prevention specialists, and clinicians should be involved in technology co-design to ensure that sensor outputs correspond to clearly defined and actionable clinical needs.

Distinct from previous technology-centric reviews that primarily categorize smart catheters by sensor modality, the novelty of this review lies in its clinically anchored, application-driven framework. By systematically mapping specific nursing challenges to corresponding sensing targets and technological approaches across urinary, vascular, respiratory, gastrointestinal, and surgical drainage

catheters, we provide a bidirectional translation interface between engineering capabilities and bedside care needs. Furthermore, we introduce a structured nursing workflow (Figure 1) that integrates signal verification, clinical reassessment, and escalation pathways, which is rarely addressed in engineering-oriented literature. The author-assigned evidence-maturity classification in Table 1 also offers a pragmatic snapshot of the translational readiness of current technologies, moving beyond mere proof-of-concept enumeration to guide realistic expectations for clinical implementation.

Several limitations of this review should also be acknowledged. First, as a critical narrative review rather than a systematic one, the literature identification was purposive and non-exhaustive; although this approach allowed us to anchor the discussion in representative application scenarios, it may have introduced selection bias and does not comprehensively cover all emerging sensing modalities or all published validation studies. Second, the majority of the referenced technologies remain at the laboratory, preclinical, or early clinical feasibility stage, and our evidence-maturity classifications reflect the highest validation level reported in each study—therefore, the clinical generalizability, long-term safety, and cost-effectiveness of these systems remain unconfirmed. Third, the review focuses primarily on English-language publications, potentially overlooking relevant studies published in other languages. These limitations highlight that the conclusions drawn here are intended to inform interdisciplinary dialogue and guide future translational research, rather than to serve as definitive clinical practice recommendations.

Accordingly, smart catheters should currently be viewed as emerging sensing and decision-support platforms whose clinical value will depend not only on sensor performance but also on reliable alarm design, nursing-workflow integration, safety assurance, and evidence of improved patient outcomes.

Author contributions

Rui Hong, Yu Qiu and Danmei Liang contributed equally to this article. Ming Yan and Xiaoyue Xu conceived the study, provided resources, and supervised the work. All authors reviewed, edited, and approved the final version of the manuscript and agree to its publication.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Grant No. 52203046), the State Key Laboratory of Advanced Polymer Materials (Grant No. sklpme2024-2-05), and the Fundamental Research Funds for the Central Universities (Grant No. 2682026CX134).

Data availability statement

No datasets were generated or analyzed for this work.

Ethics statement

Not applicable.

AI statement

The authors used DeepSeek as a language-editing tool to improve grammar, clarity, and readability. The AI tool was not used for data analysis, data generation, image processing, or scientific content creation. All outputs were carefully reviewed and verified by the authors, who take full responsibility for the final content.

Conflicts of interest

The authors declare no conflicts of interest.

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