INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4.SMR/773-31

College on Medical Physics:
Radiation Protection and Imaging Techniques

5 - 23 September 1994

Radiographic Sensitized Materials Evaluation

M. de Denaro

Unita' Sanitaria Locale
Servizio di Fisica Sanitaria
Trieste, Italy

RADIOGRAPHIC SENSITIZED MATERIALS EVALUATION

Report on A.I.F.B. Working Group activity
Group co-ordinator: G. Borasi

G.Borasi[1], P.Bregant[2], A.Crespi[3], M.de Denaro[2], F.de Guarrini[2], F.Levrero[4], P.Mozzo[5], R.Novario[6], G.Pedroli[3], A.Pilot[4], F.Predicatori[5].

Affiliations:

1) S.F.S - USL 9 - Reggio Emilia - 2) S.F.S - USL 1 - Trieste - 3) S.F.S - USL 64 - Monza - 4) S.F.S - USL 13 - Genova - 5) CRR - USL 25 - Verona

Reggio Emilia - June 1992

Introduction

Progress in Radiology is strictly related to the development of new image registration systems that give increased image-quality at a lower patient-dose.

The fundamental physical parameters which determine the effective quality ("the technological level") of the radiographic-sensitized material are related to the image quality (characteristic curve, spatial resolution, noise) and to the patient dose (sensitivity).

As these parameters are not mutually independent, it is relatively easy for the manufacturer to increase one parameter value (for example spatial resolution) at the expense of another (for example noise): however, the effective quality of a product can only result from a synthesis of all the fundamental quantities. Thus the use of carefully chosen quality indices is mandatory both for highlighting the real technological breakthrough and for supplying the user with useful purchasing suggestions.

For a given "technological level", it is self evident that the choice of the most appropriate balance of the different parameters depends on the specific clinical task.

In principle, the values of the different physical parameters of the products in a tender could be directly required from the Manufacturing Companies, as a part of the bid specification. In practice, however, Manufacturing Companies are reluctant to supply reliable quantitative data. When some data are obtained, the differences in measuring methods and conditions make these informations generally not comparable and useless.

In the following, we report the Group suggestions for measuring the basic physical parameters with particular reference to the use of low-cost instrumentation, generally available at the user level. The two last paragraphs are devoted to the quality indices and purchasing criteria.

The characteristic curve and the sensitivity

This curve relates the "blackening" (measured as Optical Density- O.D.) of the film with the corresponding X-rays exposure level of the screen-film system. The *shape* of this curve (if abscissas are in a logarithmic scale) which is substantially independent of the light emission spectra of the fluorescent screen, depends on the intrinsic properties of the film (dimensions, shape and density of sensitized grains) and on the developing conditions. The *absolute position* of the characteristic curve on the abscissa axis represents its sensitivity and depends on the radiant (mainly visible) energy that is absorbed by the film. For this reason the sensitivity of a system depends on the proper matching of screen-emitted with respect to the film absorbed light spectrum.

An in depth study of different methods for obtaining the characteristic curve was undertaken by the Verona (Mozzo, Predicatori) and Varese (Novario) groups. In general the exposure time close to the clinical conditions to avoid reciprocity-law failure. For this reason, to graduate the X-rays exposures in a physics laboratory environment, an intensity scale is adopted, using a specialised device on which the source to film distance is varied.

At the user level two methods are widely used: (1) direct X-rays exposure of screen-film system with the interposition of a step wedge on the photons' path; (2) the exposure of the bare film to a light emitting device (sensitometer). While the step wedge method can give an *absolute* characteristic curve, the sensitometer only gives the *shape* of the characteristic curve. However, the calibration of a step wedge is not a trivial task. It requires a very good tension stability of the X-rays generator and needs to be repeated for all the different X-rays spectra.

Even if results obtained with two the methods are similar (see Fig.(1)), the use of a sensitometer seems, at this time, the more practical way to get the shape of the characteristic curve. From the shape of this curve several important quantities can be derived ,in particular, the "contrast" (first derivative of the characteristic curve) and "gamma" (mean contrast between O.D.=0.25 and O.D.=2). A knowledge of these parameters is required for the image quality indices.

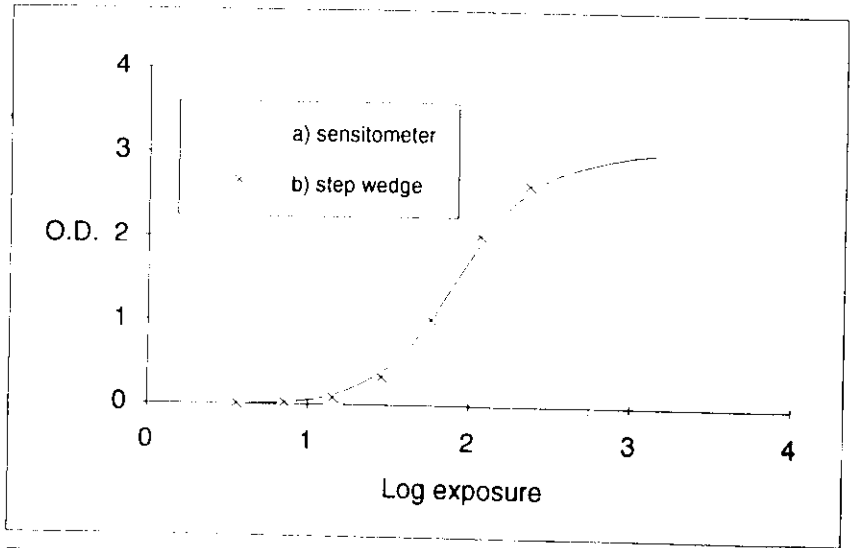

Fig.1. Comparison between characteristic curves of a radiographic film (3M Trimax XDA) obtained by: a) sensitometer, b) step wedge.

In a recent paper[1] characteristic curves obtained using specialised irradiation devices are compared with those obtained operating with single side and double side light-emitting sensitometers. This paper shows that the corresponding characteristic curves are generally in a close agreement. The paper also demonstrates one specific problem arising from the new, double-sided, low-crossover films: this kind of material requires the use of a double side emitting sensitometer.

System sensitivity is defined as the reciprocal of the radiation dose (measured as air kerma) required for obtaining an optical density of one (above the film fog).

The Group emphasises that *the characteristic curves obtained by sensitometers cannot be used for sensitivity evaluation.* Sensitivity evaluation requires direct X-ray exposure of the screen-film system so that the exposure corresponding to the O.D.=1 can be derived.

In the tender context, *relative evaluations of the different materials can be much more accurate (and thus more useful) than absolute ones.* This means that it is a very good practice to expose each film-screen system at the same time as a fixed system, used as reference standard. Of fundamental importance is the spectral quality of the radiation used for measurements, which should, in principle, simulate the radiation emerging from the object.

In the case of the general purpose radiological film, if the bid specifications require the use of the same intensifying screen for all the tests, the Group suggests using just one X-ray spectral quality (70 kV with 0.5 mm Cu of added filtration to the tube). If the bid requires that the Companies furnish the best film-screen system within a specified sensitivity interval, then at least three spectral qualities (50 kV with 0.2 mm Cu, 70 kV with 0.5 mm Cu, 90 kV with 0.7 mm Cu) should be used and the results averaged.

In this field different activities are in progress or planned: 1) inter calibration of densitometers, 2) developing conditions control, 3) the use of a specialised irradiator (at ENEA Laboratory) for obtaining the characteristic curve and the energy dependence of different materials.

The Group elaborated and tested several mathematical fitting functions for representing the characteristic curves.

The spatial resolution

"Spatial resolution" means the capability of the system to reproduce small size, high contrast details. In the case that the system is linear and isoplanar (i.e. it does not introduce image distortions), spatial resolution can be described using one of the following characteristic monodimensional functions: in the spatial domain, the edge response function (ERF), which is the system response to a step signal, or the line spread function (LSF), which is the system response to a narrow-slit signal; in the frequency domain, the modulation transfer function (MTF), which represents the contrast dependence on the spatial frequency.

MTF function depends primarily on the characteristics of the fluorescent screen even if the film effect is far from being negligible. The Modulation Transfer Function (MTF) of screen-film systems has been measured by many different techniques that are summarised in the ICRU Report n° 41[2]. These may be divided into two basic approaches: (1) the Line Spread Function (LSF) is directly measured and the MTF is obtained as Fourier transform or (2) the MTF is directly obtained by measuring the contrast of a periodic pattern.

In the first approach, the laboratory-standard method is to scan, with a microdensitometer, the image of a narrow slit, obtaining the LSF and then, using a digital computer, to calculate the MTF by Fourier transform of the LSF[3].

An alternative method using the same approach, is to determine the LSF as first derivative of the Edge Response Function (ERF) which is measured by scanning an edge pattern.

In the second approach the MTF evaluation would require, in principle, scanning of a sine-shaped pattern: due to the technical difficulties in realising this kind of test object, a square wave, instead of a sine-wave test object, has generally been employed. Using Coltman's[4] equations the square-wave response can be converted to the MTF.

The bar-pattern approach has some practical advantages over the slit method, as it requires only limited amount of specialised equipment and represents, at this moment, the standard device for Group MTF measurements.

Barnes[5] showed that results obtained by the two approaches are comparable.

In this field two parallel activities were undertaken: the Trieste Group (de Guarrini, de Denaro, Bregant) concentrated their efforts on the use of a high-level computerised microdensitometer (Perkin-Elmer Mod.1010 A) which was placed at Group disposal by the Astronomical Observatory of Trieste. A very extensive study was done on the effect of changing slit apertures, sampling steps and film alignment. The instrument linearity and the effects of correcting for the film characteristic response were analysed in depth. In addition, two different methods for MTF calculation were compared: sine fitting of squares waves and the Coltman correction methods. The two methods were found to give comparable results. The Group has decided to validate these results in by an international-level inter comparison that is planned for the near future. Then the Group will consider this instrument as the standard reference device for resolution (and noise) measurements.

Two other groups (Reggio Emilia; Borasi) and (Genova; Pilot, Levrero) did resolution measurements using low-cost, PC-based, TV-grabbing systems (TV-Digitizer). A detailed discussion of the related problems can be found in a recent paper[6].

Comparison between microdensitometer and TV-grabbing systems is still in progress. However, when intrinsic limitations of the low-cost instruments are correctly accounted for, results appear to be in close agreement as is shown in Fig. 2.

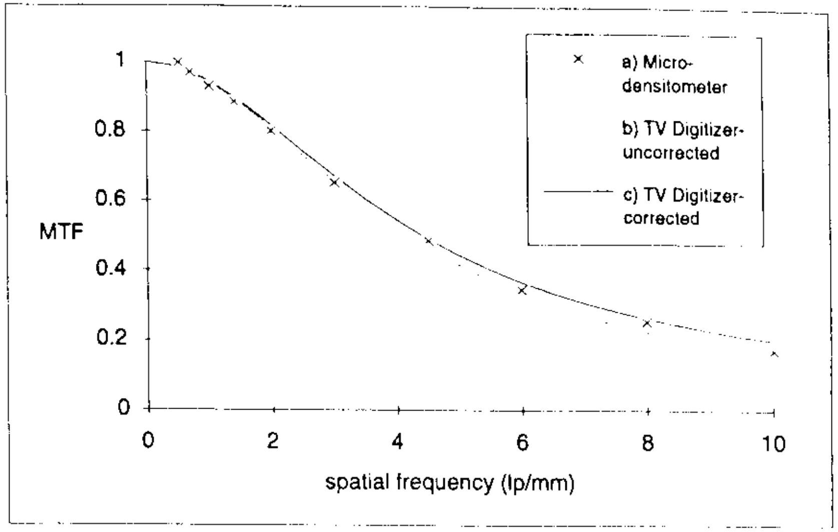

Fig. 2. Comparison between MTF curves of the same film-screen system (Kodak MinR screen plus Kodak Ortho M film) obtained using: a) the microdensitometer; b) and c) the TV grabbing system. Curve c) is corrected for the intrinsic unsharpness of the system.

In this figure data reported in curve c) are corrected for the intrinsic unsharpness of the TV-grabbing system. These results show that MTF measurements can reliably be done at the user level, using low cost instrumentation.

In this field planned activities are: 1) a more extensive comparison between the two kinds of instruments, 2) the evaluation of calculation techniques more suitable for TV-grabbing systems.

As for characteristic curves, the Group elaborated and tested several mathematical fitting functions for LSF, ERF and MTF.

The noise

This parameter expresses the intrinsic non uniformity of the image, and it is due to the "quantum noise" (i.e. the local statistical variation in the number of X ray photons), as well as to the size of grains of the screen and of the film, and to other sources related to the manufacturing and developing process. In the image, the noise limits the perceptibility of the low contrast details.

A detailed analysis of noise is based on the study of its frequency distribution, i.e., the noise spectrum (Wiener spectrum), defined as the expectation value of square modulus of the 2D Fourier transform of the image.

The Wiener spectrum can be measured on a "no-details" film obtained by exposing the screen-film system to a X-rays radiation of the same quality used for sensitivity measurements. This curve represents the random variations of the signal versus the spatial frequency and its integral represents the variance of optical density of the image.

In a previous work[7], variance measurements were performed using a TV-grabbing device. Measured data for different mammographic film-screen systems were found to be in reasonable agreement with published data. The next step of the Group activity will be to compare noise variance and the Wiener spectrum obtained with the microdensitometer with the same quantities obtained with the TV-grabbing systems.

Image quality models and indices

Since the purpose of radiographic images is to obtain information for medical diagnoses, the diagnostic accuracy that an image can provide can be regarded as a proper measure of visual image quality. Despite the complexity of the radiological decisions, the visual detection of specific image patterns is the crucial decision task. Although it is well known that detectability is related to the image contrast and spatial resolution and inversely related to the background noise, only in recent years has the statistical decision theory been used to elaborate specific models for the human visual detection process from which physical image quality indices could be derived.

In a fundamental paper[8], ten different image quality indices were compared with the observer performance in a large-scale radiographic detection experiment. Two kinds of models were compared: *displayed* models in which the characteristics of the human visual system (MTF and noise) were not taken into account and *perceived* models in which such observer characteristics were included. Different models gave different degrees of correlation with observer decisions but, in general, the more sophisticated perceived models did not give better results than the simpler displayed models.

For our purposes two image quality indices are of particular interest:

1) The *displayed statistical decision theory model* $SNR^2_{S,D}$, which gives the best overall correlation, (0.920) with the observer performance and

2) The *displayed amplitude model* $SNR^2_{A,D}$, which gives a poorer correlation, (0.681) with the observer performance but has a very simple mathematical expression.

Both indices, which represent different formulations of the (squared) signal-to-noise ratio, depend on the detector characteristics (contrast, spatial resolution and noise) and on the dimensions of the particular to be detected:

$$SNR^2_{S,D} = k\gamma^2 \frac{\left(\int_0^\infty O^2(u)M^2(u)u \cdot du\right)^2}{\int_0^\infty O^2(u)M^2(u)W(u)u \cdot du} \quad (1)$$

$$SNR^2_{A,D} = k\gamma^2 \frac{\left(\int_0^\infty O(u)M(u)u \cdot du\right)^2}{\int_0^\infty W(u)u \cdot du} \quad (2)$$

where $\gamma = 2\pi \cdot (\log_{10} e)^2$, γ is the gradient of the film at the reference density, u the spatial frequency, M and W are respectively the MTF and the Wiener spectrum of the imaging system and O is the frequency spectrum of the object. From the practical point of view, the main difference between the two expressions is in the denominator expression: the simple integral of the Wiener spectrum in (2) is *image variance* ($V = \sigma^2$) and can be directly measured, while the evaluation of the denominator of equation (1) requires detailed knowledge of the Wiener spectrum.

The dependence of the above expressions on the object dimensions could, in principle, make it impossible to associate a single image quality index to a particular imaging system (for example one system can perform better on larger details and another on smaller ones). It was shown, however, by Pedroli and Crespi (see Fig. 3) that for several screen-film systems on the market, characterised by very different physical parameters, the *relative merit* of the different systems (expressed as $SNR^2_{S,D}$ or $SNR^2_{A,D}$) does not change significantly with the detail dimensions.

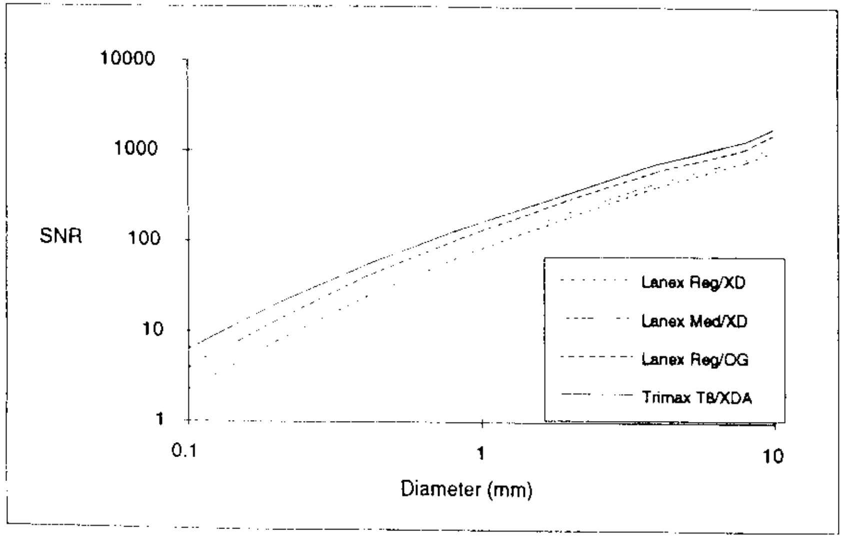

Fig. 3. Dependence on the object dimension of the statistical decision theory image quality index ($SNR_{S,D}$) for different film-screen systems.

This result allows the object size dependence to be eliminated from the above mentioned quality indices, considering, for example, their expression in the limit of vanishing object size.

One of the planned activities of the Group is to verify, in a large-scale radiographic detection experiment, if the simpler expression (2) can give reliable results when imaging system of similar characteristics (in the same sensitivity interval) are compared. If this hypothesis is verified, a very simple image quality index (IQ) could be adopted:

$$IQ = G^2 \frac{M^2(f_0)}{V} \qquad (3)$$

where G is the radiographic *gamma* (average contrast between O.D.=0.25 and O.D.=2), V is the image variance and $M(f_0)$ is the system MTF evaluated at a carefully chosen spatial frequency f_0. (For the general purpose film-screen system, a value of f_0= 2 lp/mm is generally used).

In a previous work[9], this simplified image quality index was found to have a reasonable correlation with subjective quality opinions expressed, on images of phantoms, by a trained Radiologists' group.

Global quality ("the technological level")

If the noise depended only on quantum statistics, the Poisson law would require that image variance V in equation (3) should be proportional to the number of system absorbed quanta. For a fixed quantum energy, this number is proportional to the air kerma so that the image quality index (3) should be in inverse relation with the system sensitivity S. In effect, this kind of relationship was verified on a large number of systems[7], and is shown in Fig.(4).

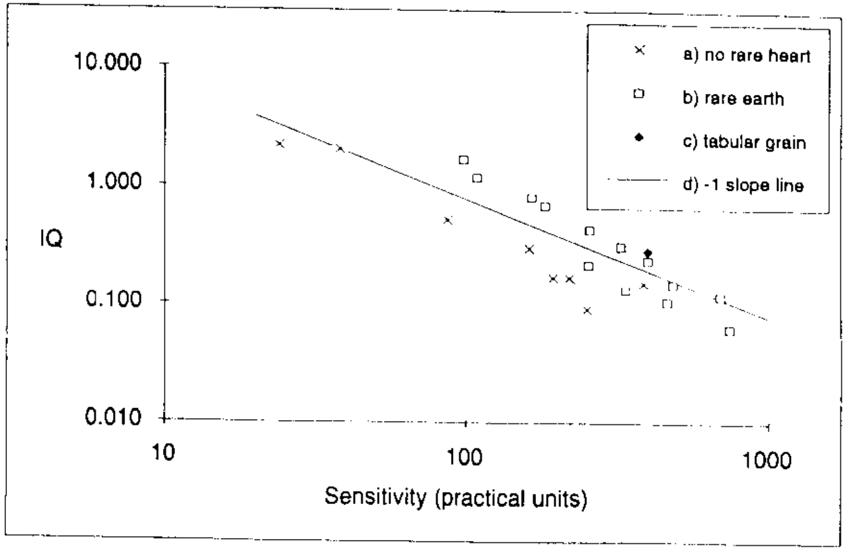

Fig. 4. Dependendence of the image quality index (IQ) on sensitivity for different generations of film-screen systems.

In this representation, the technological breakthrough related to introduction of the rare-earth based screens is well highlighted. These reflections lead to the adoption of the global quality index (Q) as the product of the image quality index IQ by the system sensitivity S, following the equation:

$$Q = IQ \cdot S \qquad (4)$$

We propose using this index to evaluate the "technological level" of the different systems.

Bid specification and purchasing criteria

The total supply should be divided into homogeneous product classes, for example: general purpose, high definition, high speed, mammography, ..etc. For each product class, the interval of the accepted values for all the significant physical parameters (in particular: contrast, spatial resolution, noise, sensitivity) should be clearly specified. For these physical quantities, measuring methods and conditions must be described.

The purchasing criteria should be "conceptually" simple and verifiable. Following the theory we have outlined in the previous paragraphs, all physical parameters of a product class are synthesised into their global quality index (Q) and the only other parameter we need for making the decision is the product price (P).

While the simple inspection of a quality-price diagram, like that shown in fig. 5, gives an immediate perspective of the characteristics of the different products, for the choice, we need a new parameter specifying the accepted "balance" (trade) between the product quality and its price.

We suggest using a dimensionless index, named quality-price (QP), defined as:

$$QP = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}} = \frac{P}{Q} \cdot \frac{\Delta Q}{\Delta P} \qquad (5)$$

In principle, this parameter expresses the (relative) amount of quality increase that is required for a given (relative) price increase. The extreme values of this parameter (zero, infinitive) correspond to purchasing criteria based only on the quality or vice versa only on the price. The analysis of the evolution during the time of the quality and price of a product class can help to fix reasonable values for this parameter. Each Institution can, obviously, choose different values of this parameter following specific economical or technical criteria. In any case, the value of this parameter has to be included as an "a priori" condition into the bid specifications.

In practice, when quality and price of the different offered products in the tender are determined, we can calculate the average product quality Q and the average product price P and from equation (5) we obtain:

$$\frac{\Delta Q}{\Delta P} = QP \cdot \frac{Q}{P} \qquad (6)$$

The quantity $\frac{\Delta Q}{\Delta P}$ represents, on the quality-price diagram, the slope of the "acceptance line" passing through the data barycenter (Q,P). Obviously, products whose points on the quality-price diagram lie over the acceptance line are better than those under this line: of the first class of products, the most convenient one has the largest distance from the acceptance line.

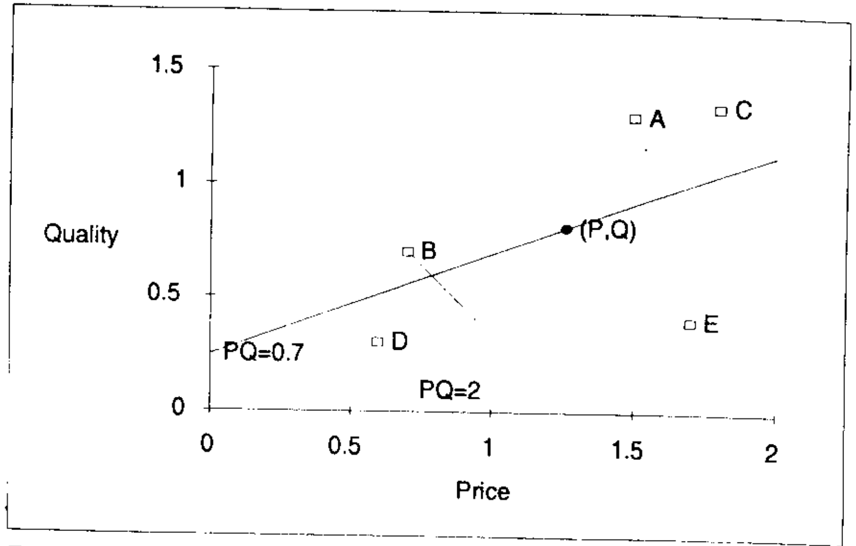

Fig. 5. Quality-Price diagram for a simulated tender of radiographic film-screen systems. The "acceptance lines" for two different decision criteria (0.7, 2) are reported.

As is shown in Fig. 5 , in which tender results are simulated, product A or B represents the best choice in correspondence with two different values (0.7, 2) of the quality-price parameter; product C or D could be chosen only if the decision is based only on quality or price (purchasing product E is not recommended!).

References

1) A.G. Haus and R.E. Dickerson,"Problems associated with simulated light sensitometry for low crossover medical x-ray films," Med.Phys, Vol.17, pp 691-695, 1990.

2) International Commission on Radiation Units and Measurements, "Modulation Transfer Function of Screen-Film Systems", ICRU Report 41,Bethesda, MD, 1986).

3) K.Doi, G.Holje, L-N.Loo, H.-P.Chan, J.M.Sandrik, R.J.Jennings, and R.F.Wagner, "MTFs and Wiener Spectra of Radiographic Scree-Film Systems," HHS Publication, FDA 82-8187 (National Technical Information Service, Springfield, Virginia, 1982).

4) J.W.Coltman,"The specification of imaging properties by response to a sine-wave input," J.Opt.Soc.Am. 44, 468-471 (1954).

5) G.T.Barnes, "The use of bar pattern test object in assessing the resolution of screen-film systems," pagg.138-151 in The Physics of Medical Imaging: Recording Systems Measurements and Techniques, Haus, A.G.,Ed. (AAPM New York, 1979).

6) G.Borasi, P.P. Ferretti, P. Berardi, V.Piccagli,"Evaluation of Radiographic Screen-Film Systems: methods and instruments," submitted to Physica Medica.

7) G.Borasi, P.Berardi, P.P. Ferretti, V.Piccagli,"Valutazione della qualità di sistemi radiografici schermo-pellicola: principi fisici e metodi di misura," Radiol.Med., Vol.80, pp. 339-346, 1990.

8) L.D. Loo, K.Doi and C.E.Metz,"A comparison of physical image quality indices and observer performance in the radiographic detection of nylon beads," Med.Phys.Biol., Vol.29, pp.837-856, 1984.

9) G.Borasi, S.Del Piano, A.Landini e Coll."Criteri fisici e psicofisici di valutazione della qualità delle immagini radiografiche," Radiol. Med.,Vol. 68, pp.401-407, 1982.