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What Is Clinical Imaging Physics?*

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1.1 Introduction

Medical imaging started with physics. Since November 8, 1895 when the German Physicist and first physics Nobel laureate Wilhelm Roentgen discovered the mysterious “x” rays, physics has had a central role in the development and continuous advancement of nearly every medical imaging modality in use today. Thus, the research role of physicists in the research and development of medical imaging is well established. The use of the images in the care of the patient has also been largely undertaken by interpreting physicians (mostly radiologists) who undergo years of specialized training to be qualified for the task. But what about clinical physics? Is there an essential role for the presence and contribution of physicists in the *clinical practice* of medical imaging? The answer is an obvious yes, but how is this role defined? What are the essential ingredients for effective contribution of medical physics to the clinical imaging practice? In this chapter we outline the basic components and expectation of quality physics support of clinical practice across the current medical imaging modalities (Table 1.1).

1.2 Key Roles of the Clinical Physicist

1.2.1 Offering “Scientist in the Room”

In recent years we have seen a drive toward evidence-based medicine [2], ensuring that clinical practice is informed by science. Physics is a foundational scientific discipline. Physicists are trained and skilled in the language and methods of science. Their perspective can thus play an essential role toward evidence-based practice. Likewise, the current emphasis on comparative effectiveness and meaningful use puts extra scrutiny on the actual, as opposed to presumed, utility of technology and processes [3–6]. This highlights the need for a scientific approach toward practice, again with an obvious role for physics. In line with these moves, medicine is also seeing a slow shift toward quantification, using biometrics that personalize the care of the patient in numerical terms [7]. This provides for better evidence-based practice for both diagnostic and interventional care. Again,

* Some of the content of this chapter is based on a prior publication [1].

Table 1.1 Key expectations and activities of modern clinical imaging physics practice.

Attribute	Practice
1) Offering “scientist in the room”	Providing scientific and quantitative perspective in the clinic toward evidence-based, quantitative, and personalized practice
2) Assurance of quality and safety	Assuring quality, safety, and precision of the imaging operation across complex sources of variability throughout the clinical practice
3) Regulatory compliance	Assuring adherence to practice for quality and safety regulatory requirements as well as guidelines of professional practice
4) Relevant technology assessment	Quantifying the performance of imaging technology through surrogates that can be related to clinical performance or outcome – evaluations performed in the context of acceptance testing and quality control
5) Use optimization	Prospectively optimizing the use of the imaging technology to ensure adherence to balanced performance in terms of dose and image quality
6) Performance monitoring	Retrospective auditing of the actual quality and safety of the imaging process through monitoring systems – quality control at the practice level; troubleshooting
7) Technology acquisition	Guidance on comparative effectiveness and wise selection of new imaging technologies and applications for the clinic
8) Technology commissioning	Effective commissioning of new imaging technologies and applications into the clinic to ensure optimum and consistent use and integration
9) Manufacturer cooperation	Serving as a liaison with the manufacturers of the imaging systems to facilitate communication and partnership in devising new applications
10) Translational practice	Engaging in quality improvement projects (clinical scholarship) and ensuring discoveries are extended to clinical implementation
11) Research consultancy	Providing enabling resources and advice to enhance the research activities involving medical imaging
12) Providing education	Providing targeted education for clinicians and operators on the technical aspects of the technology and its features

physics is a discipline grounded in mathematics and analytics with direct potential for the practice of quantitative imaging. Finally, the mantra of value-based medicine [8] highlights new priorities for safety, benefit, consistency, stewardship, and ethics. To practice value-based care, the value needs to be quantified, which again brings forth the need for numerical competencies that physics can provide. Physicists have an essential role in the clinical imaging practice to serve as the “scientists in the room.”

1.2.2 Assurance of Quality and Safety

The overarching reason for the presence of medical physicists in the clinic is to assure the quality and safety of the practice. Medical imaging devices are diverse and complex. Their heterogeneity manifests itself in their diversity of type, make and model, and technical parameters. Combined with the diversity in patients, human operators, and stakeholders of varying (sometimes competing) interests, the practice left on its own creates variability in the quality of care. This variability is not insignificant and has a cost. A recent report from the National Academy of Medicine reports most people will experience at least one diagnostic error in their lifetime [9]. In fact 10% of patient deaths and 6–17% of hospital adverse events are due to diagnostic errors. Medical imaging being

largely a diagnostic process contributes to these statistics. The presence of clinical physicists in the clinic directly tackles this challenge. By overseeing the setup and use of the equipment and imaging processes, physicists offer an essential scrutiny of the operation to enhance consistency and minimize the likelihood of mishaps.

1.2.3 Regulatory Compliance

Toward the assurance of quality and safety, regulatory compliance and adherence to professional guidelines and standards offer a “scaffolding,” a safeguard against quality issues that have been documented previously. Apart from federal and state regulation, The Technical Joint Commission (TJC), Centers for Medicare and Medicaid Service (CMS), Environmental Protection Agency (EPA), American College of Radiology (ACR), American Association of Physicists in Medicine (AAPM), and others provide useful standards, the meeting of which require active engagement of clinical imaging physicists. However necessary, the regulation and compliance-weighted focus of the current clinical physics practice may not be enough; the newest clinical practice guidelines from the ACR and AAPM highlight this limitation [10, 11]. Physics is most relevant to the extent that it seeks to address clinical needs and limitations. Regulations, by necessity and their reactive tendencies, are always a step behind clinical opportunities, needs, and realities. Clinical physics practice should extend beyond compliance and should inform the development and refinement of regulations and accreditation programs.

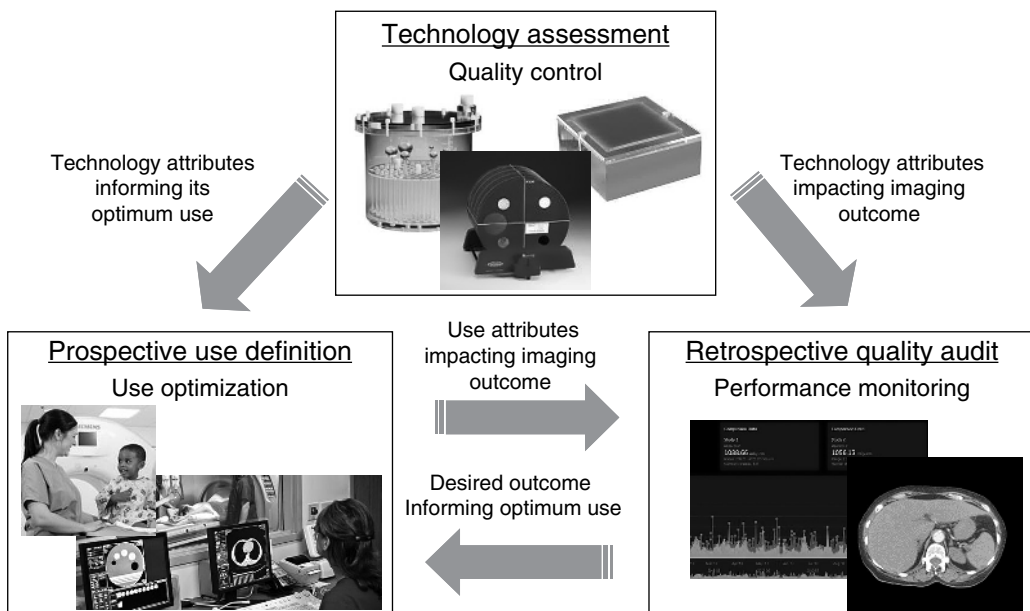


Figure 1.1 The three major components of clinical imaging physics practice according to the Medical Physics 3.0 paradigm. Attributes and assessment of technology (represented in the upper square) inform its optimum use (left square), and the two of them impact image outcome (right square). Outcome analysis conversely informs the optimum use of the technology.

1.2.4 Relevant Technology Assessment

The modern practice of clinical physics, as encouraged through the Medical Physics 3.0 paradigm [12], is based on three elements (Figure 1.1). One primary goal of clinical physics practice is technology assessment based on metrics that reflect the attributes of those technologies and relate to expected clinical outcomes. Toward that goal, the characterization of devices to ensure their adherence to vendor claims or regulatory guidelines is necessary but not enough; we must move from compliance-based to performance-based quality assurance. New physics practices should aim to devise and implement new metrics that are reflective of the performance of new technologies as well as the expected clinical outcome [12]. For example, characterizing the performance of a system in terms of detection or estimation indices (as opposed to the more conventional physics quantities of resolution or noise alone) can directly speak to the capability of the technology to deliver an objective clinical goal. In this way, physics can offer a quantification that is evidence-based and that can enable the meaningful comparison and optimization of new technologies and applications.

1.2.5 Use Optimization

Having ensured the intrinsic capability of the technology, as its second goal, the physics practice uses those attributes to ascertain how the technology can best be deployed in clinical service to ensure the desired image quality and safety for a given patient. This speaks to the optimized use of the technology so that a desired clinical outcome can be targeted [13–18]. A significant component of this activity is protocol development and optimization, addressing specific clinical needs including dose optimization, adjustments for patient attributes, indication-specific image quality, and contrast agent administration.

1.2.6 Performance Monitoring

The combination of relevant assessment and prospective optimization stated above should ideally provide actual optimum image quality and safety. In reality, however, there are many factors that influence the actual outcome of the image acquisition including unforeseen conditions, technological variability, and human factors. This is partly addressed by the troubleshooting mandate of clinical physicists. But that action is sporadic and only address the most noticeable issues of the practice. The physicist should in addition analyze the output of the imaging operation to ensure adherence to targeted expectations [19–26]. Using aggregate curated data sets such as those currently used in dose monitoring, this analysis can ensure that the actual output of the imaging technology matches its promise, capturing both its inherent capability and its optimum use. This type of analysis can target both the quality and the consistency of the operation, helping to better understand and mitigate variability in the clinical operation, and to quantify the actual impact of new technologies. Medical physicists, due to their content expertise and numerical training, are uniquely qualified to undertake this data science-based analysis.

1.2.7 Technology Acquisition

Medical imaging has been and remains subject to perpetual technological innovation. This is evident across all modalities: wireless digital technology and cone-beam multi-dimensional imaging in radiography and fluoroscopy, 3D imaging in mammography, advanced reconstructions and

spectral imaging in computed tomography (CT), new pulse sequences and functional applications in magnetic resonance imaging (MRI), 3D imaging and elastography in ultrasonography, hybrid imaging and molecular quantification in positron emission tomography (PET) and single photon emission computed tomography (SPECT), just to name a few. Each new technology offers new features, a good number of which are founded on physical and technological foundations. Which system among an array of commercial offering, and which options of that system are best suited for a clinical setting? Clinical physicist, with their strong technical background, can provide crucial advice in the selection of a system and decisions about the array of features that it may provide. They can evaluate the comparative advantages of the new features, predict how the new features may deliver their claim, and how they can be integrated within the existing practice at the site. This provides crucial input on evidence-based purchasing, to be supplemented with additional consideration for wise selections, such as cost, from the other members of the health-care team.

1.2.8 Technology Commissioning

Once a new medical imaging technology or system is installed, clinical physicists can play a vital role in their effective implementation in the clinic. New technologies cannot be assured to provide superior performance until their use is properly commissioned and optimized. A case in point is the transition from film to digital technology which led to a marked degradation of consistency across practice due to additional adjustment factors that were not optimized. Physics engagement is essential to ensure that well-intentioned and well-designed technologies are used effectively for the improvement of patient care.

Further, physicists can and do play an essential role in “commodifying the technology” so that the new addition does not compromise the consistency of care. The diversity of technology across a practice, while natural considering the evolving nature of the field, new innovations, and life cycle of systems (no institution can upgrade all its system all at once) creates a challenge to the consistency of image quality and dose across practice. While the consequent diversity is natural, it needs to be managed since an overarching hallmark of care is consistency. We cannot afford variability of care depending on what imaging room a patient is scheduled into. Good quality clinical physics can help manage and minimize this source of variability. Thus clinical physics can ensure wise selection as well as effective implementation of new technologies and applications consistent with the overarching new priorities of medicine (evidence, effectiveness, quantification, and value).

1.2.9 Manufacturer Cooperation

Considering the high innovation in the technology used in medicine today, the best practices are often enabled by a strong connection with the manufacturers that develop the technology. Best use of the technology requires understanding it well. Physicists, by expertise, tend to be best positioned to understand the technology. As such they are often ideal individuals from the institution to liaise with the manufacturer on the technical and operational features of the technology. Since they often have a perspective on the broad implication of the technology, they can also offer advice to manufacturers on how to best condition their products (e.g. making sure their image processing has adapted to the latest innovation in their detectors). They are also often best positioned to facilitate partnership to develop and advance new applications considering the nuances of the imaging systems that they can understand and communicate with the rest of the clinical team.

1.2.10 Translational Practice

A direct benefit of having a “scientist in the room” is the opportunity to improve the imaging practice through quality improvements, aka clinical scholarship. Many physicists engage and inform in research projects at healthcare institutions – a worthwhile added benefit of having physicists on staff. But beyond those, the scientific mind and the quantitative reasoning of the physicist can be put to use to address challenging elements of the clinical practice which by themselves might not even be considered “physics,” but nonetheless can benefit from the scientific approach. Examples include optimizing workflows across a clinic, discrepancies in the exam coding and billing, or devising key performance indicators (KPIs). The improvements can include direct physics expertise as well, such as devising a new method to test magnetic resonance (MR) coils, keeping track of ultrasound transducers across a QC program, or image analysis methods for more efficient physics testing. For any of these projects, a clinical physicist can and should ensure the scholarship involved is extended to workable clinical implementation, as clinical scholarship is oriented not only toward generalizable knowledge and dissemination (as in regular scholarship) but dissemination to clinical practice for the ultimate benefit of the patient.

1.2.11 Research Consultancy

Clinical physicists can be catalysts and enablers for academic research. They can serve this function even though their primary mission is and should be clinical. Nonetheless, this is of primary relevance to academic healthcare institutions with a mission toward research. Meaningful and impactful research in medical imaging often requires an understanding of the imaging system deeper than that needed in clinical practice. Clinical physicists, by the virtue of their expertise, which always needs to remain current, are best positioned to provide the consultancy and sometimes crucial resources to enable academic research involving medical imaging. Obviously, this aspect of clinical physics should be put in balance with their primary focus, which should claim the majority of their effort; however, as good citizens of the institution, seasoned clinical physicists are able to manage their clinical responsibilities while providing limited but needed assistance toward academic pursuits.

1.2.12 Providing Education

Physicians, tasked with the interpretation of medical images, in addition to specialized medical competency, require technical competency. Physicists are the essential experts to provide the necessary training for physicians in terms of four required elements of physician technical competencies: (i) the foundations of contrast formation in a given imaging modality; (ii) the technological components that enable the acquisition of an image; (iii) the modality’s operational parameters and their influence on image quality and patient safety; and (iv) how to practice imaging within the constraints of the imaging modality and the needs of the indication [27]. These elements are cornerstones of the physics competency expected from radiologists by the American Board of Radiology. Additional training in the effective use of new technologies, for either physicians or technologists is also necessary, so those individuals can be best empowered to focus on *their* direct mandate: patient care. Physicists are uniquely tasked and qualified to provide the needed education to such practicing clinicians.

1.3 Challenges to Effective Clinical Physics Practice

Quality practice of clinical physics can be challenging. The challenges are not insurmountable, as seasoned physicists and physics practices have been able to find practical ways to manage these challenges. However, mindfulness of these challenges can be informative as the discipline advances and quality educational methods are devised for the next generation of clinical physicists.

1.3.1 Scope of Competency

The first challenge is simply the magnitude of knowledge that a clinical physicist is expected to master to practice effectively in the clinic. This is not just traditional medical physics knowledge, which by itself is ever expanding thanks to the progressive nature of medical imaging; but further, a clinical medical physicist needs to have enough foundational clinical and associated peripheral knowledge to be effective clinically. For these peripheral areas, the physicist should have enough knowledge to be able to communicate across diverse clinical disciplines. Equally importantly, they should know, with confidence, what they know and what they do not know to be able to engage with the clinical process effectively. New topics that require expanded mastery include, but are not limited to, data science and artificial intelligence, process engineering, multi-factorial optimization, bio-informatics, radiomics, and radiogenomics.

Added to this list are the so-called soft skills of leadership and communication that have become essential for clinical practice. Good communication skills are essential for leading and working with clinical teams and for communicating with patients in matters related to dose or technical aspects of patient care. With those skills, clinical physicists should take ownership in closer collaboration with physicians and other healthcare professionals. Many physics outputs and services are currently oriented toward physicist “audiences.” To fully harness the value of those services, the physicists should own an increasingly inter-disciplinary strategy to seek their full clinical impact, for which leadership and communication competences are needed alongside seasoned physics expertise. A clinical physicist should thus perpetually seek wisdom and mentorship in balancing the breadth and depth of these needed competencies for good practice.

1.3.2 Balancing Rigor and Relevance

Clinical imaging physicists are both scientists and care providers. As scientists they have been trained to seek perfection and seek reality, yet as practitioners they need to be equally aware of practical limitations and care delivery. The science that they pursue by itself is highly applied – not oriented toward generalizable knowledge, even though that is sometimes the case – but oriented toward applicable benefit to the patient. Maintaining this balance of scientific rigor and clinical relevance is a challenge. A perfect solution is often out of reach, due to lack of time, or money, or external support, but a solution is needed nonetheless. Navigating this landscape is yet another area where mindfulness, mentorship, and wisdom are needed for better practice.

1.3.3 Managing Surrogates

In clinical imaging physics we seek to assess and optimize the quality and safety of the practice toward the assumed eventual improvement of the care outcome. However, a direct relationship between our measures and the outcome is very difficult to ascertain given the diversity across the

patients and confounding effects within the care process. Short of having conclusive evidence, we are left with surrogates (Figure 1.2). Within that space, measures that are more directly related to the quality and safety of care for the patient are likely most relevant. For example, organ dose and validated detectability indices are more closely related to the radiation burden and quality of a CT exam than computed tomography dose index (CTDI) and noise. However, more progressive surrogates such as organ dose are also more prone to estimation errors. Balancing the benefit of a high relevance of a metric and its limited approximation is a delicate choice that needs to be made on a situation by situation basis to ensure the most effective practice of clinical physics.

1.3.4 Integrating Principle- and Data-Informed Approaches

Most of physics is based on methodical principles and their logical conclusions. However, that can never be assumed to be without potential error, thus the reason for experiments. Applying the same to clinical medical physics, we may apply our knowledge of imaging devices and processes to devise their optimum use. However, the actual image data that they produce give us highly-relevant information about the effectiveness of our assumptions. A clinical physicist should be able to seamlessly integrate the principle-informed approaches of clinical physics with data-informed methods to ascertain and target the best practice. The current focus of healthcare on machine-learning and artificial intelligence provides ample resources toward that goal if physicists can learn to navigate and use these resources, and be a catalyst in their effective use in clinical care [28, 29].

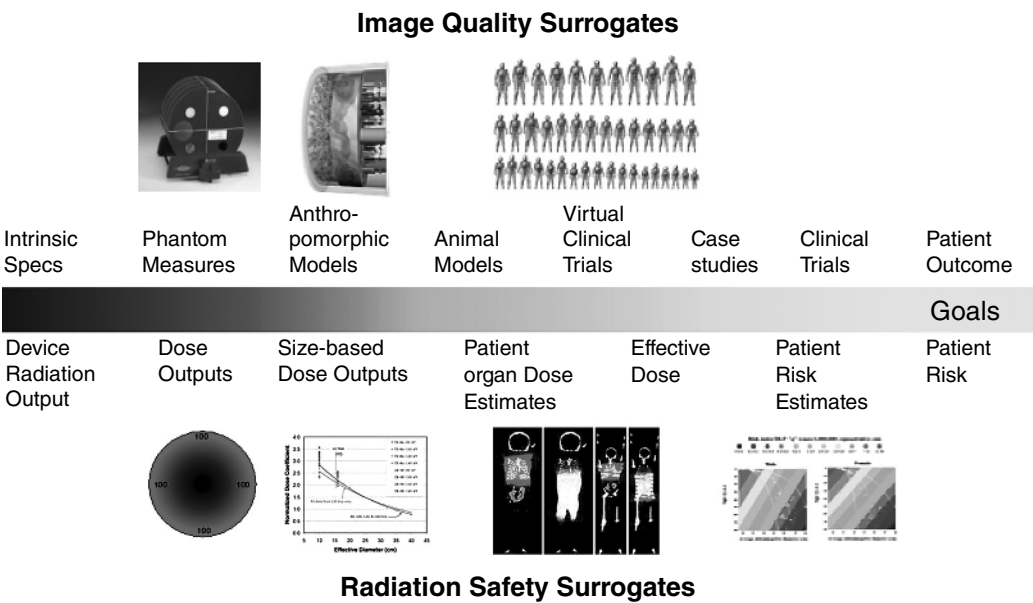


Figure 1.2 The spectrum of the surrogates of image quality (top) and radiation safety (bottom) (for radiation imaging modalities) to reflect the desire goals of the assessments (i.e. patient outcome and patient risk). Short of that knowledge, clinical physicists use reasonable surrogates along a spectrum. The ones on the left are easier to assess but relevance is inferred, while the ones toward the right tend to be more relevant but subject to estimation error. Balancing the two competing desires of relevance and robustness becomes a requirement of effective clinical physics practice.

1.3.5 Effective Models of Clinical Physics Practice

As outlined here and detailed in the chapters of this book, the values that clinical physics offer to clinical practice of medical imaging go well beyond compliance with current regulatory standards. However, that is not widely recognized within the healthcare enterprise today. Clinical physicists should secure justification for the contribution of their expertise to clinical practice. This call for a deeper investment in medical physics toward enhancing patient care comes at a time when radiologic interpretation duties consume even more time than before and National Institutes of Health (NIH) funding concerns and economic pressures in hospitals potentially pull physics and radiology apart. Many institutions are either not aware of this potential, or opt for the minimum of regulatory compliance. Some institutions, however, seem able to manage these pressures and effectively harness the value of physics in their practice. How? What are the best working models that can enable better concordance and integration of radiology and physics?

There are differences even among best practices, but all institutions that have managed to harness the full value of clinical physics in their practice toward improved patient care share certain common attributes:

- 1) There is high degree of consciousness at the leadership of the institution about the historical track record and value of medical physics.
- 2) Exemplary physicists have been able to go beyond the realm of theoretical possibility and demonstrate the value of physics within the clinical practice in practical ways.
- 3) The complementary nature of the expertise of the physician and the physicist is recognized and respected. A feature of civilized society is its ability to use professionals for its specialized needs. Such is the case for institutions that defer to physicists on issues that need physics solutions.
- 4) Funding for physics services is justified based on added value. At one institution, 2% of radiology revenue is allocated to radiological physics based on the track record that the investment has paid more than its share in ensuring the quality and safety of the operation, wise investment in equipment acquisition and replacement, and minimum liability for near misses.
- 5) In an era in which patients have choices, these institutions recognize that the distinction of a high-quality and high-safety operation can lead to greater market-share of healthcare services.

The above model of practice and justification of physics services in the imaging departments is based on the “in-house” model of physics practice. In recent years, there has emerged a steady and growing practice of consulting physicists that provide an essential service to the community. Providing physics services beyond meeting the regulatory compliance can readily be offered through these consulting practices provided that the clinical services are aware of the richness of physics contribution to clinical practice, as outlined in this chapter and detailed in the modality-specific chapters of this book. Encouraging physics-informed practices and adapting the practice models to meet the demand should be a high priority for the evidence-based and value-based practice of medicine. Indeed, the reimbursement framework itself needs to be modified to recognize the value of diagnostic clinical medical physics, both in quality of patient care and in cost savings due to improved efficiencies. Clinical physics should not be seen just as a cost center, but a central component of diagnostic imaging.

1.4 Conclusions

Medical imaging and interpretation continue to provide unprecedented value to healthcare. Innovative technologies offer enhanced opportunities for high-quality imaging care. These new clinical realities, however, require the utmost rigor in the effective use of technology in the drive

toward high-quality, consistent practice of medical imaging that is patient-centered, evidence-based, and safe. Medical physics enables innovative precision care through the targeted clinical application of physical sciences. The relationship between medicine and physics is mutual and essential for the overall goal of medicine: fostering human health. In the current healthcare landscape of enhanced and diverse imaging options, optimized use of the technology cannot be assumed. Clinical physics can address this gap by extending beyond compliance testing toward intentional evidence-based and value-based use of the technology to serve clinical care.

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