CHAPTER 2

REVIEW OF RELATED LITERATURES

2.1 Theory

2.1.1 Intensity modulated radiation therapy (IMRT) [6]

The primary aim of radiation therapy is the delivery of a spatially constant, sufficiently high dose to an identified 3-dimensional tumor target while tumor surrounding healthy tissues and radiosensitive structures are maximally spared from any radiation burden. In conventional radiation therapy this is accomplished by the selection of usually 3 - 7 incident beam directions from which the tumor is irradiated with a constant fluence over the lateral profile of the beam aperture. In this approach the tumor is almost automatically covered with a homogeneous dose. The absolute fluence values for the individual beams including the beam directions are employed to achieve the desired dose sparing for organs at risk (OARs).

This technique, however, fails for patient geometries where OARs are located in close proximity to - or are even embedded within - a complicated 3-dimensional tumor shape. Acceptable dose distributions for these special clinical cases can only be achieved, if the fluence for each individual photon beam is modulated across its aperture. Consequently, a homogeneous tumor dose distribution within the tumor can be guaranteed only by superposition of the inhomogeneous dose distributions originating from the individual beam directions. The application of these intensity modulated beams in comparison to the conventional technique defines IMRT and schematically is shown in Figure 2.1.

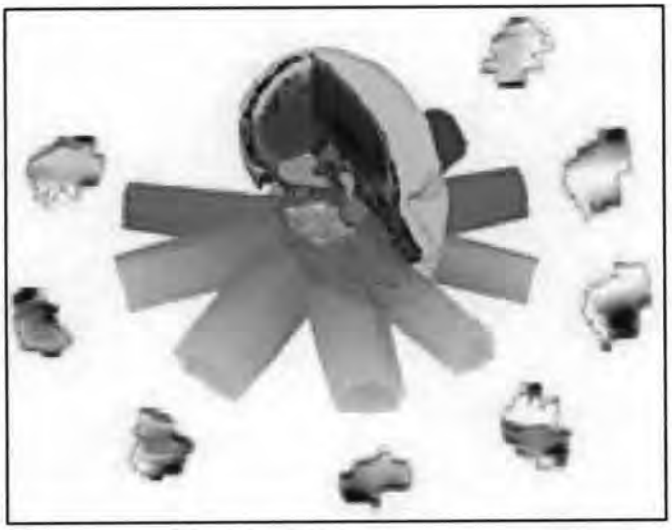

Figure 2.1 Intensity modulated radiotherapy (IMRT) delivers radiation beams in multiple arcs, similar to 3D conformal (http://www.mayfieldclinic.com)

2.1.2 Treatment planning [7]

Radiation treatment planning requires the calculation of a set of parameters for the delivery of a certain radiation dose to the patient. Ideally, radiation dose distribution should be designed to conform perfectly to the entire tumor volume while completely avoiding surrounding normal tissues. Although achievement of this goal is practically impossible, a computer optimization can potentially simplify the tedious planning procedure and yield the best possible plans. Computer optimization becomes necessary for IMRT treatment planning because of the vast search space. The implementation of the general concept of inverse planning differs from system to system. The degree of optimality of the final solution is generally determined by (1) the form of objective function; and (2) methods to search for the minimum (or maximum) of the objective functions.

2.1.3 Inverse planning [7]

An inverse planning requires constructing an objective function to establish a link between the output dose distribution and the input beam parameters (beamlets weights or beam profiles). The objective function measures the goodness of a selected plan and its choice is crucial for therapeutic plan optimization. The objective function can be based solely on dose or it can use a radiobiological model. The former is concerned with the interaction between radiation and matter and calls for accurate dose distributions, with the biological aspect being implicitly given in the physician's prescription. The biological model argues that optimization should be based on the biological effects produced by the underlying dose distributions. The treatment objective is usually stated as the maximization of the tumor control probability (TCP) while maintaining the normal tissue complications probability (NTCP) to within acceptable levels. A TCP is related to a dose distribution by the dose response function, which is not sufficiently understood. At this point, the dose-based approach is still widely used in practical optimization whereas biological models are often used conceptually. Both dose-based and dose-volume-based objective functions are used in the commercial inverse planning systems.

2.1.4 Dynamic multileaf collimator (DMLC) [8]

Dynamic multileaf collimator (DMLC)-intensity modulated radiation therapy (IMRT): A method used to deliver intensity modulated beams using an MLC, with the leaves in motion during radiation delivery. The *sliding window* technique is a form of DMLC-IMRT in which the window formed by each opposing pair of leaves traverses across the tumor volume while the beam is on.

Dynamic MLC motion implies that the leaf positions are changing with respect to time, in terms of the MLC controller it is the change in position with respect to monitor units (MUs) delivered that is important. The inputs required are the leaf positions at various control points, the fractional number of MUs to be delivered at each control point, and the total number of MUs to be delivered for that beam.

Each leaf is controlled by a separate motor. The leaf positions are indicated by encoders attached to the motors. An independent secondary feedback mechanism verifies correct leaf positioning. During DMLC delivery, the control software monitors the leaf positions and compares them to their prescribed positions. The beam is

interrupted momentarily if any leaf position is outside tolerance [for Varian DMLCs this is a user-defined parameter selectable from 0.1 to 5.0 mm.

An important factor for DMLC-IMRT leaf sequencing and delivery is the maximum leaf speed (position with respect to time). For the Varian MLCs this is approximately 3 cm/s at isocenter. If the requested leaf speed exceeds the dose rate used for the delivery of the DMLC field, then the dose rate will be reduced. If the dose rate is continually reduced, then the treatment time will increase.

2.1.5 Pretreatment dose verification [7]

Clinical implementation of IMRT involves a dosimetric verification of each IMRT field to ensure that the intensity pattern matches that intended by the treatment planning system and that the MUs specified by the treatment planning system will in fact deliver the intended dose. This QA step is typically completed using either film or ionization chamber dosimetry systems.

Radiographic film is currently a practical dosimeter for IMRT delivered with DMLC because it provides excellent spatial resolution and integration of time-varying modulated dose. Although the film measurement is mostly selected as a state-of-the-art dosimetric verification method in clinic routine, it has some limitations in usage such as non-linearity of energy response due to over response to low energy photons and a relatively poorer reproducibility due to uncertainty in each dosimetric procedure including film positioning in the phantom, film development, scanning, and analysis. Also, a national/international standard film measurement protocol is not yet established for IMRT dose verification.

At the beginning of IMRT commissioning, we made a decision that an IMRT QA procedure for each patient and beam has to be performed to verify IMRT planning and treatment. The IMRT QA procedure consists of two phases. The first is an independent MU check in a patient geometry by Monte Carlo calculation and the second is a pretreatment dose delivery verification within flat phantoms by comparison of film measurement and calculation.

2.1.6 Film dosimetry

2.2.6.1 General [9]

Photographic film consists of a radiation sensitive emulsion coated on a transparent polyester base. The emulsion consists of silver halide crystals (typically 95% silver bromide and 5% silver iodide) embedded in gelatin. The exact composition of emulsions varies with the manufacturer and is a closely guarded industrial secret. For protection against mechanical damage, the base is covered with a thin layer of gelatin. When the emulsion is exposed to radiation, excitation and ionization takes place in the silver halide that leads to the formation of a latent image.

Film development is a chemical process, which amplifies the latent image by a factor of millions. This development produces silver grains, i.e. microscopically small irregular aggregates of metallic silver, which cause the film to become opaque. Electron micrographs of some films commonly used in dosimetry reveal a vast difference in grain size and uniformity between the different types of film.

2.1.6.2 Film base and emulsion [9]

The silver halide of a radiographic film is contained in an emulsion coated on a polyester base and protected by a thin gelatin layer for mechanical integrity. Radiographic films are available in different sizes (e.g. 25.4 x 30.5 cm^2), and their radiation dose range is between several mGy and several Gy. They require a wet chemical processing as well as a special device for read out, the densitometer.

It consists of the radiation-sensitive emulsion usually coated on both sides of a transparent sheet of plastic called the base. A thin layer of adhesive provides firm attachment between the emulsion and the film base. The delicate emulsion is protected from mechanical damage by layers known as supercoating. The composition of a dosimetric film is shown in Figure 2.2 [9].

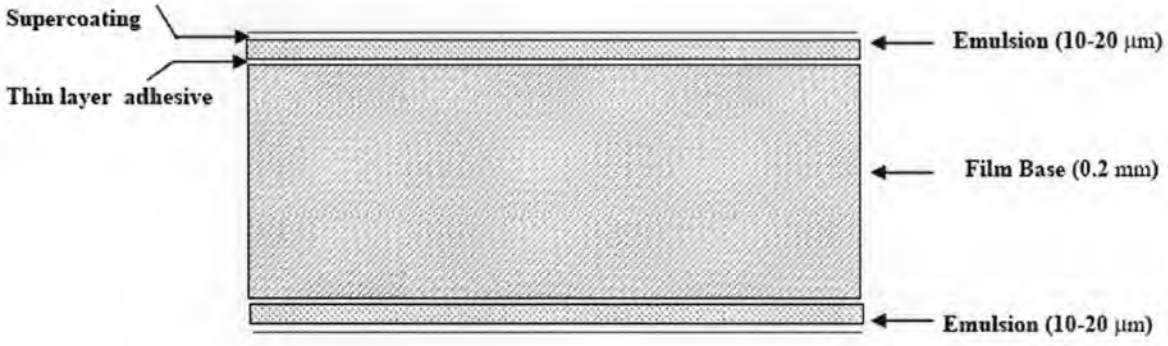

Figure 2.2 Cross section of a double emulsion x-ray film

The function of the film base is to provide a support for the fragile photographic emulsion. Three characteristics of the base must be considered. First, it must not produce a visible pattern or absorb too much light when the radiograph is viewed. Second, the flexibility, the thickness, and strength of the base must allow for ease of processing (developing) and produce a film mechanically strong enough has to "snap" under the hanger of a view box. Third, the base must have dimensional stability; i.e. the shape and size of the base must not change during the developing process or during the storage time of the film.

The most important ingredients of a photographic emulsion are gelatin and silver halide. Gelatin satisfies several exacting requirements better than any suspension medium. It keeps the silver halide grains well dispersed and prevents the clumping of grains. Processing (developing and fixing) solutions can penetrate gelatin rapidly without destroying its strength or performance, and gelatin is available in reasonably large quantity and uniform quality.

Silver halide is the light sensitive material in the emulsion. The halide in medical x-ray film is about 90 to 99% silver bromide and about 1 to 10% silver iodide (the presence of AgI produces an emulsion of much higher sensitivity than a pure AgBr emulsion). The production reaction involves the addition of silver nitrate to a soluble halide to form the silver halide:

$$AgNO_3 + KBr \rightarrow AgBr + KNO_3$$

The silver iodo-bromide crystals are precipitated and emulsified in the gelatin under exact conditions of concentration and temperature, as well as the sequence and the rate at which these chemicals are added. The method of precipitation determines the crystal size, and the structural perfection. The silver halide in a photographic emulsion is in the form of very small crystals suspended in the gelatin. The crystal is formed from ions of silver (Ag^+), ions of bromide (Br^-) and ions of iodide (I^-) arranged in a cubic lattice[10].

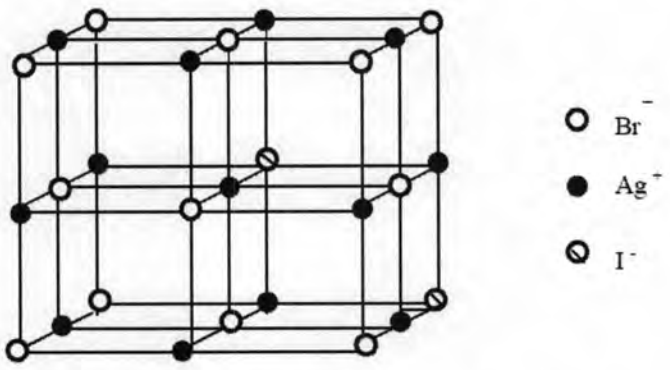

Figure 2.3 The silver iodo-bromide crystal lattice

These grain shaped crystals in medical x-ray film emulsion are very small, but still relatively large compared to fine grain photographic emulsions. The crystal size varies about an average of 1.0 to 1.5 μm in diameter with about 6.3×10^9 grains per cubic centimeter of emulsion, and each grain contains an average of 10^6 to 10^7 silver ions. Figure 2.4 shows the unprocessed emulsion in the electron microscope; the scale is given by the grain size of about 1 μm.

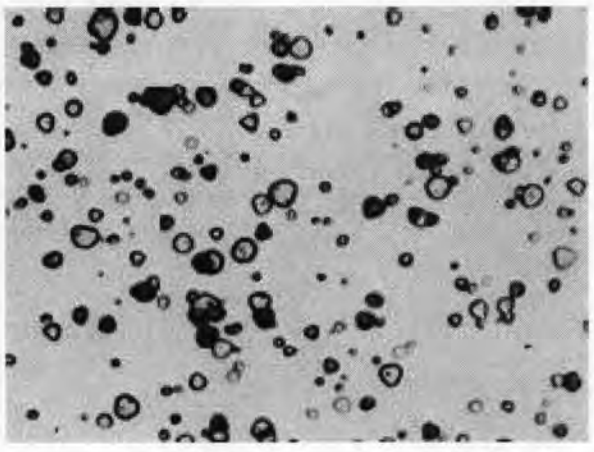

Figure 2.4 Electron micrograph of the unprocessed emulsion of an x-ray film

The silver iodo-bromide grain is not a perfect crystal, because a perfect crystal has almost no photographic sensitivity. There are several types of crystal defects. A point defect consists of a silver ion which has moved from its normal position in the lattice; these interstitial silver ions are able to move in the crystal. When they are

neutralized in the encounter with occupied electron traps, they form the latent image, which consists of clusters of silver atoms. A dislocation is a line imperfection in the crystal, and may be thought of a brick wall which obtains one row in which the bricks are not the same size as all the other bricks, thus causing a strain in the wall structure. This may be the way in which the iodine ion strains the crystal. Chemical sensitization of a crystal has several forms. Commonly, this is produced by adding a sulphur containing compound, such as allylthiourea, to the emulsion, which reacts with silver halide to form sulphide. The silver sulphide is usually located on the surface of the crystals and is referred to as the sensitivity speck. It is the sensitivity speck, which traps electrons to begin the formation of the latent image.

In the structure of silver bromide, each of the silver atoms has given one orbital electron to a bromine atom, which then has become a bromine ion (Br^-). The silver atoms, lacking one negative charge, have an effective positive charge and are known as silver ions (Ag^+).

Within the crystal, there are silver ions that do not occupy the "lattice position" shown in Figure 2.3, but rather are in the spaces between. These are known as interstitial silver ions. The number of the interstitial silver ions is, of course, small compared to the total number of silver ions in the crystal. In addition, there are distortions of the uniform crystal structure. These may be "foreign" molecules, within or on the crystal, produced by reactions with the components of the gelatin, or distortions or dislocations of the regular array of ions shown in Figure 2.3. These distortions may be classed together and called "latent-images sites" as shown in Figure. 2.5.

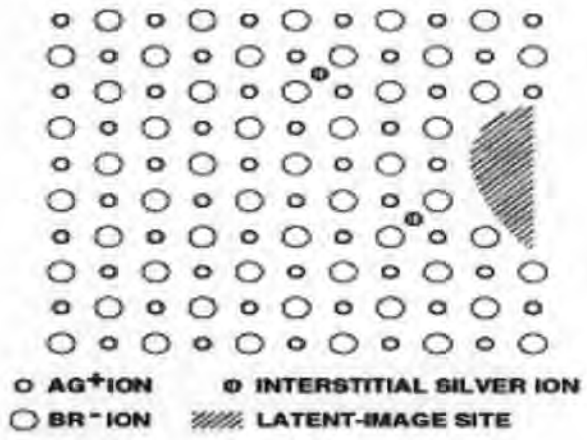

Figure 2.5 Layer of ions in an AgBr crystal. Two interstitial silver ions and a sulphide region, functioning as a latent image site, are shown schematically

2.2.6.3 Photographic process [11]

The production of film density and the formation of a visible image is a two step process. The first step in this photographic process is the exposure of the film to light, which forms an invisible latent image. The second step is the chemical process that converts the latent image into a visible image with a range of densities, or shades of gray.

Film density is produced by converting silver ion into metallic silver, which causes each processed grain to become black. The process is rather complicated and is illustrated by the sequence of events shown in Figure 2.6.

Each film grain contains a large number of both silver and bromide ions. The silver ions have a one-electron deficit, which gives them a positive charge. On the other hand, the bromide ions have a negative charge because they contain an extra electron. Each grain has a structural "defect" known as a sensitive speck. A film grain in this condition is relatively transparent.

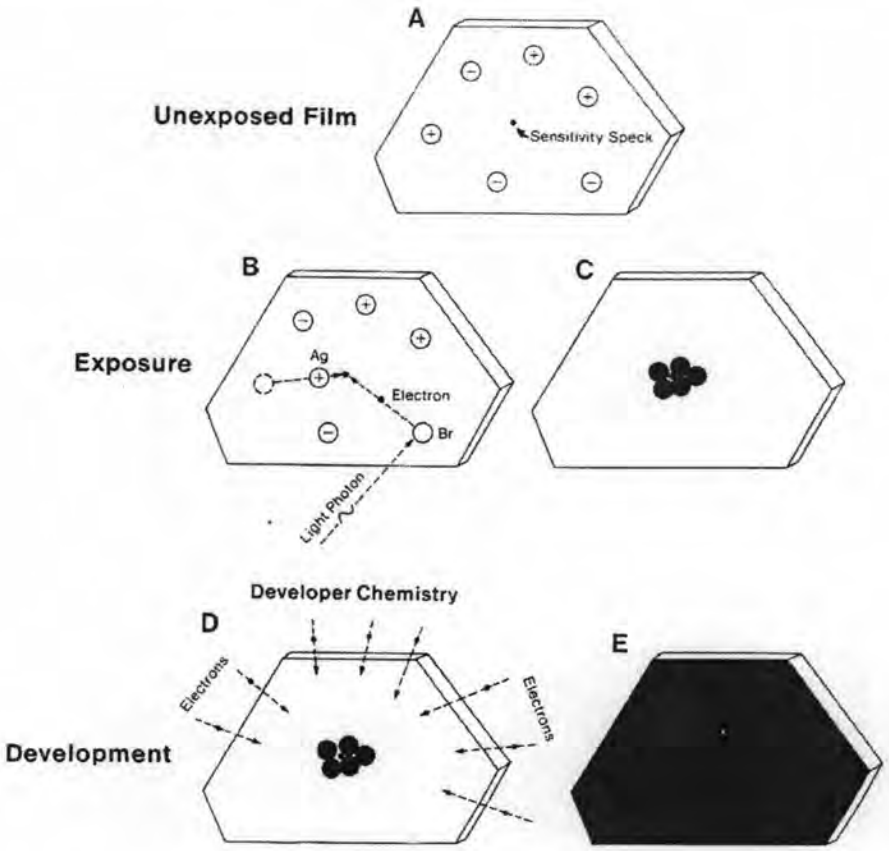

Figure 2.6 Sequence of events that convert a transparent film grain into black metallic silver

2.1.6.4 Latent image formation [11]

The first step in the formation of the latent image is the absorption of light photons by bromide ions, which frees the extra electron. The electron moves to the sensitivity speck, causing it to become negatively charged. The speck, in turn, attracts one of the positively charged silver ions. When the silver ion reaches the silver ions speck, its positive charge is neutralized by the electron. This action converts the silver ion into an atom of black metallic silver. If this process is repeated several times within an individual grain, the cluster of metallic silver at the sensitive speck will become a parameter arrangement. The number of grains in the emulsion that reach this status depends on the overall exposure to the film. The grains that received

sufficient exposure to from a permanent change are not visually distinguishable from the unexposed grains, but are more sensitive to the action of the developer chemistry. The distribution of these activated, but "invisible," grains throughout the emulsion creates the latent image.

2.1.6.5 Fading [12]

The latent image may fade over a period of time. This decay, usually exponential in time, is due to the dissociation of silver clusters that form the latent image. Researchers have hypothesized a chemical oxidation mechanism. However, if the emulsion is desiccated and, preferably, sealed in a moisture-proof pouch, fading may be greatly reduced.

The American National Standards Institute (ANSI PH 2.9-1974) recommends that, for carrying out sensitometry of photosentive materials, the film should be processed not sooner than 30 minute nor more than 8 hours after exposure. The speed of the decay of the latent image is increased by higher temperatures and humidities and decreased by lower temperatures and humidities and storage in an oxygen free environment (in an inert gas or in a vacuum). This is of practical importance for film dosimetry in radiation protection applications.

2.1.7 Dosimetry and response curve [13]

The degree of blackening of the film is measured by determining the optical density with a densitometer. This instrument consists of a light source, a tiny aperture through which the light is directed and a light detector (photocell) to measure the light intensity transmitted to the film. Since the optical density (OD) is defined in $OD = \log (I_0 / I)$, where I_0 is the signal corresponding to the amount of light collected without the film and It the signal corresponding to the amount of light transmitted through the film, the immediate reading of a densitometer is called "measured optical density". In dosimetry, the quantity of interest is usually the "net optical density" (net OD), which is obtained by subtracting the "fog" reading (i.e. the OD of unexposed, but processed film) from the measured optical density. A plot of the net OD as a function of radiation exposure or dose is termed the sensitometric curve, or Hurter and Driffield (H&D) curve, which we call "response curve". Those films, which have a steep blackening curve, are also called "fast films" and those with a smaller slope are called "slow films".

In the ideal for film dosimetry, the net optical density versus exposure graph is a straight line passing through the origin (see Figure 2.7). The curve significantly departs from linearity only when the exposure becomes so great that appreciable energy is wasted on grains that have already been made developable. For commercially available fine-grain x-ray films the density versus dose curve may be essentially linear up to densities of 2.0 or even higher.

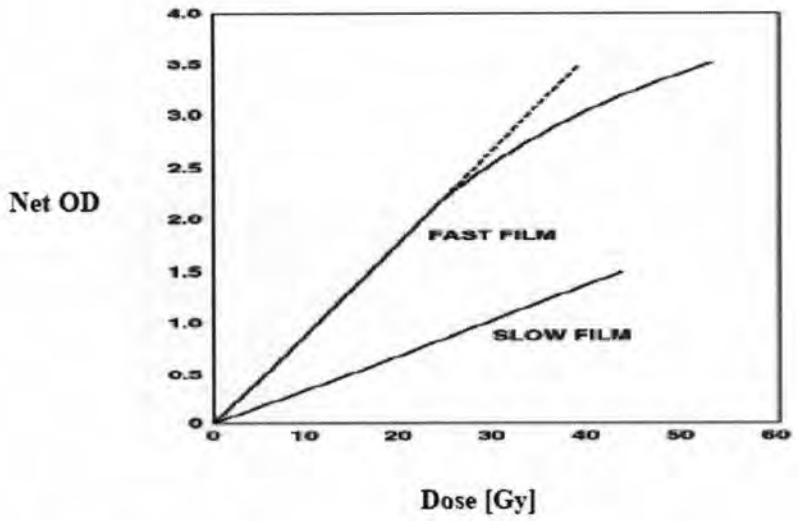

Figure 2.7 Typical response curve, i.e. net optical density versus dose curves of radiographic films for direct x-ray exposure

The fairly straight-line relation between dose and net optical density is of considerable use for photographic monitoring of radiation, permitting a saving of time in the interpretation of densities observed on dosimetric films, and for clinical dosimetry.

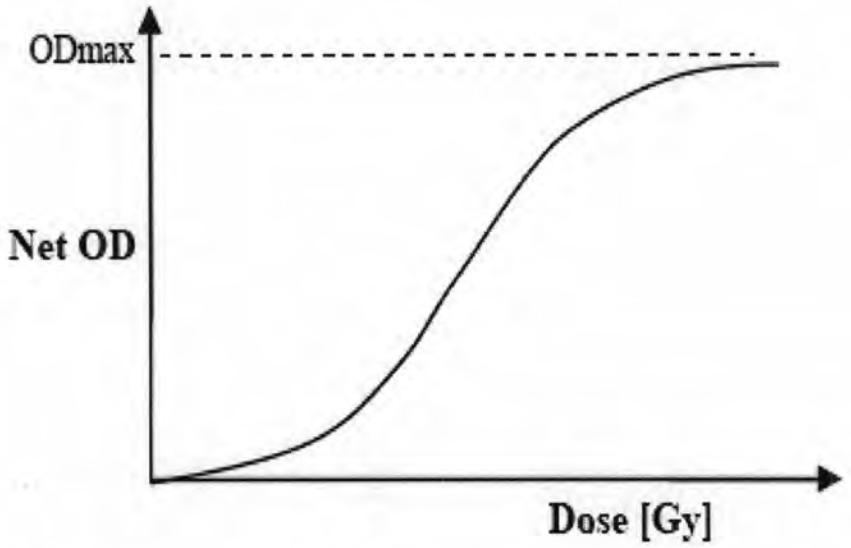

Figure 2.8 Scheme of a non-linear response curve due to the requirement of two instead of one silver cluster per AgBr crystal

In the practical, not-ideal case, the response curve may be somewhat S-shaped as in Figure 2.8. The reason for this non-linearity is that some fraction of the AgBr crystals may require not one, but two silver clusters for being developable into silver grains. This may be due to the variation in size of the silver clusters and due to the variation of the amount of energy deposited in an electron traversal.

2.1.8 Quantitative radiographic film response to radiation [13]

The opacity of the developed film can be quantified as an optical density (OD):

$$OD = \log (I_0 / I) \qquad (2.1)$$

Where I is the transmitted light intensity in a film densitometer and I_0 is the incident light intensity (see in Figure 2.9). This implies that the lower the film opacity is (i.e., higher I), the OD is, and vice versa.

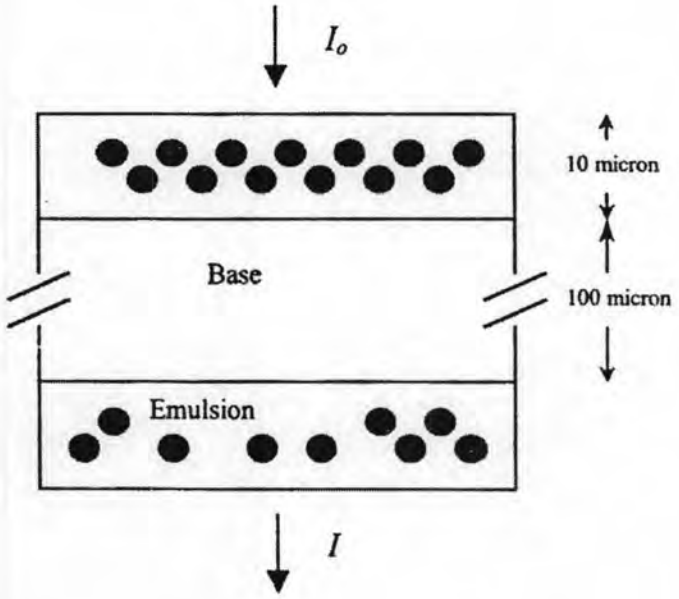

Figure 2.9 Developed radiographic film under film densitometry. Double coating emulsion is typical for verification film. The grain (dark circles) diameter is less than 1 micron, which limits the spatial resolution

If we define the following quantities:

σ_d = probabilistic area of interaction of a single developed grain with source light,
n = the number of developed grains/cm^2, and
dx = infinitesimal emulsion thickness between x and x+dx,

then the fractional reduction of the light intensity is

$$dI/I = -n\,\sigma_d dx \qquad (2.2)$$

where the scattered light quanta are assumed to have been removed from the transmitted intensity (so very thin emulsion and/or narrow light beam geometry are assumed). If we integrate the equation (2.2) over the thickness x, then

$$I = I_0 e^{-n \sigma dx} \tag{2.3}$$

and

$$OD = k\sigma_d x n \tag{2.4}$$

where k is log e = 0.4343. n can be related to the dose the film has received by employing the target hit model, the target being the grains and a hit being a radiation interaction event leading to the formation of a latent image. Therefore, dose delivered to tissue can be extracted from the amount of grains represented by OD left in the developed film.

If one denotes that $N_i(t)$ is the number of grains per unit volume that have received i hits at the exposure time t, then $N_i(t)$ can be modeled following the Poisson distribution:

$$N_i(t) = N \frac{(\lambda t)^i}{i!} e^{-\lambda t} \tag{2.5}$$

where N is the initial number of grains and λ is the (average) reaction rate between grains and incident particles.

Depending on the radiation field, λ contains the terms that account for the interaction of a grain with either an electron (e), an x-ray photon (p), or a visible light quantum (I). In general, for a mixed field of e, p, and I, $\lambda = \sigma_e \phi_e + \sigma_p \phi_p + \sigma_I \phi_I$ where σ_e, σ_p and σ_I are the cross section of interactions (i.e., hits) of a grain with an electron, an x-ray photon, and a visible light quantum, respectively, and a σ_e, σ_p and σ_I are the respective fluence rates.

Assume that m is the number of hits requires for generating a latent image, then

$$n(t) = N - \sum_{i=0}^{i=m-1} N_i \tag{2.6}$$

$$= N\left[1 - e^{-\lambda t} \sum_{i=0}^{i-m-1} \frac{(\lambda t)^i}{i!}\right]$$

where the summation term represents the total number of undeveloped grains that have received some numbers of hits less than m. that is, per unit volume of emulsion, the number of developed grains is equal to the total number of grains less the number

of undeveloped grains(which will be dissolved in the fixing stage of the film developing process).

The *OD* can be related to λt by substituting Equation (2.6) into Equation (2.4):

$$OD = k\sigma_d xN\left[1 - e^{-\lambda t}\sum_{i=0}^{i=m-1}\frac{(\lambda t)^i}{i!}\right] \qquad (2.7)$$

This formula is not completely new; it simply replaces the relative exposure (or dose) term in the deviation by Dixon and Ekstrand (1976) with λt. Since λt is proportional to dose, OD is also a function of the total dose film has received. However, the significance of this expression is that it relates OD to the number of reactions (i.e., λt) and the number of hits *i*, as illustrated in the following developments.

For electrons and x-ray photons, for which the single hit model is applicable (*m*-1), and visible light, for which the multiple-hit model (m≥3), is applicable, the ODs (OD_e, OD_p and OD_l,) defined by equation (2.7) can be respectively expressed. Let us consider the typical situation of x-ray radiation therapy, in which the film within a phantom is exposed only to the mixed field of electrons and photons. Then, the number of developed grains (*n*) can be obtained by subtracting the number of grains that received no hit (N_0) from the initial number of the total grains (*N*). That is,

$$\begin{aligned} n &= N - N_0 \\ &= N\left(1 - e^{-\lambda' t}\right) \end{aligned} \qquad (2.8)$$

where $\lambda' = \lambda_e + \lambda_p$ with $\lambda_e = \sigma_e\phi_e$ and $\lambda_p = \sigma_p\phi_p$ consequently, the optical density in a film exposed without scintillation screens(OD_n) is

$$OD_n = OD_s\left(1 - e^{-\lambda' t}\right) \qquad (2.9)$$

where $OD_s = k\sigma_d xN$, the optical density at saturation(i.e., t = ∞).

When scintillation screens are used in contract with the film in imaging or therapy, the film is exposed to additional visible light quanta. If a value of 3 for *m* is assumed for visible light exposure, one can obtain the number of developed grains (*n*) by subtracting, from the initial number of the total grains (*N*), the number of grains that received no hit (N_0), the number of grains that received one hit by visible light quanta ($N_1\ \lambda_l/\lambda$), and the number of grains that received two hits by visible-light quanta ($N_2\ (\lambda_l/\lambda)^2$). That is, from equation (2.5),

$$n = N - N_0 - N_1(\lambda_l / \lambda) - N_2(\lambda_l / \lambda)^2$$

$$= N\left[1 - \left(1 + \lambda_l t + \frac{(\lambda_l t)^2}{2!}\right)e^{-\lambda t}\right] \qquad (2.10)$$

where $\lambda = \lambda' + \lambda_l$ with $\lambda_l = \sigma_l \phi_l$ consequently, the optical density (OD_{mx}) in film in contract with a scintillation screen is

$$OD_{mx} = OD_s\left[1 - \left(1 + \lambda_l t + \frac{(\lambda_l t)^2}{2!}\right)e^{-\lambda t}\right] \qquad (2.11)$$

It can be observed that if $\lambda_l >> \lambda'$, and then OD_{mx} is reduced to OD_1 given by equation (2.7), with λ replaced by λ_l. On the other hand, if $\lambda_l << \lambda'$ or $\lambda_l \cong 0$, OD_{mx} should approach OD_n of equation (2.9). The foregoing derivations, based on equation (2.7), describe OD as a function of particles of concern. These mathematical formulae represent the typical trend of the film response shown in Figure 10. A film exposure to visible light requires some threshold dose to respond, corresponding to the multiplicity of hits required to produce a latent image, whereas the film exposure to x-rays and electrons shows good linearity starting from a zero dose, corresponding to the singularity of the required hits. In addition, they show that the saturation density is proportional to silver-bromide content; the film with smaller grains (smaller λt) saturates more slowly (i.e., greater dose range of linearity).

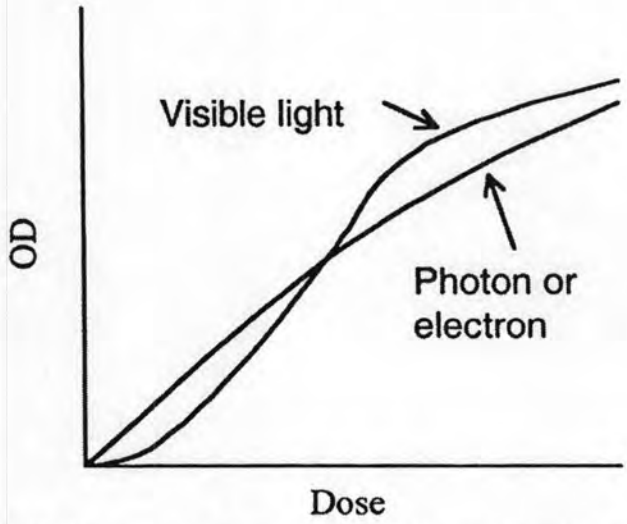

Figure 2.10 Characteristic curves of radiographic film to radiation

2.1.9 Energy dependence of radiographic film response to radiation [13]

If film is placed in a phantom under an x-ray beam, it absorbs both secondary electrons and photons (see Figure 2.11). The trend of film dose per unit tissue dose with depth in a phantom is an indicator of how good a dosimeter is in terms of the energy dependence of its response. Film dose is represented by the OD generated in the film. The film response to electrons (i.e., the film dose per unit tissue dose) dose not change significantly with depth as the electron fluence spectrum changes with depth in a phantom. The change of film dose per unit tissue dose with depth delivered by electrons originates from the change with depth in the ratio between the stopping powers (SRs) of the film emulsion and tissue (or water), averaged over the depth specific spectrum.

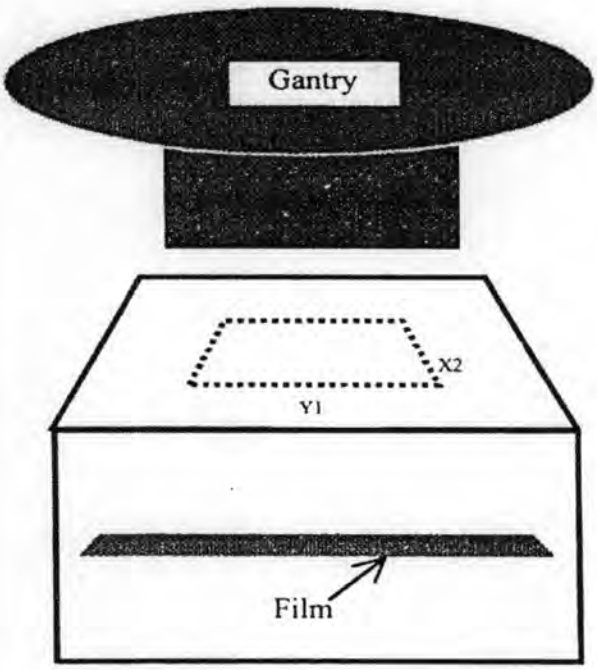

Figure 2.11 Film dosimetry setup

With respect to film response to photons, however, film dose per unit tissue dose changes significantly with depth as incident photon fluence spectrum is attenuated with depth in a phantom, as illustrated by Figure 2.12. The reason for this variation is that film dose per unit tissue dose changes with the photon energy and that the low energy (less than 400 keV) component of the photon fluence spectrum to which film is sensitive increases as depth increase, even though the overall photon beam spectrum hardens. For example, Compton scattering at 180° can reduce the energy of a 4 MV photon to 240 keV. The change of film dose per unit tissue dose delivered by photons originates from the change with depth in the ratio between the mass attenuation coefficients (MACs) of the film emulsion and tissue (or water), now averaged over the depth specific spectrum.

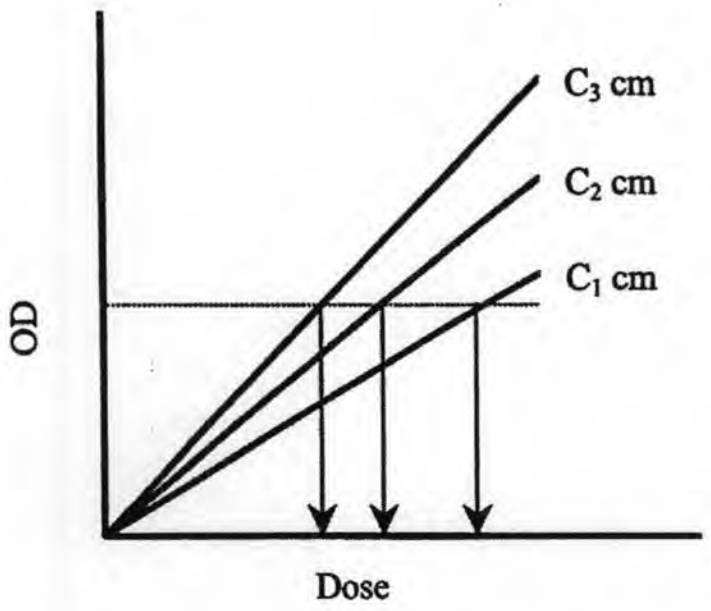

Figure 2.12 Linearized characteristic curves. The same OD, if measured at different condition from that of calibration, corresponds to different doses. C_3 may correspond to a condition where the low-energy (< 400 keV) photons are present in the largest proportion

2.1.10 Impact of film over response to low-energy photons on IMRT measurement [13]

The same physical principle applies to IMRT, but with more complexity, when the film is used for measuring an IMRT beam for treatment verification. For an ordinary open beam, the depth change varies the photon fluence spectrum. For an IMRT beam, however, intensity modulation on the perpendicular plane to the beam axis at a fixed depth causes additional variation of photon fluence. This can be explained more with the illustration of Figure 2.13. A point on a single fluence map is irradiated by the combined in field and outside penumbra areas of beamlets. The two areas are significantly different in terms of their photon spectra: the outside penumbra areas mainly contain low energy scattered photons. The relative proportion of two areas offers intensity modulation: relatively high dose regions in the map are irradiated by a greater number of beamlets and thus by a greater proportion of in field areas, whereas relatively low dose regions are irradiated by a smaller number of beamlets and thus by a grater proportion of outside penumbra areas. For this reason the fluence spectrum varies significantly across a single fluence map. This variation in experimental dosimetry implies that at a single depth of measurement, multiple characteristic curves (Figure 2.12.) exist, corresponding to the photon spectrum at each point on a fluence map. Therefore, no calibration of film response at a single condition is proper for the film dosimetry for IMRT.

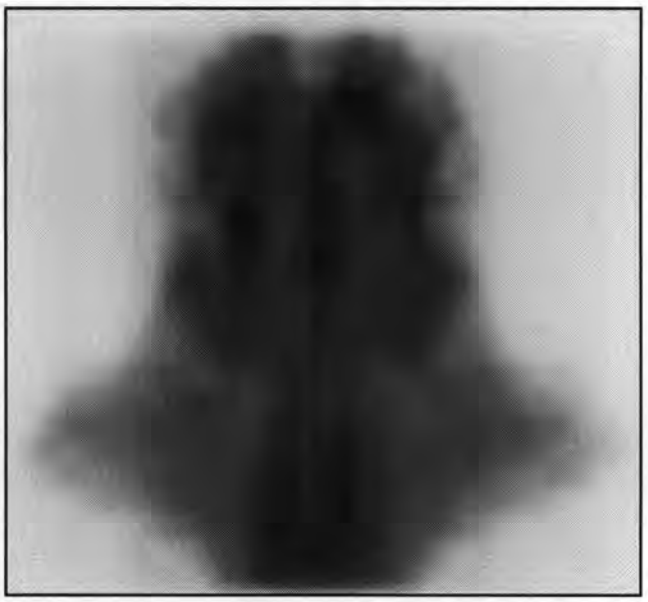

Figure 2.13 IMRT fluence profile for head and neck cancer.

2.1.11 Film type for IMRT verification [3]

XV film is the most common radiographic film used in radiation therapy clinics, including for verification of dose distributions of IMRT. The main limitation of XV film for IMRT applications is its limited dose range. Recently, EDR2 film from Kodak has become available. Some of the physical properties of EDR2 and XV films are listed in Table 2.1. EDR2 film uses very fine monodispersed, pure AgBr grain cubic microcrystals, with an effective dimension of 0.2 μm. Grains for XV film are mixed AgBr and AgI crystals. The silver halide crystals of XV film are composed of different sizes and shapes, with the largest more than 10 times larger than the smallest. The effective edge length of silver halide crystals of XV film is approximately 0.4 μm. The volume of an EDR2 grain is approximately 1/8 of the volume of an XV grain. These physical characteristics of EDR2 film result in high contrast and a wide dose range. Because saturation doses for EDR2 and XV are approximately 700 cGy and 200 cGy, respectively, EDR2 film is better suited to the verification of dose distributions used for patient treatment. Because the dependencies of film response to depth and field size have been suggested to increase with the amount of silver halide present in the film, it seems that, due to the decrease in the emulsion thickness of EDR2 films, these dependencies should, likewise, decrease in comparison to XV film.

Table 2.1 Physical properties of EDR2 and XV films

	EDR2	XV
Grain crystal	AgBr	AgBr and AgI
Total silver density (g/m^2) (both side of the film)	2.303	4.237
Effective dimension (μm)	0.2[b]	0.4[c]
Grain size distribution	Monodisperse	Variation in size and shape
Base thickness (μm)	0.18	0.18
Cellulose coating thickness (g/m^2) (per side)	5	3
Double sided	Yes	Yes

[b]Side of cubic
[c]Effective edge length

2.1.12 Quality control of the film processor

Although the film processor is the last step to create the image of x-ray film, but a quality assurance of film processing is an important factor for a quality control of film. The quality assurance of the film processing should be checked daily before the works begin. A photosensitometer is the equipment of quality control of the film processing. This sensitometer consists of a stable light source, timer, diffusion panel, optical step wedge, and pressure plate to provide firm film contract during exposure. When a film is exposed on both sides to light form the device, the optical step wedge provides a series of light intensities. The film is processed and the curves are plotted between step number and optical density. A lot of the film optical density versus the step number is called the characteristic curve or sensitometric curve or H & D curve. Since the light source and timer furnish constant light exposure for each film, any variation in the graded optical densities to reflect a change in processing conditions. For routine processor monitoring, three measurements of optical density should be made [14]. One measurement is denoted as base plus fog density and should be made in a region of the film that is not exposed to light. This density is measured at first step of control film. The second measurement is obtained in a region of wedge image where the optical density is near 1.0 over base plus fog density. This step is refereed to as the speed index. The third measurement should be made in the region of the wedge image where the density is about 0.25 and 2.0 over base plus fog density. The density difference of these steps is denoted as a contrast index. Moreover, the temperature of the developer solution should be inspected either. To establish the averaged baseline values for these variations, measurements should be obtained on five films. These base line values are the initial data for a processor control chart illustrated in Figure 2.14 Since daily measurements are expected to vary somewhat from the baseline values, tolerance limit must be established for each value. Daily measurements should not vary outside the tolerance limits. Reasonable tolerance

limits are ± 0.03 density variations for base plus fog, ± 0.20 density variation for speed and contrast index, and ± 0.20 degree Celsius for developer temperature.

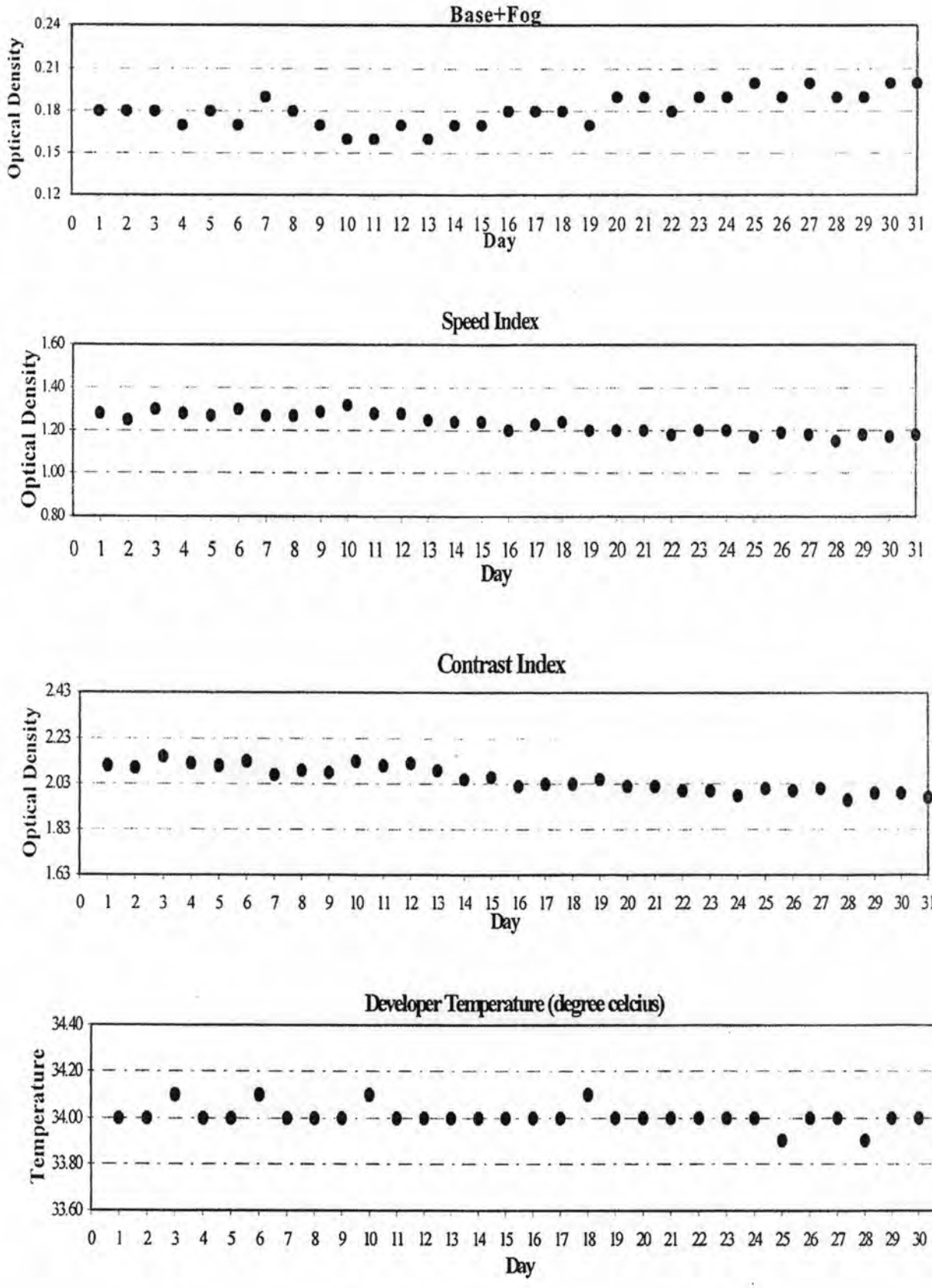

Figure 2.14 The control chart for the quality assurance of the film processing

A sensitometric wedge image should be obtained everyday and the base plus fog density, speed and contrast index should be measured and plotted on the process control chart. As long as the measurements remain within the tolerance limits, the processor may be assuming to be function properly. If a measurement fall outside of the tolerance range, it should be repeated on a second sensitometric film. When the second measurement also falls outside the tolerance range, then processing systems should be checked and initiate corrective accuracy before using. Figure 2.14 is one month example of doing the OD of processor in December 2002, the result shows the variation within the limit. This QA program was done by the division of diagnostic x-ray owing in the month that the film dosimetry has been preformed.

2.1.13 Gamma analysis [13]

Although the use of the factors provides the independent evaluation of a dose difference and misalignment, the gamma offers a composite analysis with the two variables collapsed into one parameter. The gamma is defined as the square root of a linear quadratic addition of the two factors, while they are provided in relative magnitude to their acceptance criteria (C_{DTA} and C_{DD}), that is.

$$\Gamma = \sqrt{\left(\frac{DTA}{C_{DTA}}\right)^2 + \left(\frac{DD}{C_{DD}}\right)^2} \qquad (2.12)$$

Gamma analysis thus compromises between the DD and DTA (Distance to agreement) for investigate the cause of the result (acceptance or not) of the comparison. Such superposition can be acquired along a line passing through the suspicious regions assigned with high values of the gamma. The gamma analysis and superposition of dose profiles are complementary to each other and thus become a useful set of dose comparison tools.

2.2 Related literatures

Esthappan J. et al. [3] investigated the dosimetric properties of EDR2 film and compared to XV2 film. The dose responses of both film types to 6 MV and 18 MV x-ray beams were investigated for depths of 5 cm, 10 cm, and 15 cm and field sizes of 4 x 4 cm^2 and 15 x 15 cm^2. The analysis involved the determination of sensitometric curves for XV2 and EDR2 films, the determination of dose profiles from exposed XV2 and EDR2 films, and the comparison of the film generated dose profiles to ionization chamber measurements. For the combinations of photon beam energy, depth, and field size investigated there, their results indicated that the sensitometric curves are nearly independent of field size and depth of calibration. For a field size 4 x 4 cm^2, a single sensitometric curve for both EDR2 and XV2 film can be used for the determination of relative dose profiles. For the large field size, the sensitometric curve for EDR2 film is superior to XV2 film in regions where the dose falls below 20% of the central axis dose, due to the effects that the increased low energy scattered photon contributions have on film response. The limited field size and depth dependence of

sensitometric data measured using EDR2 film, along with the inherently wide linear dose response range of EDR2 film, makes it better suited to the verification if IMRT dose distribution.

Zhu X R, et al. [4] studied the shape of the sensitometric curves, EDR film with kilovoltage x-rays, ^{60}Co gamma rays, megavoltage x-rays, and electron beams. As a comparison, XV film was also studied with the same beams mentioned above. The model originally developed by Silberstein was used to fit experimental data. It was found that the single hit model can be used to predict the sensitometric curve for XV films irradiated by all beams used in that work and for EDR films exposed to kilovoltage x-rays. For EDR film irradiated by ^{60}Co gamma rays, megavoltage x-rays, and electron beams, the double hit model is used to fit the sensitometric curves. For doses less than 100 cGy, a systematic difference between measured densities and that predicted by the double hit model was observed. Possible causes of the observed differences are discussed. The results of that work provide a theoretical explanation of the sensitometric behavior of EDR2.

Olch A. J, [2] studied and compared the two types of film with respect to absolute dose accuracy for IMRT plans, percent depth dose accuracy for square fields between 2 and 20 cm, ability to measure composite plan isodoses and single beam fluence maps for IMRT cases, and sensitivity to processor variations over time. The EDR2 film was able to achieve an absolute dose accuracy of better than 2% vs. over 4% for XV2 film. The EDR2 film was able to reproduce ionization chamber and diode measured percent depth doses to 20 cm depth generally to within 1% over the range of field sizes tested compared to about 10% for the XV2 film. When compared to calculations, EDR2 film agreed better than XV2 film for both composite plan isodoses and single beam fluence intensity maps. The EDR2 film was somewhat more resistant to processor changes over time than the XV2 film, with a standard deviation of dose reproducibility of less than 2% compared to 6%, respectively.

Danciu C, et al. [5] investigated for two types of film, Kodak X-Omat V and Agfa Structurix D2. Films were positioned in a solid phantom, either perpendicular or (almost) parallel to the beam axis, and irradiated to different dose levels using various photon beams (Co-60, 6 MV, 15 MV, 18 MV, and 45 MV). It was found that the sensitometric curves of the Kodak film derived at different depths are almost identical for the four x-ray beams. For the Kodak film the differences in OD with depth are less than 2%, except for the Co-60 beam, where the difference is about 4% at 10 cm depth for a 15 cm x 15 cm field. The slope of the sensitometric curve of the Agfa film is somewhat more dependent on photon beam energy, depth and field size. The sensitometric curves of both types of film are almost independent of the film plane orientation, except for shallow depths. For Co-60 and for the same dose, the Kodak and Agfa films gave at dose maximum and OD lower by 4% and 6%, respectively, for the parallel compared to the perpendicular geometry. Good dosimetric results can be obtained if films from the same batch are irradiated with small to moderate field sizes (up to about 15 cm x 15 cm), at moderate depths (up to about 15 cm), using a single calibration curve, e.g., for a 10 cm x 10 cm field.

Zhu X R, et al. [15] evaluated a new type of radiographic film, Kodak EDR2 film, for dose verification of IMRT delivered by a static multileaf collimator (SMLC). A sensitometric curve of EDR2 film irradiated by a 6 MV x-ray beam was compared with that of Kodak X-OMAT V (XV) film. The effects of field size, depth and dose rate on the sensitometric curve were also studied. It is found that EDR2 film is much less sensitive than XV film. In high energy x-ray beams, the double hit process is the dominant mechanism that renders the grains on EDR2 films developable. As a result,

in the dose range that is commonly used for film dosimetry for IMRT and conventional external beam therapy, the sensitometric curves of EDR2 films cannot be approximated as a linear function, $OD = c^{*}D$. Within experimental uncertainty, the film sensitivity does not depend on the dose rate (50 vs. 300 MU/min) or dose per pulse (from 1.0×10^{-4} to 4.21×10^{-4} Gy/pulse). Field sizes and depths (up to field size of 10×10 cm^2 and depth=10 cm) have little effect on the sensitometric curves. Percent depth doses (PDDs) for both 6 and 23 MV x- rays were measured with both EDR2 and XV films and compared with ionization chamber data. Film data are within 2.5% of the ionization chamber results. Dose profiles measured with EDR2 film are consistent with those measured with an ionization chamber. Examples of measured IMRT isodose distributions versus calculated isodoses are presented. They have used EDR2 films for verification of all IMRT patients treated by SMLC in their clinic. In most cases, with EDR2 film, actual clinical daily fraction doses can be used for verification of composite isodose distributions of SMLC based IMRT.

Bucciolini M, Buonamici FB and Casati M. [16] reported the quality control procedure developed for dosimetric verification of IMRT technique. In particular a system of film dosimetry for the verification of a 6 MV x-ray beam has been implemented, with the introduction of the scattered radiation filter in the clinical practice that permits one to achieve an absolute dose determination with a global uncertainty within 3.4% (1 S.D.). The film has been calibrated to be used both in perpendicular and parallel configurations. The work also includes the characterization of the Elekta MLC. Ionimetric independent detectors have been used to check single point doses. The film dosimetry procedure has been applied to compare the measured absolute dose distributions with the ones calculated by the treatment planning system (TPS), both for test and clinical plans. The agreement, quantified by the gamma index that seldom reaches the 1.5 value, is satisfying considering that the comparison is performed between absolute doses.

Childress NL, Dong L and Rosen II, [17] developed and test a method for measuring a film sensitometric curve using a single sheet of film exposed with a two field step-and-shoot MLC treatment for Kodak XV2 and EDR2 films. With this technique a film sensitometric curve can be completed in only 10 minutes, making it practical to generate new film calibrations daily. That method was applicable to film calibrations for all purposes, but was particularly useful in IMRT treatment verification due to the method's use of small field. That method agree with the traditional large field multifilm calibration within 0.5% and will produce sensitometric curves with errors less than 1% throughout the dose range, including uncertainties in dose delivery, film response, and optical density measurements. OD values for XV2 and EDR2 films were consistent in the middle of exposure areas at high depths, but the XV2 film penumbra regions showed large amounts of over-response as the calibration depth increased. If XV2 film was used for IMRT treatment verification, it was necessary to reduce the fluence of low energy photons in areas around the film by using thin lead shields. EDR2 film was shown to have minimal energy dependence, as it accurately represented penumbra areas and yielded identical sensitometric curves generated with 6 and 18 MV x-ray beams. However, its darker tint may make it more sensitive to scanning laser film digitizers' horizontal nonuniformities. This single film method proved to be superior to traditional calibration method and allows fast daily calibrations of films for highly accuracy IMRT delivery verifications.