Bob's first decade: In at the beginning

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ABSTRACT

Arriving at the Bureau of Radiological Health in 1972, Bob Wagner was thrust into the Bureau's quandary over how to quantify the imaging benefit associated with the radiation dose cost of medical imaging procedures. In short order he had set up the framework for FDA imaging research for the next 36 years. Bob played a key role in these early years in assisting in the founding of the SPIE Medical Imaging series of meetings, in measuring and organizing round robin comparisons of imaging measurements of the fundamental physical quantities required for performance evaluation, and in developing the framework for how these measurements could be combined to provide meaningful assessment figures of merit. He worked assiduously to counter both those who claimed that radiology was an art not a science and those who made extravagant claims for the dose reduction/image quality benefits of their particular variety of image capture/image processing system. In the process he became one of the founding fathers and key participants in the medical image performance assessment community as represented today at SPIE Medical Imaging 2009.

Keywords: Robert Wagner, imaging performance, medical imaging

1. INTRODUCTION

Dr. Robert F. Wagner was a distinguished member of the medical imaging research community. His numerous (160 plus) publications and collegial interactions with his peers have left an indelible imprint on the field. His death this past June 30 has left a void in the research world and a wound in the hearts of those who knew him. It is therefore fitting to look back fondly over his career, toast his accomplishments, and dedicate ourselves to continuing on the path his footsteps trod so deftly and well. Having been his friend for over 30 years, and addressing this to an audience many of whose members have similarly known him for many years, I will take the liberty of referring to him simply as "Bob." I also will be unashamedly parochial in viewing his work from the perspective of our imaging laboratory, formerly part of the Bureau of Radiological Health (BRH), Food and Drug Administration (FDA) and now organized in the Center for Devices and Radiological Health (CDRH), FDA.

Let us hearken back to Bob's early years (Fig. 1), which were also early years for the quantitative performance analysis of medical imaging systems. Bob was a proud Philadelphian, born 10 January 1938, a south Philly guy who graduated from Villanova as valedictorian and who frequently returned to visit family and friends. Bob committed his life to the Catholic faith and received his MA in theology from Augustinian College in Washington, DC. However, he came to the realization that his true leanings were not with the church but with the intellectual stimulation of the discipline of physics. Bob graduated from Catholic University with a degree in (nuclear) physics in 1969. After three years in the nation's hinterland at Ohio University, he returned to his "home base" by obtaining a position at BRH.

When Bob entered BRH in July 1972, the Bureau was recently armed with a fresh congressional mandate for the regulation of radiation emitting products: The Radiation Control for Health and Safety Act of 1968, Public Law 90-602. In its inimitable fashion, Congress partitioned off a new category of radiation: "electronic product radiation," which includes mechanical vibration, e.g., ultrasound, as well as the entire electromagnetic spectrum—as long as it is produced by an electronic device (thereby ruling out radioisotopes and Ringo Starr). Regulation of x rays from color TVs and microwave leakage from ovens was straightforward: get rid of it; however, medical imaging presented a problem: the harmful radiation is an integral part of the imaging process. A cost-benefit analysis was in order, requiring not only dose

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Fig. 1. Bob's early years. Left: Bob pre-BRH. Right: Bob after three months at BRH, in the 1972 SPIE proceedings [1].

measurements, at which the Bureau excelled, but also quantification of the benefit, i.e., the quality of the produced image. Regulation of medical radiation had to entail a detailed understanding of the imaging process and of its "product," the medical image.

Bob was tasked with putting together a review of the field as it pertained to the then dominant film/screen radiographic systems. This review was published in the proceedings of the original precursor to the Medical Imaging series of meetings: the SPIE Application of Optical Instrumentation in Medicine, held in Chicago in November 1972 [1]. Viewed from today's perspective, Bob's 1972 paper seems prescient and hardly conceivable as the work of a three-month novice to the field. Bob identified the best current work in the field and the ideas from outside that were most relevant to it. He referenced papers by Lloyd Bates [2], Kurt Rossmann [3], Russell Morgan [4], Kunio Doi [5], Martin DeBelder [6], and other researchers with whom he would have many productive interactions. Even more significantly, he referenced such creative thinkers as Otto Schade [7], Claude Shannon [8], Albert Rose [9], and Lee Lusted [10], whose ideas he would profitably pilfer and augment over the remainder of his career (and Woody Allen [11], another source of inspiration). Just like Willie Sutton, Bob had a keen sense of where the "money," i.e., good ideas, were, and he had a tremendous talent for incorporating them into our new field.

In his 1972 review, Bob described the elements of sensitometry, modulation transfer-function (MTF), and noise-power (Wiener) spectrum that would occupy the laboratory's measurement program for the next decade. He laid out the details of various image quality indexes and discussed the concepts of signal-to-noise ratios, optimal detectors, and receiver operating characteristic (ROC) curves. He baldly asserted that "One thing, however, is certain – that it [image quality] must be defined in terms of the task that the image is destined to perform," setting the laboratory on the course of the task-based performance assessment that remains at the center of our program. Clearly, Bob (and the rest of us) were subsequently vastly overpaid. If he could do such a thorough job of dissecting the field in three months, only a few more should have sufficed to polish off all of its remaining unresolved difficulties.

Over the course of the next two years, Bob developed the measurement and analytical capabilities of the BRH laboratory to apply these techniques to the assessment of screen-film radiography. His "coming out party" was the 1974 SPIE Medical X-ray Photo-Optical Systems Evaluation meeting in Columbia Maryland (Fig. 2), which he played a key role in organizing, at which he presented his results, and which established him as a significant figure in the field for the first time [12]. This meeting also cemented the SPIE as the home of a key segment of the medical imaging community. SPIE and all of his friends and colleagues who have participated in the Medical Imaging series of symposia meant a great deal to Bob and he to it and them. Much of his best work was presented here, and many of the ideas critical to the development of the field were nurtured on the personal conversations fostered by the meeting.

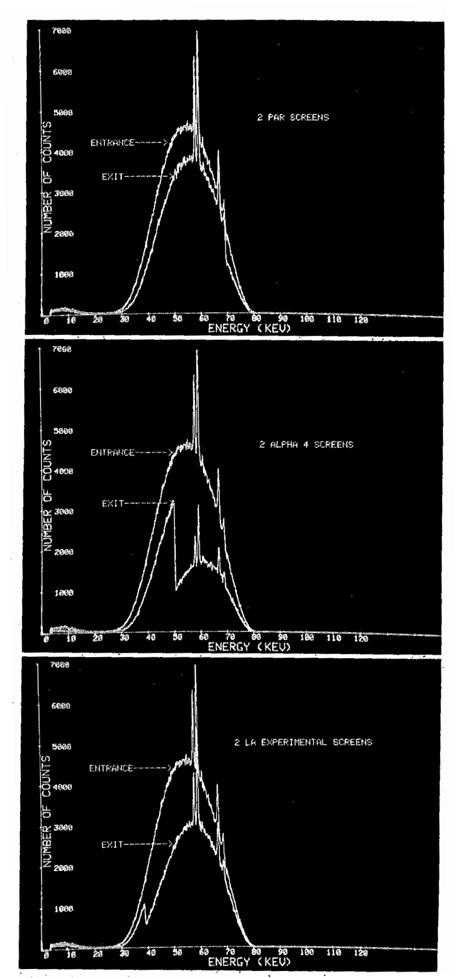

Figure 2. The fundamental reason for the approximation in Figure 1 being Gaussian. This Figure is also approximately Gaussian.

Fig. 2. Two figures from the 1974 SPIE proceedings [13]. Left: Entrance and exit spectra from pairs of intensifying screens demonstrating the increased x-ray absorption of new rare-earth screens, top – standard calcium tungstate screens, center – 3M Alpha 4 rare-earth screens, bottom - experimental lanthanum screens. Right: An example of Bob's characteristic humor, referencing the distribution of optical density readings for a noisy radiograph (or Gaussian portrait).

2. SCREEN FILM SYSTEMS

As Bob noted in his 1972 review:

> An integral part of the diagnostic x-ray system which was not addressed …is the image receptor system (film-screen combinations, grids, cassettes, etc.) and the associated film processing. Therefore we are developing laboratory capabilities and methodology in order to assess and test the performance of these items as a prerequisite to possible inclusion of expanded performance requirements under the diagnostic x-ray standard.

Bob became an experimentalist. The sight of a theoretician in the lab can be a terrifying spectacle; however, Bob managed very well, with a little help from his friends (Fig. 3). With radiation dosimetry, spectroscopy, and microdensitometry capability, a well-calibrated x-ray tube on an optical bench, a state-of-the-art HP computer

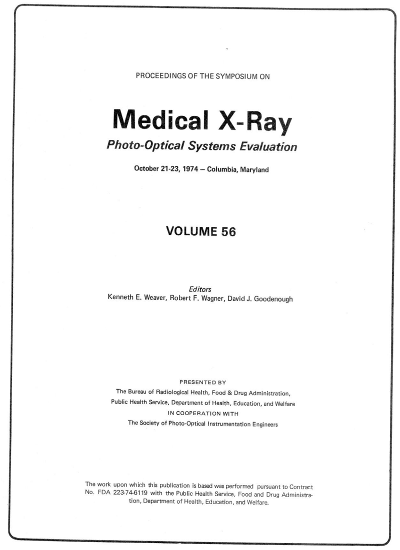

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Fig. 3. Left: Bob with a few of his friends, The Medical Physics Imaging Group in 1981: Left to right, Dean Elbert, David Brown, Tom Fewell, Pam Clatterbuck, Roger Schneider (boss), Mal Bruce, Mary Pastel, Ralph Shuping, Bob Jennings, Bob, John Sandrik, John Villforth (boss boss), Right: Cover page from the 1974 SPIE Columbia, MD meeting [12].

(64 kilobytes of memory and both magnetic and punched paper tape capability), Bob had the whole package of physical measurements for the assessment of screen-film radiographic systems. Bob introduced digital noise analysis to radiography and proved that noise power and MTF measurements could be made reliably on an absolute scale. He launched a program of inter-laboratory comparison of measurements on radiographic film samples that were circulated among fifteen commercial, government, and academic laboratories world wide. In the process he became the prime mover for work toward consensus methodology for quantitative imaging performance measurements. Interactions with Kunio Doi and his laboratory at the University of Chicago, Ken Hansen at Las Alamos, and Murray Cleare at Kodak were particularly significant during this period.

3M had recently brought out new rare-earth-phosphor based screens using technology from the color TV industry. The screens were noticeably noisier than the standard calcium tungstate screens and were not well received by the radiology community despite the dose savings that they offered. Spectroscopic measurements demonstrated that the increased radiation stopping power of the screens provided a factor of two dose savings (Fig. 2); however, 3M over-reached by achieving an additional factor of four by increasing the number of light photons per absorbed x-ray—thereby increasing the noise to an unacceptable level. Bob worked closely with academic colleagues and with the film-screen manufacturers to understand the tradeoffs involved and played a major role in providing the fundamental underpinnings to what would prove to be the greatest dose reduction to the U. S. population ever achieved.

3 SYSTEMS AND SIMULATION

Bob established the principle that the laboratory would be concerned with the entire imaging process, from the x-ray focal spot to the image capture mechanism. Subsequently he extended this to image display and the human (or other) observer of the images as well. Bob recognized that there were inefficiencies at all stages of the imaging process, and that to understand the performance of an imaging device, all of them had to be considered. Bob's collaboration with Bob Jennings in the "Bottom line" paper [14] was particularly significant as an example of the payoff from this approach. The Bobs were able to show that significant dose savings were possible by using a "systems" approach to the problem. Changes to one component of a system have ramifications for the appropriate choices of other components and therefore can't be considered in isolation.

This principle is also a precondition for system optimization and for computer simulation or "in silica" studies. There are simply too many parameters to tweak in an advanced imaging system to be able to investigate its performance in "parameter space" in the lab. Virtual optimization using the computer had become a necessity and with the quantitative

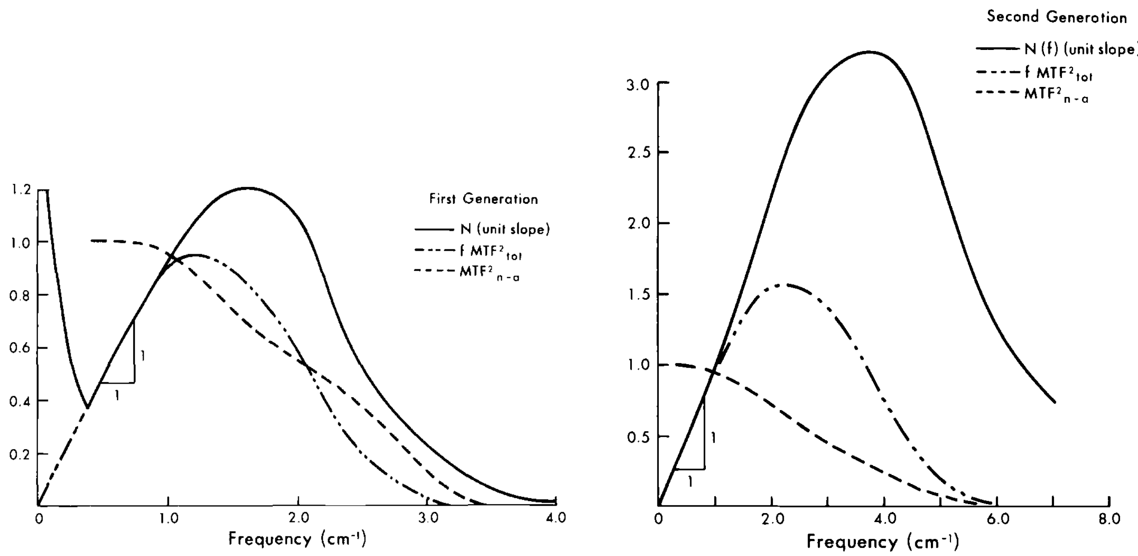

Fig. 4. Noise power spectra of (left) the EMI Mark I and (right) the EMI CT505 normalized to unit slope in low frequencies and construction for obtaining information bandwidth integral (IBWI). The ordinate scale is dimensionless except for the lower two curves for which it is in units of frequency (cycles/cm) [16].

characterization of the effect of each component of the chain, it had become tractable—or at least would be with the advent of increased computational resources.

4. COMPUTED TOMOGRAPHY

What an incredible period of technological development has occurred over the past several decades. The development and commercialization of computed tomography (CT) systems in the early 1970s was a truly revolutionary development, joining the radiologist inextricably to modern mathematics and computer science. Reconstruction imaging was coming into its own.

These new technologies led to a concomitant revolution in the assessment of imaging technologies. Bob was in the thick of this struggle. The enemies were art, the ad hoc, and the grandiose. One school claimed radiography as an art: the interaction between the radiologist and the image were far too complicated to be expressed in mathematical form, and a system were good only in so far as the radiologist (the artist) judged it to be so. The second school was content to come up with a few engineering figures of merit, e.g., point signal to noise ratio, to characterize imaging performance—without any regard to underlying fundamental theory. Finally, the third school was so impressed with the promise of new technology that it believed all constraints could be overcome, all limitations resolvable.

CT was heavily represented by the "third school," in particular by algorithm developers with unbounded belief in the potential efficacy of their algorithms and feelings of unremitting urgency for NIH to fund their development efforts. As I recall, it was the spring of 1978 that Bob, Mary Pastel, and I met with one such enthusiastic soul down on the NIH campus, who declared that his calculations showed a 100-fold dose reduction could be attained. Other investigators, e.g., Moran et al. [15] published similar (if less sweeping) claims for potential dose reduction.

Bob set out to resolve this issue. The results of his analysis were published in 1979 as "Application of information theory to the assessment of computed tomography" [16]. The analysis was grounded in information theory as formulated by Shannon. It was presented in terms of spatial frequency analysis, produced algorithm-independent measures of CT detection capability, and was applied to actual data from early CT systems—as shown above in Fig. 4. As noted in that paper, the conclusion was clear:

> The latter authors' suggestion for drastic dose savings is not consistent with our analysis…. First and second generation EMI CT are nearly quantum limited systems for large low-contrast signals.

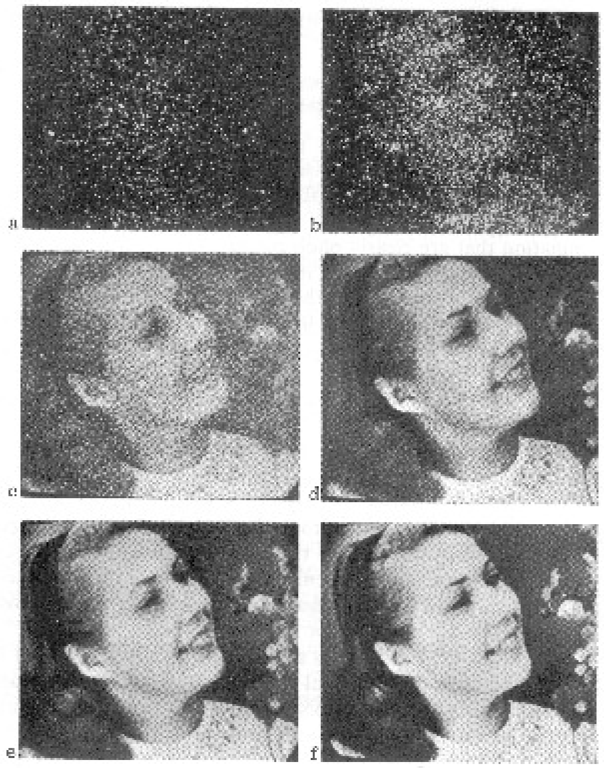

Fig. 5. Would a rose with fewer quanta smell so sweet? Pictures made with an increasing number *N* of photons: a. $3x10^3$, b. $1.2x10^4$, c. $9.3x10^4$, d. $7.6x10^5$, e. $3.6x10^6$, f. $2.8x10^7$. "The numbers of photons *N* refer to the total number of photons in the picture if the picture were uniformly at its high-light brightness," per Rose [17].

Bob demonstrated that CT is by nature a high dose technique and that we have the ability to understand its performance based on a first-principles analysis.

5. GRAND UNIFIED THEORY

Bob searched throughout his career for unifying principals and themes. He read widely in many areas of science, and one of his recurrent themes was word-play on the effort then being made in fundamental physics to discover a grand unified theory of everything, tying together the strong, weak, electromagnetic, and gravitational forces into one neat package. That effort proved rather more difficult than the physicists of the 1970s hoped; however, both they and we have seen considerable progress in our respective fields.

For Bob, one of the earliest of these great unifying ideas was expressed most clearly by Albert Rose (Fig. 5) [17]. Rose showed how for images made by light photons, the "quality" of the image depended directly upon the number of photons used in making the image. Any image would be made by a certain number of photons. An ideal system would require the fewest photons to make that same image—the number of photons the image was "worth." Therefore, the efficiency of a system could be obtained by dividing the number of photons an image were worth by the number actually required to produce it.

These concepts could be naturally extended to the ideas of noise-equivalent quanta (NEQ) and detective quantum efficiency (DQE) that were fundamental to so much of Bob's work. When incorporated within the spatial frequency framework that was also a key feature of his thinking, they gained added power and relevancy. Subsequently, the shortcomings of working in the frequency domain would become evident; however, the fundamentals of Bob's early analysis have held up very well over the years.

Table 1. Table 2 from "Unified SNR analysis of medical imaging systems [18], showing noise power spectra and SNR^2 for ten different imaging modalities—and no, I'm not going to explain it further, so you'll just have to read the reference.

Table 2. Noise power spectra and SNR^2 for ten modalities. $\mathrm{SNR}^2 = A \times (\text{aperture factors})$.

Mode	Noise power spectrum, $W(f)$	A	Aperture factors: For $\mathrm{SNR}_{\mathrm{qi}}^2$	Aperture factors: For $\mathrm{SNR}_{\mathrm{i}}^2$	$\mathrm{SNR}_{\mathrm{qi}}^2(a_{\mathrm{alg}} \to 0)/\mathrm{SNR}_{\mathrm{i}}^2$	$\mathrm{SNR}_{\mathrm{qi}}^2(\text{optimal } a_{\mathrm{alg}})/\mathrm{SNR}_{\mathrm{i}}^2$
2D projection radiography	$\mathrm{NEQ}_2^{-1}\mathrm{MTF}_{\mathrm{alg}}^2(f)$	$(\Delta\mu t)^2\mathrm{NEQ}_2$	$\left(\frac{a_0}{2}\right)^2 \frac{a_N}{a_{\mathrm{i}}^2}$	$\left(\frac{a_0}{2}\right)^2 \frac{1}{a_0+a_{\mathrm{AP}}}$	1	1
2D energy selective radiography	$\mathrm{NEQ}_i^{-1}\mathrm{MTF}_{\mathrm{alg}}^2(f)$	$(\Delta t_{\mathrm{I}})^2\{\Sigma_i[\mathrm{cof}(\mu_{1i})]^2/\mathrm{NEQ}_i\}^{-1}$	$\left(\frac{a_0}{2}\right)^2 \frac{a_N}{a_{\mathrm{i}}^2}$	$\left(\frac{a_0}{2}\right)^2 \frac{1}{a_0+a_{\mathrm{AP}}}$	1	1
2D CT X-rays	$(\pi f/\mathrm{NEQ}_1)\mathrm{MTF}_{\mathrm{alg}}^2(f)$	$\Delta\mu^2\mathrm{NEQ}_1$	$\left(\frac{a_0}{2}\right)^2 \frac{2}{\pi}\frac{a_N^{3/2}}{a_{\mathrm{i}}^2}$	$\left(\frac{a_0}{2}\right)^2 \frac{1}{(a_0+a_{\mathrm{AP}})^{1/2}}$	$\frac{2}{\pi}$	$\frac{3^{3/2}}{2\pi}$
2D PET	$\frac{\rho_2 D \exp(+\mu D)}{\eta m}\pi f\, \mathrm{MTF}_{\mathrm{alg}}^2(f)$	$\frac{C^2 m\rho_2\eta \exp(-\mu D)}{D}$	$\left(\frac{a_0}{2}\right)^2 \frac{2}{\pi}\frac{a_N^{3/2}}{a_{\mathrm{i}}^2}$	$\left(\frac{a_0}{2}\right)^2 \frac{1}{(a_0+a_{\mathrm{AP}})^{1/2}}$	$\frac{2}{\pi}$	$\frac{3^{3/2}}{2\pi}$
2D CT, NMR	$\frac{4kTR_e\Delta fF}{mD}\pi f\, \mathrm{MTF}_{\mathrm{alg}}^2(f)$	$\frac{\Delta V_2^2 mD}{4kTR_e\Delta fF}$	$\left(\frac{a_0}{2}\right)^2 \frac{2}{\pi}\frac{a_N^{3/2}}{a_{\mathrm{i}}^2}$	$\left(\frac{a_0}{2}\right)^2 \frac{1}{(a_0+a_{\mathrm{AP}})^{1/2}}$	$\frac{2}{\pi}$	$\frac{3^{3/2}}{2\pi}$
2D FT, NMR	$\frac{4kTR_e\Delta fF}{XY}$	$\frac{\Delta V_2^2 XY}{4kTR_e\Delta fF}$	$\left(\frac{a_0}{2}\right)^2 \frac{a_N}{a_{\mathrm{i}}^2}$	$\left(\frac{a_0}{2}\right)^2 \frac{1}{a_0+a_{\mathrm{AP}}}$	1	1
3D CT, line integrals, γ rays	$\frac{\rho_3 D \exp(+\mu D)}{\eta m}2f\, \mathrm{MTF}_{\mathrm{alg}}^2(f)$	$\frac{C^2 m\rho_3\eta \exp(-\mu D)}{D}$	$\left(\frac{a_0}{2}\right)^3 \frac{\pi}{4}\frac{a_N^2}{a_{\mathrm{i}}^3}$	$\left(\frac{a_0}{2}\right)^3 \frac{1}{a_0+a_{\mathrm{AP}}}$	$\frac{\pi}{4}$	$\frac{8\pi}{27}$
3D CT, planar integrals, γ rays	$\frac{\rho_3 DL \exp(+\mu D)}{\eta m}2\pi f^2\mathrm{MTF}_{\mathrm{alg}}^2(f)$	$\frac{C^2 m\rho_3\eta \exp(-\mu D)}{DL}$	$\left(\frac{a_0}{2}\right)^3 \frac{1}{3}\frac{a_N^{5/2}}{a_{\mathrm{i}}^3}$	$\left(\frac{a_0}{2}\right)^3 \frac{1}{(a_0+a_{\mathrm{AP}})^{1/2}}$	$\frac{1}{3}$	$\frac{5^{5/4}}{9}$
3D CT planar integrals, NMR	$\frac{4kTR_e\Delta fF}{mD}2\pi f^2\mathrm{MTF}_{\mathrm{alg}}^2(f)$	$\frac{\Delta V_3^2 mD}{4kTR_e\Delta fF}$	$\left(\frac{a_0}{2}\right)^3 \frac{1}{3}\frac{a_N^{5/2}}{a_{\mathrm{i}}^3}$	$\left(\frac{a_0}{2}\right)^3 \frac{1}{(a_0+a_{\mathrm{AP}})^{1/2}}$	$\frac{1}{3}$	$\frac{5^{5/4}}{9}$
3D FT, NMR	$\frac{4kTR_e\Delta fF}{XYZ}$	$\frac{\Delta V_3^2 XYZ}{4kTR_e\Delta fF}$	$\left(\frac{a_0}{2}\right)^3 \frac{a_N^{3/2}}{a_{\mathrm{i}}^3}$	$\left(\frac{a_0}{2}\right)^3 \frac{1}{(a_0+a_{\mathrm{AP}})^{3/2}}$	1	1

Fig. 5 is also a good example of Bob's concern for finding concrete images to help get across his ideas. Bob liked to use the image of the average "Metro" rider as someone with whom he were trying to communicate. He tried to give "feelys" to his audience—images, rather than abstract mathematical forms, that made his presentations more understandable and meaningful to us (if not necessarily to the average Metro rider).

Bob's earliest work dealt with projection radiography, with its obvious connection between x-ray quanta and image noise. He then extended his analysis to include x-ray reconstruction imaging (CT), and more imaginatively, to address aspects of ultrasound imaging, for which speckle could play the role of x-ray quanta. In 1985 he moved even more aggressively to include the whole field of medical imaging. Table 1 is taken from "Unified SNR analysis of medical imaging systems" [18], in which he calculated performance metrics for ten different modalities, including positron emission tomography and several variants of magnetic resonance imaging when it was still "nuclear magnetic resonance" imaging.

In that publication Bob's goal was to show how using only "a few fundamentals of signal detection theory and the classical imaging measurements... we derive the task-dependent ideal observer signal to noise ratio." This could be used for system performance evaluation, e.g. during system development/optimization and indicate the kinds of constraints which limit an imaging system. It showed conclusively how the many different imaging modalities could be considered within the rubric of one unified approach.

6. CONCLUSION

Bob was a seminal figure at the beginning of the field of quantitative imaging performance assessment. His contributions to making this a scientific discipline grounded in the fundamentals of information science, in unifying the field around a few key concepts, and in demystifying it of outdated ones were of critical importance. More than that, he gave of himself readily, mentoring a succession of close collaborators and interacting collegially with a much wider circle of researchers. His work was appreciated by the Agency (Fig. 6), and by his peers—as witness his rank of "fellow" in many professional societies, first and foremost, of course, SPIE.

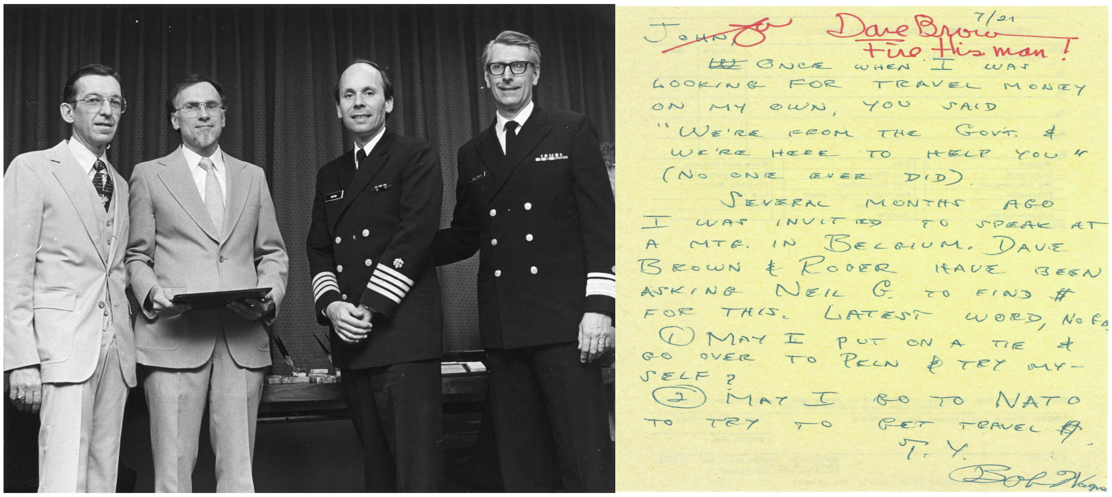

Fig. 6. Bob was always appreciated and honored, well nearly always. Left - with the usual cast of supervisory salad dressing (David Brown and John Villforth) being presented an award by FDA Commissioner Arthur Hayes, far left. Right – acerbic note from the Admiral (Villforth) upon discovering Bob's latest indiscretion.

Walt Whitman wrote poignantly on the death of Lincoln:

O Captain! My Captain! Our fearful trip is done;
The ship has weather'd every rack, the prize we sought is won;
The port is near, the bells I hear, the people all exulting,
While follow eyes the steady keel, the vessel grim and daring:
But O heart! Heart! Heart!
O the bleeding drops of red,
Where on the deck my Captain lies,
Fallen cold and dead….

Bob is sorely missed. He was our Captain, our guiding spirit, our intellectual leader, our friend and companion. Right from the start of his service with the FDA, he had a clear vision of the path forward for our field and with few missteps slogged forward pushing and pulling many of the rest of us with him. When we approach a new problem, we still think "what would Bob say," and when a seminar speaker makes a dubious point, we look around for Bob to raise his hand and move toward the microphone. Bob had a tremendous impact on us and on the field as a whole, and we are all better off for his having lived among us and worked with us.

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