RADIATION EXPOSURE TO PERSONNEL DURING PORTABLE FLUOROSCOPIC IMAGING OF EQUINE LOWER LIMBS

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by
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ABSTRACT

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Radiation exposure rates were mapped in 4 directions around the suspended c-arm of a portable fluoroscopy unit, while imaging the fetlocks, carpi and tarsi of equine cadaver limbs. Exposure rates were highly dependent on distance and direction relative to the c-arm, and were consistently highest on the tube side. Maximum exposure rates ranged from 2.3 to 59.5 mSv/h among the 3 joints. Radiation exposure fell rapidly with increasing distance from the c-arm, but remained significantly above background levels until approximately 4.7 m, depending on direction (range, 2.7 to 9.9 m).

During examinations of the same joints in live horses, exposure rates to the fluoroscopist (thyroid region, tube and image-intensifier hands) and the assistant (thyroid region) were measured. The exposure rate was consistently highest at the fluoroscopist’s tube hand (56.2 mSv/h). During a typical fluoroscopic examination of the carpus, radiation exposure to the fluoroscopist’s thyroid area and hands was approximately 25 and 40 times greater, respectively, than that previously reported for a comparable radiographic study. Exposure to the assistant was approximately 30 times greater than similar radiography.
By observing an experienced fluoroscopist in practice, mean imaging times for routine examinations of the fetlock, carpus and tarsus were determined. Radiation exposure to the fluoroscopist and the assistant, per examination (reported above) and over a conservatively based 40-week working year, was estimated using the previously determined exposure rates. Annual exposure to the assistant’s thyroid, and the fluoroscopist’s thyroid, image-intensifier hand and tube hand were 11, 47, 187 and 1082 mSv, respectively. Recommended maximum permissible doses (MPD) of radiation are: 20 mSv/year, averaged over 5 years and not exceeding 50 mSv in any given year, to the whole body (estimated by thyroid exposure); and 500 mSv/year to extremities.

Portable fluoroscopic imaging of equine lower limbs clearly represents a significant radiation-safety hazard. There is no “safe” distance from the c-arm for personnel within the same room. Radiation-safety procedures during fluoroscopy are just as, if not more, important than during standard radiography. Annual MPD will be rapidly exceeded if radioprotective clothing, which is required by law, is not worn.
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DECLARATION OF WORK PERFORMED

I declare that all work reported in this thesis was performed by me, with the exception of some design, programming and interpretation associated with statistical analysis, which was performed by Anne Valliant.
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1.0 - INTRODUCTION

People are exposed daily to ionizing radiation from a variety of sources. By far, the most significant exposure is from the natural environment and the radiation used in medicine. Nuclear industries, such as nuclear weapons testing and nuclear power plants, are less important sources. Accidents within these industries, however, such as the Chernobyl disaster in 1986, can make significant contributions. The detrimental effects of ionizing radiation have been well documented. The results of excessive exposure include cell death, carcinogenesis and genetic mutations. However, the exposure level below which no harmful effects will occur has not been determined (Steinhausler, Uzunov & Pohl 1985; Keller & Muth 1990).

There are currently no recommendations regarding exposure to radiation from the natural environment. However, legislative authorities impose limits on maximum permissible occupational exposure. Maximum annual doses are defined for both designated radiation workers and the general public (Table A). Most regulatory authorities will investigate an individual's work environment when their radiation dose exceeds 1/10 of the permissible limit (Anonymous 1990b). Over the last half-century, there has been a gradual lowering of acceptable radiation exposure due to increased understanding of the effects of radiation and greater public awareness. In medicine, concerns over radiation exposure have risen as radiation technology has advanced. Not only has the general use of radiology increased, but so has the use of higher-dose procedures (Miller, Davis, MacClean, et al 1983).
Fluoroscopic imaging has increased with the development of more sophisticated medical diagnostic and therapeutic techniques. Procedures such as cardiac catheterization, application of biliary stents, transjugular intrahepatic stents, and complex orthopedics can result in large radiation doses to both operators and patients (Kelsey, Lane & Somers 1984; Le Heron & Mitchell 1985; Labbe, Chui, Rzeszotarski, et al 1994). Protection is needed from both the primary x-ray beam and stray radiation, which represents a combination of scatter radiation and tube leakage. Scattered radiation, which is highest near the surface of the patient, causes increased exposure to the fluoroscopist's head, neck and hands (Boone & Levin 1991). Potential long-term radiobiologic effects of this exposure include thyroid dysfunction, cataracts and the development of skin cancers (Miller et al 1983).

In human medicine, radiation exposure to operating room personnel has been measured during fluoroscopically guided orthopedic procedures. The primary and assistant surgeons were adequately protected by a standard lead apron, and exposure to the scrub nurse and circulating nurse was so low as to be nonmeasurable (Miller et al 1983). Another study evaluated the dose to orthopedic surgeons' hands during a variety of fluoroscopically guided procedures. The dose received by the surgeon performing the greatest number of procedures was extrapolated over a year, and did not approach the annual dose limit of 500 mSv for extremities (Goldstone, Wright & Cohen 1993).

Fluoroscopy has been used with increasing frequency in veterinary medicine (Trumble, Stick, Arnoczky, et al 1994; Loyer & Thomas 1995; Hanson, Smalley, Huff, et al 1997). In equine practice, a new hand-held portable fluoroscopic unit has gained popularity for the detection of orthopedic injuries. Its use has also grown as a survey tool
during prepurchase examinations. There is no published data regarding radiation exposure to personnel during fluoroscopic examination of equine patients.
1.1 - STATEMENT OF GOALS AND HYPOTHESES

The goals of this study were to determine: 1) the radiation exposure to personnel during portable fluoroscopic imaging of equine lower limbs, and 2) a “safe” distance from the c-arm at which no radioprotective clothing is required. The hypotheses were: 1) all personnel directly involved with portable fluoroscopic imaging of equine limbs receive radiation exposure significantly greater than background level, and 2) for all practical purposes, there is no “safe” distance from the c-arm for those personnel.
1.2 - LITERATURE REVIEW

1.2.1 - Ionizing Radiation

Ionizing radiation represents a small part of the electromagnetic spectrum, which also includes radiowaves, radar, microwaves and ultraviolet radiation. The major sources of ionizing radiation are the natural environment, occupational exposure to radiation workers, nuclear energy production, consumer products such as radioluminous timepieces, televisions and smoke detectors, and exposure through medical uses (Mettler & Upton 1995a). Ionizing radiation involves the transfer of energy through space in the form of either electromagnetic waves or subatomic particles that are capable of causing ionization in matter. During ionization, atoms lose or gain electrons and become electrically charged (ions). When ionizing radiation passes through matter, energy is imparted to the matter as ions are formed. Each ionization event causes approximately 33 eV (electron volts) of energy to be deposited in the absorbing material (Khan 1994a).

X-rays are indirectly ionizing. They interact with atoms of an absorbing material and cause the liberation of high-speed electrons. These electrons have the capacity for direct ionization. There are five different ways that an x-ray photon can interact with matter. These are the photoelectric process, Compton scattering, coherent scattering, pair production and photodisintegration. Only Compton scattering and the photoelectric process are important in diagnostic radiology.

**Photoelectric Process** - The positively charged nucleus of an atom is surrounded by negatively charged electrons, which are held in specific orbits or shells. The innermost orbit is the K-shell, which has the highest binding energy. When an x-ray photon of
sufficient energy interacts with a K-shell electron, the electron is ejected from its orbit. In doing this, the photon gives up all its energy to the ejected electron, which becomes a negative ion (photoelectron). The atom's K-shell is now left with a void, which is filled almost immediately by an electron from a more peripheral shell. When this electron drops into the K-shell, it gives up energy in the form of an x-ray photon. The amount of energy released is characteristic for the elemental composition of the material involved, and is thus called characteristic radiation. This characteristic radiation may also interact with another electron in a more peripheral orbit. If the energy transferred to this electron exceeds its binding energy, the electron is expelled from its orbit as an Auger electron.

The photoelectric effect always involves the production of characteristic radiation, a negative ion (the photoelectron), and a positive ion (the initial void in the K-shell leaves the atom with a net positive charge). An Auger electron may also be produced (Curry, Dowdey & Murry 1990b).

Three factors determine the probability of a photoelectric reaction occurring.

1) The x-ray photon must have sufficient energy to overcome the binding energy of the K-shell electron. 2) A photoelectric reaction is most likely to occur when the x-ray photon energy and the electron binding energy are almost the same. 3) The tighter an electron is bound in its orbit (i.e., the closer the orbit is to the nucleus, or the larger the nucleus), the more likely that the electron will be involved in a photoelectric reaction.

Thus, a photoelectric reaction occurs most often with relatively low-energy x-ray photons and with elements having high atomic numbers. The photoelectric process accounts for
much of the contrast necessary in diagnostic radiology and little of the undesirable scatter radiation (Curry et al 1990b).

**Compton Scatter** - The major source of scatter radiation in the diagnostic energy range is a result of Compton scattering. This reaction occurs at higher x-ray photon energy levels than the photoelectric process, and is not influenced by the atomic number of the absorbing material. The incident x-ray photon interacts like a “billiard ball” with a relatively loosely bound electron in a peripheral orbit, causing ejection of the electron from its orbit. Part of the incident photon energy is given to the free electron (recoil electron) as kinetic energy, and the remainder continues on as a less-energetic deflected photon. This deflected photon usually retains most of its original energy due to the relatively low binding energy of an electron in a peripheral orbit. However, the energy of the deflected photon also depends on the angle of collision between the incident photon and the electron (Curry et al 1990b).

Scatter radiation from the Compton effect is not only a significant cause of film fog, but is also an important consideration in radiation safety. The deflected photons retain most of their original energy in the diagnostic range. Therefore, Compton-scatter radiation, such as produced during fluoroscopy, has energy levels similar to the primary x-ray beam and represents a significant safety hazard to the unit operator (Curry et al 1990b).

**Coherent Scatter** - Coherent scattering represents less than 5% of all interactions between radiation and matter; and although present in the diagnostic energy range, it does not play a significant role. The two types of coherent scattering, Rayleigh and Thomson,
both involve the interaction of x-ray photons and electrons. In these interactions, however, the energy of the photon is relatively low compared to the mass of the electron or electron cloud. Therefore, little or no energy is transferred from the photon to the atom, and no ionization occurs. The only effect is deflection of the incident radiation (Curry et al 1990b).

**Pair Production** - Pair production becomes important at energy levels above 1.02 MeV, which is far outside the energy range of diagnostic x-rays. In pair production, energy is initially converted into mass. Interaction of the energy photon with the nucleus of an atom in the absorbing material results in the production of a positron and an electron. A positron has the same mass as an electron, but carries a positive charge. The positron then interacts with another electron, during which both are annihilated. The combined mass of the annihilated positron and electron is converted to energy through the production of two 0.51-MeV photons (annihilation photons) (Khan 1994a).

**Photodisintegration** - Photodisintegration involves the partial destruction of the nucleus of an atom. A high-energy photon causes ejection of a neutron, a proton, an alpha particle, or a cluster of particles. This interaction cannot occur at photon energy levels of less than 7 MeV and is, therefore, unimportant in diagnostic radiology (Curry et al 1990b).

### 1.2.2 - X-Ray Production

A diagnostic x-ray tube consists of an anode and a cathode, sealed in a vacuum within a Pyrex glass tube. The tungsten cathode, or filament, is the negative electrode and
the source of electrons for x-ray production. When a current flows through the coiled filament it becomes heated, causing the atoms to absorb thermal energy and allowing electrons to escape. This effect, termed thermionic emission, does not occur until the tungsten filament is heated to 2200°C. The emitted electrons form a cloud, or space charge, around the filament. When a potential difference is applied between the anode and cathode, the electrons are accelerated across the tube toward the positive anode. The number of electrons flowing from the cathode to the anode each second equals the x-ray tube current in milliamperes (mA). The anode in the portable fluoroscopy unit under investigation is stationary, consisting of a small tungsten target embedded in a large amount of copper. When the accelerated electrons interact with the tungsten target in the anode, x-rays are produced by energy conversion. However, less than 1% of the electrons' energy is converted into x-rays; the remainder is dissipated as heat. The voltage applied across the tube to produce electron acceleration is expressed as peak kilovoltage (kVp). X-rays are formed by two different processes when the electrons interact with the target atoms, producing primarily general (bremsstrahlung) radiation and a small amount of characteristic radiation (Curry, Dowdey & Murry 1990a).

**General (Bremsstrahlung) Radiation** - When an electron passes near the nucleus of an atom, it is attracted by the positive charge of the nucleus, and is deflected from its original path. The kinetic energy lost by the electron as it slows down from the directional change, is emitted as a photon of general or bremsstrahlung (German for "braking radiation") radiation. The energy of the emitted photon depends on three factors: the energy of the electron (essentially a 15-eV minimum), how close the electron passes to the
nucleus, and the charge of the nucleus (i.e., the atomic number). The electrons initially striking the target in the anode have widely different energies, and each electron will interact with many atoms before finally coming to rest. Therefore, a continuous spectrum of photon energies is present in the bremsstrahlung x-ray beam, with the maximum energy determined by the kVp (Curry et al 1990a).

**Characteristic Radiation** - Characteristic radiation results when the electrons bombarding the tungsten target eject electrons from the inner orbits of the target atoms. To eject the target electron, the energy of the bombarding electron must be greater than the binding energy of the orbit (approximately 70 keV for a tungsten K-shell). Any remaining energy is shared between the bombarding electron and the ejected electron. Similar to the previously described photoelectric process, the newly-ionized positively-charged tungsten atom must return to a more stable state. The orbit left with a vacancy is immediately filled by an electron from the adjacent outer orbit. As this electron moves into the inner orbit, it gives up energy as an x-ray photon. This photon's energy is “characteristic” for the orbits involved and the target material (e.g., tungsten K-shell vacancy filled from the L-shell). This process may be repeated as vacancies are sequentially created and filled in different orbits, thus producing characteristic x-ray photons of different energies. The characteristic x-rays may also interact with electrons in more peripheral orbits to produce Auger electrons (Curry et al 1990a,b).
1.2.3 - Fluoroscopic Image Production

Fluoroscopic imaging offers several potential benefits over conventional radiographs. These include ease of use, rapid acquisition of multiple oblique projections, immediate viewing of real-time images, and a decreased requirement for assistants.

Fluoroscopic and conventional radiographic units both produce x-rays in the same way, but differ in the manner of image creation and viewing. To produce a bright fluoroscopic image of diagnostic quality, an image intensifier is required. After x-ray photons have passed through and been attenuated by the patient, they enter the image intensifier. There are five main components to an image intensifier: an input fluorescent screen, a photocathode, an electrostatic focusing lens, an accelerating anode, and an output fluorescent screen. The x-ray photons are converted to light photons by the input fluorescent screen. These light photons cause the photocathode to emit photoelectrons, which move toward the output fluorescent screen under the influence of the 25-to-35 kV accelerating anode. Between the input and output fluorescent screens, the electrons pass through the electrostatic focusing lens, which ensures that no distortion of the image occurs. The photoelectrons are absorbed by the output screen, causing emission of light photons. These light photons either carry the image directly to the fluoroscopist’s eye, or to a video camera for viewing on a television monitor (Curry, Dowdey & Murry 1990c).

1.2.4 - Radiation Units and Quantities

There were no defined units of radiation prior to 1928, which severely hampered any attempt to introduce radiation dose limits. The Roentgen (R) was introduced between
1928 and 1937 by the International Commission on Radiological Protection (ICRP). It is
a measure of ionization in air, not of absorbed dose. The Roentgen reflects the amount of
radiation that will produce ionization totaling 1 electrostatic unit of charge per cubic
centimeter of air (U.S./British system), or $2.58 \times 10^{-4}$ Coulombs/kg of air (SI units)
(Curry, Dowdey & Murry 1990d).

The basic dosimetric quantity in radiation protection is the absorbed dose (D),
which is defined as the energy absorbed per unit mass. The SI unit for absorbed dose is
the Gray (Gy), equal to 1 Joule/kg; while the older but still-used U.S./British unit is the
rad, equal to 100 erg/g. One Gy = 100 rad.

The average absorbed dose for a whole organ or tissue is of greater interest in
radiation protection than the absorbed dose at a given point. This quantity is weighted for
the type and energy of the radiation causing the dose, by the radiation-weighting factor
($W_R$). The equivalent dose in a tissue or organ is given by the expression:

$$H_T = \sum_R W_R \cdot D_{T,R}$$

where, $H_T$ = equivalent dose in tissue T

$W_R$ = radiation weighting factor

$D_{T,R}$ = absorbed dose averaged over tissue or organ T by radiation R

The equivalent dose is measured in Sieverts (Sv), Joule/kg, in the SI system and in rems in
the old U.S./British system. One Sv = 100 rem (Anonymous 1990b).

The relationship between the probability of detrimental health effects (see section
1.2.6) and the equivalent dose is dependent on the type of organ or tissue irradiated. The
tissue weighting factor ($W_T$) is used to account for the contribution of a given organ or
tissue to the total detriment resulting from whole-body irradiation. The effective dose is the sum of the weighted equivalent doses in all the tissues and organs of the body, and is given by the expression:

\[ E = \sum_{T} W_{T} \cdot H_{T} \]

where, \( E \) = effective dose
\( H_{T} \) = equivalent dose in tissue \( T \)
\( W_{T} \) = weighting factor for tissue \( T \)

The effective dose is also measured in Sieverts (Anonymous 1990b).

1.2.5 - Measurement of Radiation

*Gas-Ionization Detectors* - There are a variety of methods available for the measurement of radiation. Gas-ionization detectors are commonly used in diagnostic radiology. A gas-ionization detector consists of a volume of gas, usually argon, placed between two electrodes (wires, plates, concentric cylinders, etc.). The electrodes are connected to the positive and negative sides of a DC power supply, establishing a potential difference across the electrodes. A microammeter to measure current flow is also included in the circuit. Negative ions (free electrons) and positive ions (ionized gas atoms) are produced by ionization when radiation passes through the gas in the detector. An average of 25 to 35 eV of energy is required to form each positive and negative ion pair. The negative and positive ions are attracted to the anode and cathode respectively, inducing a current to flow through the circuit. The magnitude of this current, as measured by the
ammeter, reflects the amount of energy given up by the radiation (Mann, Ayres & Garfinkel 1980).

When a gas-ionization detector is subjected to a constant source of radiation, the resulting current (signal) increases as the potential difference (applied voltage) across the two electrodes is increased (Fig A). At very low applied voltages, there is insufficient potential difference to effectively move the ions toward the electrodes, and recombination of the ions occurs. Less ions are detected than are formed. As the strength of the applied field increases, recombination is prevented and the probability of detecting all ions formed approaches 100%. This applied voltage is termed the saturation current, and is represented by the ionization-chamber region (first plateau) in Figure A.

The gas-ionization principle is utilized in three different types of radiation detectors: ionization chambers, proportional counters and Geiger-Müller counters. These three detectors may be differentiated by the voltages at which they operate.

*Ionization chambers* operate at relatively low applied voltages, 50 to 300 V (Fig A). Although this voltage is sufficient to clear all ions from the gas volume between the electrodes, the resultant current from individual particle interactions is too small to be detected accurately. The total current induced in the gas volume is measured, not individual radiation events. Since a relatively large amount of radiation energy is required to obtain a usable signal, ionization chambers are most commonly used to measure radiation fields (e.g., pocket dosimeters) (Martin & Harbison 1979).

*Proportional counters* operate at an applied voltage higher than that of ionization chambers (Fig A). This voltage (400 to 900 V) is sufficient to accelerate the ions in the
gas volume to a point where they cause secondary ionizations. These secondary ions may, in turn, be accelerated to cause tertiary ionizations, and so on. The current flow resulting from this "gas amplification" is sufficient to measure individual particle interactions. The individual signal pulse produced is directly proportional to the energy deposited in the detector. Therefore, proportional counters are used most often to detect and to distinguish alpha-particles, beta-particles and electrons (Martin et al 1979).

*Geiger-Müller counters* operate at an applied voltage (600 to 1,200 V) higher than that of proportional counters. As with proportional counters, the applied voltage is sufficiently high to cause gas amplification by inducing secondary ionization. In Geiger-Müller counters, however, this process is maximized by a factor as high as $10^4$. Ultraviolet radiation is produced as the accelerated electrons approach the positive electrode. This ultraviolet radiation subsequently causes additional ionizations, in which additional ion pairs are produced and migrate to their respective electrodes. This ongoing avalanche of ionization can eventually be terminated by a process called quenching. A quenching gas, commonly chlorine, is placed at the cathode as an electron donor to neutralize the positive ions (Mann et al 1980).

Due to the maximum gas amplification in Geiger-Müller counters, they are extremely sensitive, and are the detector of choice as general room monitors or when surveying for low-level contamination (Martin et al 1979). However, the time required for the above quenching process to occur (approximately 300 $\mu$s) prevents their use in the measurement of high-intensity radiation fields. The signal produced by Geiger-Müller counters is not proportional to the energy of the incoming radiation. They are true
"pulse-type detectors", measuring only the number of radiation events (photons), not their energy (Mann et al 1980).

**Solid-State Detectors** - Solid-state systems are also available for radiation dosimetry. Unlike the previously described gas-ionization detectors, these require calibration in a known radiation field before use. The two types of solid-state detectors are electrical-conductivity dosimeters and integrating dosimeters. Included in the second category are thermoluminescent crystals, radiophotoluminescent glasses and optical-density dosimeters, such as glass and film. Film-badge and thermoluminescent dosimeters are the most commonly used systems (Khan 1994b).

Several thermoluminescent phosphors are available, including lithium fluoride, lithium borate and calcium fluoride. Lithium fluoride is most commonly used. When a crystal is irradiated, a minute fraction of the absorbed energy is stored in the crystal lattice. The thermoluminescent phenomenon occurs when the crystal is later heated and the stored energy is released as visible light. A photomultiplier tube measures the emitted light and converts it to an electrical current, which is amplified and recorded (Khan 1994b).

Radiographic film consists of a transparent cellulose-acetate or polyester-resin base, coated on both sides with an adhesive and a silver-halide crystal emulsion. These crystals are radiation sensitive, forming a latent image when exposed to ionizing radiation or visible light. When the film is developed, the exposed crystals form small grains of metallic silver and the unexposed crystals are removed. It is the metallic silver which produces the black areas on a developed radiograph. The degree of film darkening therefore reflects the amount of radiation absorbed. In film-badge dosimetry, this degree
of blackness is measured by determining its net optical density (OD) with a densitometer. Net OD is obtained by subtracting the OD of processed unexposed film from the OD of film in the dosimeter (Khan 1994b).

1.2.6 - Health Effects of Ionizing Radiation

Detrimental health effects of ionizing radiation are classified as either deterministic (nonstochastic) or stochastic. Deterministic effects depend on the dose received, volume of tissue irradiated, quality or type of radiation, and time over which the dose is received. An established threshold level must be reached before a clinical effect occurs (Mettler & Upton 1995c). The clinical effect results from the killing of cells, which, if the dose is large enough, causes sufficient cell loss to impair the function of the tissue or organ. Above this threshold for clinical effect, the severity of harm increases directly with dose. Highly radiosensitive tissues, including cells of the testes, ovaries, bone marrow and lens of the eye, are more likely to be affected (Anonymous 1990c).

Deterministic effects have been classified as either immediate, acute (days to weeks) or delayed (months to years). Acute effects occur from damage to rapidly proliferating cell lines, such as intestinal mucosa, bone marrow and germinal cells. The four acute radiation syndromes involve the central nervous, cardiovascular, gastrointestinal and hematopoietic systems. All acute syndromes usually lead to death after a period of 24 hours to 6 weeks. Fortunately, they are not of concern regarding exposure to radiation in the diagnostic energy range (Mettler et al 1995c).
Cataract formation, or opacification of the lens of the eye, is a well-recognized delayed deterministic effect of exposure to ionizing radiation. The threshold for cataract formation is believed to be a single dose of 2 to 5 Sv, or 10 Sv fractioned over several years (McGuire, Baker & Vandergrift 1983). Since exposure to the eye varies from 0.5 to 2 times that of collar-region film-badge readings (McGuire et al 1983), a threshold dose could be acquired fairly quickly, despite the relatively low-energy radiation used in diagnostic radiology. Cataract formation, thyroid dysfunction and skin cancers are of particular concern to fluoroscopists, since their head, neck and hands receive the greatest exposure (Miller et al 1983). Scatter from the fluoroscopist's head can also be a significant source of radiation exposure (Cousin, Lawdahl, Chakraborty, et al 1987).

Stochastic effects, unlike deterministic effects, have no defined threshold level for occurrence. They result when an irradiated cell is modified but not killed. It is assumed that stochastic effects are less likely at low dose levels. Although the probability of a stochastic change occurring in a population of cells is proportional to the amount of radiation exposure, the severity of that change is not necessarily dose-related (Mettler & Upton 1995b). After a prolonged delay, stochastic-modified cells may undergo neoplastic transformation. Leukemia, the most common neoplasia from radiation exposure, has a median latent period of 8 to 10 years (Curry et al 1990d). Solid tumors of the breast and lung have a latency 2 to 3 times longer. If germinal cells are involved, hereditary stochastic effects may be revealed in future generations (Anonymous 1990c).
1.2.7 - History of Radiation Protection

X-rays were discovered by W.C. Roentgen in 1895. Their potential diagnostic and therapeutic benefits were recognized rapidly, however, it was some time before their concurrent deleterious effects were accepted. Between 1895 and 1921, there were multiple reports of radiation-induced dermatitis, malignancy and death. One report was by an American physicist who directly exposed his finger to an x-ray beam over a period of several days. The resultant swelling, pain, blistering and stiffness lead to one of the earliest recommendations for reduced exposure to x-rays (Vanbekevoort, Ponette & Baert 1995).

The British X-Ray and Radium Protection Committee was established in 1921 to instigate methods of radiation protection. Informal dose limits were initially aimed at avoiding physical symptoms. Recommendations were based on the skin-erythema dose, which was defined as the exposure necessary to cause erythema in 10 to 14 days. The first limit was set at 1/10 of the skin-erythema dose per year. This was later lowered to 1/100 of the skin-erythema dose per month (Vanbekevoort et al 1995). Initial attempts at setting dose limits were also hampered by the lack of well-defined units of radiation (Curry et al 1990d). However, it has since been shown that the skin-erythema dose was approximately 6 Sv, making the aforementioned dose limits equivalent to 600 mSv/year and 60 mSv/month (Vanbekevoort et al 1995).

In 1928, the International Commission on Radiological Protection (ICRP) was established to define the Roentgen (R) as the unit of exposure, however, this task was not completed until 1937. The ICRP is the one internationally recognized body responsible
for recommending maximum permissible doses (MPD) to ionizing radiation. It was not until 1931, some 46 years after the discovery of x-rays, that the first formal MPD of 0.2 R per day or 50 R per year was introduced in the United States by the Advisory Committee on X-Ray and Radium Protection. This committee later became known as the National Council on Radiation Protection and Measurement (NCRP). The NCRP is a private organization of American scientists, all experts in various aspects of radiation, who operate under a congressional charter, but without any legal status. Both the ICRP and the NCRP can only make recommendations regarding radiation protection. However, most provincial and federal laws are based on their recommendations (Curry et al 1990d).

As knowledge of the hazards of radiation increased, attention shifted from the acute biologic effects to the delayed, chronic and potential genetic effects. This has lead to lowering of the MPD for occupationally exposed individuals on three separate occasions since its inception (Vanbeckevoort et al 1995).

1.2.8 - Radiation Protection

The primary aim of radiation protection is to provide safety standards for people exposed to radiation, without unduly limiting the potential benefits of that exposure (Anonymous 1990a). Since it must be assumed that all exposure to ionizing radiation is harmful, a level below which no harmful effects will occur cannot be determined. This applies particularly to stochastic effects, which are not subject to dose thresholds (Curry et al 1990d). Therefore, radiation-protection guidelines are aimed at preventing deterministic effects by recommending varying dose limits to different sections of the
population. Guidelines are also based on distinguishing between practices which cause exposure to radiation and interventions which decrease exposure.

Recommendations for interventions to decrease radiation exposure are based on two general principles. 1) The intervention should do more good than harm (i.e., benefits from the reduced dose should justify any harm, costs or social effects of the intervention). 2) The method of intervention should be optimized to maximize its net benefits (Anonymous 1990a).

Recommendations for practices causing radiation exposure are based on three principles. These principles try to ensure that no individual is exposed to radiation risks which are judged to be unacceptable in normal circumstances. 1) Justification of the practice - no practice involving exposure to radiation should be performed unless its benefits to exposed individuals or to society offset any detriments. 2) Optimization of protection - in any practice, the size of individual doses, the number of people exposed, and the potential for exposure should all be kept as low as reasonably achievable. 3) Individual dose and risk limits - in any practice, the exposure of individuals should be subject to dose limits or to some control of risk (Anonymous 1990a).

Based on the above three principles, MPD have been recommended for both the general public and those who are occupationally exposed. The NCRP recommends a dose limit for occupationally exposed individuals of 20 mSv per year, averaged over 5 years. This dose should also not exceed 50 mSv in any single year. The MPD for the general public is significantly lower, at 5 mSv per year (Table A) (Curry et al 1990d). Radiation-protection standards have been established for each Canadian province. In
Ontario, enforcement of the X-Ray Safety Regulation is the responsibility of the Ministry of Labour. The MPD recommendations in Ontario, all other Canadian provinces, and throughout the United States are the same as those recommended by the NCRP.

1.2.9 - Methods of Reducing Radiation Exposure

Radiation exposure can be reduced by a combination of three methods: increasing distance from the primary beam, reducing the time of exposure, and the use of barriers. Radiation exposure is inversely proportional to the square of the distance from the source ("inverse square law"). Increasing distance from the primary beam is obviously a simple method of reducing exposure. Time limitations may be applied to an area, to specific body parts, or to the use of the x-ray machine, all resulting in reduced dose levels (Curry et al 1990d).

Barriers may be primary or secondary. A primary barrier provides protection from the primary beam of radiation. Secondary barriers provide protection from stray radiation, which is a combination of scatter radiation and tube leakage. Four factors must be considered when determining the exposure of a given area in an x-ray facility:

1) workload (W), the quantity of x-rays produced per week (mA.min/wk); 2) use factor (U), the percentage of time that the beam is directed at a particular area; 3) occupancy factor (T), the percentage of time that the particular area is occupied; and 4) distance (d) from the x-ray tube to the area. Once these have been determined, the necessary thickness of primary and secondary barriers can be decided (Curry et al 1990d).
Radioprotective clothing is a form of secondary barrier. All personnel involved in restraint of an animal during a radiographic examination must wear an apron and gloves or mittens which provide protection equivalent to at least 0.5 mm of lead. All other staff who are required to be present during the exposure must wear similar protection (Anonymous 1986). Materials other than lead may be used in radioprotective clothing. Between energies of 29 and 88 keV, tin is a better absorber of x-rays than lead on a gram for gram basis. Most diagnostic radiographs are made in an energy range of 20 to 110 keV. Given that tin is approximately 35% lighter than lead, tin-containing protective clothing could provide lighter, and equal or better protection than lead-containing clothing in many situations. This has obvious practical benefits for people required to wear protective clothing for long periods or those requiring greater freedom of movement (Curry et al 1990d).

Regulations for radiation protection during fluoroscopy are the same as those for exposure to radiation under any other circumstance. However, given the relatively high exposure rates at the fluoroscopist’s head, radioprotective eyewear is also recommended. Scatter from the head can increase exposure to the eye by 21% (Cousin et al 1987). Most regular eyeglasses with glass lenses afford some radioprotection, because materials such as lead or barium are often added to increase the refractive index of glass. Purpose-manufactured lead-containing radioprotective glasses reduce radiation transmission to less than 10%. Conversely, plastic or polycarbonate lenses in regular eyeglasses allow 95 to 98% transmission of radiation, and are not recommended for use during fluoroscopy (Cousin et al 1987).
Table A - Maximum permissible doses to ionizing radiation, as recommended by the National Council on Radiation Protection and Measurement (NCRP)

<table>
<thead>
<tr>
<th>Class of exposed individuals</th>
<th>mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Occupational exposure</strong></td>
<td></td>
</tr>
<tr>
<td>Stochastic - total body</td>
<td>20 /yr (averaged over 5 yr) &amp; ≤ 50 in any given yr</td>
</tr>
<tr>
<td>Deterministic (annual)</td>
<td></td>
</tr>
<tr>
<td>Lens of eye</td>
<td>150</td>
</tr>
<tr>
<td>All other areas</td>
<td></td>
</tr>
<tr>
<td>(bone marrow, breast, lung, gonads, skin, extremities)</td>
<td>500</td>
</tr>
<tr>
<td><strong>Lifetime cumulative exposure</strong></td>
<td>10 x Age in years</td>
</tr>
<tr>
<td><strong>Public exposure (annual)</strong></td>
<td></td>
</tr>
<tr>
<td>Stochastic - total body</td>
<td>5</td>
</tr>
<tr>
<td>Deterministic</td>
<td></td>
</tr>
<tr>
<td>Lens of eye</td>
<td>15</td>
</tr>
<tr>
<td>All other areas (skin, extremities, etc.)</td>
<td>50</td>
</tr>
</tbody>
</table>


1.2.11 - Figures

Figure A - Saturation curve for gas-ionization detectors. Curve regions:

1) recombination, 2) ionization-chamber (saturation current), 3) proportional,
4) Geiger-Müller, and 5) continuous/spontaneous discharge.

[Graph showing a saturation curve with regions labeled 1 to 5, each representing a different region of operation.]
2.0 - RADIATION EXPOSURE TO PERSONNEL DURING PORTABLE FLUOROSCOPIC IMAGING OF EQUINE LOWER LIMBS

(For submission to J Am Vet Med Assoc)

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2.1 - Abstract

Objectives - Determine radiation exposure to personnel during portable fluoroscopic imaging of equine lower limbs, and a "safe" distance from the c-arm at which no radioprotective clothing is required.

Design - Prospective study.

Animals - Part 1, 1 forelimb and 1 hind limb of 5 equine cadavers; Part 2, 5 adult horses; Part 3, 9 adult horses.

Procedure - Radiation exposure rates were mapped in 4 directions around the suspended c-arm of a portable fluoroscopy unit, while imaging fetlocks, carpi and tarsi of cadaver limbs. During examinations of the same joints in live horses, exposure rates to the fluoroscopist (thyroid, each hand) and the assistant (thyroid) were measured. Mean imaging times for routine fetlock, carpal and tarsal examinations were determined by observing an experienced fluoroscopist in practice. Exposure to fluoroscopist and assistant per examination and annually was estimated.

Results - Radiation exposure rates were highly dependent on distance and direction relative to the c-arm, and were consistently highest on the tube side. Exposure remained significantly above background levels until approximately 4.7 m from the c-arm, depending on direction (range, up to 9.9 m). During examination of live horses, exposure was consistently highest at the fluoroscopist's tube hand. During a typical fluoroscopic study of the carpus, exposure to the fluoroscopist's thyroid area and hands was approximately 25 and 40 times greater, respectively, than that reported for a comparable radiographic examination.
**Clinical Implications** - Fluoroscopic imaging of equine limbs represents a significant radiation-safety hazard. Recommended annual maximum permissible doses will be rapidly exceeded if radioprotective clothing, which is required by law, is not worn.
2.2 - Introduction

Fluoroscopic imaging has been used with increasing frequency in veterinary medicine. In equine practice, a relatively new hand-held portable fluoroscopic unit has gained popularity for detection of orthopedic injuries. Its use has also grown as a survey tool during prepurchase examinations.

Similar to routine radiography, involved personnel should be protected from both the primary x-ray beam and stray radiation during fluoroscopic imaging. Exposure to scattered radiation is greatest to the fluoroscopist’s head, neck and hands. The deleterious effects of exposure to ionizing radiation are well known and can be extensive. Thyroid dysfunction, cataracts and skin cancer of the face and hands are all reported long-term radiobiologic effects from excessive exposure during fluoroscopy.

Many users of the portable fluoroscopic system described above seem to be under the impression that personal protection against primary and stray radiation is totally unnecessary, despite statements to the contrary in the manual from the manufacturer. There have been no published data regarding radiation exposure to individuals during fluoroscopic examination of equine patients. The objectives of this study were to:

1) determine exposure to personnel involved in routine examinations of equine lower limbs with a hand-held fluoroscopic unit, and 2) determine a “safe” distance from the primary beam of this unit, at which no radiation protection was required.

2.3 - Materials and Methods

Part 1 - One forelimb and 1 hind limb were collected from each of 5 equine cadavers, weighing 450 to 500 kg. Limbs were frozen at -20°C until required, and then
thawed before use. Using a portable fluoroscopic imaging system (0.05 to 0.25 mA, 40 to 70 kVp, 6.7-cm field of view), standardized examinations of 5 fetlocks, 5 carpi and 5 tarsi were performed. Fetlocks were randomly selected from either the front or hind limb.

The fluoroscopic c-arm and each limb were suspended from the center of an aluminum frame (2.1 m long, 1.8 m high) with 0.5-cm-diameter cotton rope (Addendum-Fig A). Limbs were positioned vertically, with the hoof resting flat on the floor. The 8.4-kg c-arm was positioned with the c-arm body and primary x-ray beam in a horizontal plane and with the c-arm receptor plate 1 cm from the limb (Addendum-Fig B). C-arm positioning was also adjusted to center the primary x-ray beam on: a) the metacarpo/metatarsophalangeal joint space in each fetlock, b) the proximal row of carpal bones in each carpus, or c) the central tarsal bone in each tarsus. Lateromedial and dorsopalmar/plantar fluoroscopic images were obtained by rotating the limb, while leaving the c-arm stationary. The system console, which contained the power unit, digital image processing unit, thermal printer and video monitor, was positioned approximately 3 m from the c-arm. For all examinations, diagnostic images were produced by setting the system’s kVp at its maximum of 70 and the mA at 0.15. This relatively high-kV/low-mA technique was selected to help decrease potential radiation exposure to personnel.5

During the examination of each joint, radiation exposure rates were measured with 4 general-purpose ionization-chamber survey meters. Each meter was suspended horizontally by 0.5-cm-diameter cotton rope from 1 of 4 polyvinyl-chloride pipes, which radiated at 90° intervals from the center of the aluminum frame described above. Accordingly, each pipe was assigned as meter position 1, 2, 3, or 4. Orientation of the c-arm always remained constant relative to the 4 meters (Fig 1; Addendum-Fig A and
B). Radiation exposure rates were initially recorded with each meter at the same level (horizontal plane) as the c-arm and at a distance of 30 cm from the center of the limb (just beyond the borders of the c-arm body). Measurements were repeated at distances of 60, 90, 120, 150, 180, 230 and 280 cm. A similar series of measurements were obtained after moving each meter to a level 30 cm above, 60 cm above, and 30 cm below the level of the c-arm. Due to the proximity of the fetlock to the ground, exposure rates were measured only at or above the level of the c-arm when examining this joint. Imaging time (i.e., x-ray on) was limited to that required to obtain a reading at each meter position. Throughout data collection, the investigator wore a standard 0.5-mm lead-equivalent radioprotective gown and thyroid collar.

Before beginning and after completing data collection, each survey meter was calibrated against a calibrated x-ray beam by the Radiation Protection Service, Ontario Ministry of Labour. Exposure-rate readings from each meter were adjusted according to its calibration curve (correction factor versus keV). Fifty percent of the c-arm kVp setting was used to approximate the mean energy (keV) of its polychromatic x-ray beam. Daily during data collection, each meter was also evaluated for any drift against an americium-241 standard (Addendum).

Data were analyzed with a mixed linear model for repeated measures (proc Mixed in SAS®), with any differences between horses (i.e., limbs) treated as random effects. Exposure rates were examined for: 1) significant differences between joints, fluoroscopic views and meters (direction relative to the c-arm), and interaction between these variables; and 2) significant change due to distance from the joint. For data analysis, the direct (i.e., straight-line) distance between the center of the joint being imaged and each meter was
calculated from the measured horizontal and vertical distances. In cases of significant interaction between variables, the simple effects were analyzed for each joint, meter or fluoroscopic view. When significant effects were detected, contrast statements were used to evaluate differences within each variable. Significance was set at \( P < 0.05 \). A Bonferroni correction was applied when multiple comparisons were made on the same data.

Exposure rates from each of the 4 meters were plotted against distance for each joint/view combination, with subsequent quadratic-regression fits of the data points. Mean exposure rates at various distances from the joint and the distance at which radiation exposure approached background level (\( \leq 0.1 \text{ mSv/h} \)) were calculated from the regression equations.

Part 2 - Five adult horses, ranging from 421 to 498 kg in weight, were randomly selected from the teaching herd at Ontario Veterinary College. Each horse was restrained by an assistant and was sedated with romifidine\(^d\) (0.04 mg/kg [0.02 mg/lb], IV). For each horse, standardized examinations of 1 front fetlock, 1 carpus and 1 tarsus, each selected at random, were performed using the portable fluoroscopic imaging system described above.

The fluoroscopic c-arm was hand-held by the fluoroscopist and positioned to obtain images of each joint similar to Part 1. However, mediolateral views were substituted for lateromedial views. Mediolateral views were easier and safer to acquire when imaging a live horse, due to the size and contour of the c-arm and the location of the cable connecting the c-arm to the system console. Diagnostic images were again produced for all examinations by setting the system's kVp at its maximum of 70 and the
mA at 0.15. For each horse, the examination series (fetlock, carpus and tarsus) was performed 3 times by the same fluoroscopist in a randomized sequence. During each examination, the assistant stood at the level of the horse’s throat latch on the same side as the fluoroscopist.

Radiation exposure rates to the fluoroscopist and the assistant were measured during each examination with 1 of the general-purpose ionization-chamber survey meters used in Part 1 (Addendum-Fig C to E). The meter was calibrated and its readings were appropriately adjusted as previously described. Exposure rates for the collar/thyroid region of both the fluoroscopist and the assistant were determined by obtaining readings on both sides of the subject’s neck whenever possible (i.e., sufficient space between horse and subject), and then recording the higher value. Exposure rates for each of the fluoroscopist’s hands were determined by placing the meter against the hand, at the point where the hand was closest to the primary x-ray beam. Each hand was identified by its location on either the tube side or the image-intensifier side of the c-arm. For all measurements, the meter was directed at the primary beam. The distance from each meter position to the center of the joint being imaged was also recorded for each view. As in Part 1, imaging time was limited to that required to obtain a meter reading. All personnel again wore standard radioprotective gowns and thyroid collars. However, radioprotective gloves or mittens were not used by the fluoroscopist since they made grasping and operating the c-arm for sufficient periods almost impossible. Statistical analysis of exposure-rate data was comparable to Part 1, using a mixed linear model for repeated measures to examine for differences between joints, fluoroscopic views and the 4 meter positions.
Part 3 - Established routine techniques for complete examination of the fetlock, carpus and tarsus were observed at an equine practice, which had used hand-held portable fluoroscopic imaging extensively for 7 years. For the past 6 months, a fluoroscopic unit identical to that in Parts 1 and 2 had been employed. The actual imaging time (x-ray on) was recorded from a total of 5 fetlock, 5 carpal and 5 tarsal examinations on 9 adult equine patients. All examinations were performed in real-time, and included lateromedial, dorsopalmar/plantar, dorsomedial-palmaro/plantarolateral oblique, and dorsolateral-palmaro/plantaromedial oblique projections. A flexed lateromedial view was added to fetlock studies. A flexed lateromedial view and 2 dorsoproximal-dorsodistal skyline views (proximal and distal carpal bones) were added to carpal examinations. The system’s mA and kVp settings were generally comparable to those used in Parts 1 and 2.

From these observations, mean imaging times were calculated for each of the 3 joints. Radiation exposure to the fluoroscopist and the assistant during routine examination of each joint was estimated, using the mean exposure rates determined in Part 2. Practice records were also reviewed over the past 3 months to assess the number and type (i.e., joint distribution) of fluoroscopic examinations per week. Annual radiation exposure from these commonly performed studies (fetlock, carpus and tarsus) was estimated for both the fluoroscopist and the assistant. This calculation was conservatively based on a 40-week year to account for seasonal caseload fluctuations in the practice area.

2.4 - Results

Before beginning and after completing data collection, the fluoroscopic unit used in Parts 1 and 2 was evaluated by the manufacturer as performing within specifications.
During daily evaluations of the survey meters against the americium-241 standard, differences between meters and fluctuations within each meter were both insignificant (< 0.02 mSv/h).

**Part 1 - Distance from the primary x-ray beam had the most significant effect on radiation exposure (P < 0.01; Fig 2).** Among the 3 joints, maximum exposure rates ranged from 2.3 to 59.5 mSv/h (mean ± SEM, 11.4 ± 0.7 mSv/h). In meters 2 and 3, maximum exposure usually occurred at, or close to, the shortest direct distance from the joint (30 ± 0.4 and 32 ± 0.8 cm, respectively) on the same level as the c-arm. In meters 1 and 4, however, maximum exposure usually occurred in the plane 30 cm above or below the level of the c-arm, at a direct distance of 42 ± 0 and 38 ± 1.1 cm, respectively (Table 1, Fig 1).

As distance from the primary x-ray beam reached 0.5, 1 and 2 m, exposure rates respectively fell to approximately 39, 12 and 4% of maximum. Despite these reductions, however, means at these distances still ranged from 1.5 to 11.0, 0.5 to 3.7, and 0.2 to 1.3 mSv/h, respectively. Radiation exposure approached background level (≤ 0.1 mSv/h) at approximately 4.7 m, but variation among the different joints, views and meters remained relatively great (range, 2.7 to 9.9 m; Table 1, Fig 2).

Directional position relative to the fluoroscopic c-arm (i.e., meter number) also had a significant effect on radiation exposure. Measurements were usually highest in meter 2 (P < 0.01) and consistently lowest in meter 4 (P < 0.01; Table 1, Fig 1 and 2). As described above, exposure rates in meters 1 and 4 tended to be greater above or below the level of the c-arm at short distances. Although statistical differences were also noted
between joints, between views, and due to joint/view interaction, these results appeared to be driven by the overwhelming effects of distance and directional position.

Part 2 - Meter position consistently had the most significant effect on radiation exposure ($P < 0.01$), regardless of the joint or fluoroscopic projection. By far, the fluoroscopist's tube hand received the highest dose ($56.2 \pm 1.6$ mSv/h), followed by the fluoroscopist's image-intensifier hand ($9.9 \pm 1.0$ mSv/h), the fluoroscopist's collar ($2.3 \pm 0.1$ mSv/h), and finally the assistant's collar ($0.5 \pm 0.1$ mSv/h). The difference in collar readings between the fluoroscopist and the assistant was not statistically significant ($P = 0.10$). However, significant differences were noted during individual contrasts between all other meter positions ($P < 0.01$; Table 2, Fig 3).

Unlike Part 1, distance from the primary x-ray beam was now considered relatively "fixed" to meter position (Table 2). Distance to the assistant's collar was always greatest ($173 \pm 6$ cm), but naturally changed with the joint being imaged (carpus = $140 \pm 2$, fetlock = $160 \pm 2$, and tarsus = $218 \pm 4$ cm). Although the influence of distance on exposure rates was obvious, an inconsistency was noted when comparing readings between the fluoroscopist's hands. Distance from the joint to the tube hand was always about 1.5 times that to the image-intensifier hand, but exposure to the tube hand was almost 6 times greater ($56.2 \pm 1.6$ versus $9.9 \pm 1.0$ mSv/h; Table 2, Fig 3).

Although statistical analysis indicated significant joint and fluoroscopic-view effects ($P < 0.01$), no consistent trends were evident. Clinically relevant differences were apparent in only 2 instances. 1) Radiation exposure to the fluoroscopist's image-intensifier hand was respectively 3 and 10 times higher when imaging the carpus.
(6.5 ± 0.8 mSv/h) and fetlock (21.2 ± 1.2 mSv/h), than when imaging the tarsus (2.2 ± 0.2 mSv/h). 2) Exposure rates to the assistant’s collar were about 10 times greater from dorsopalmar/plantar images (1.0 ± 0.1 mSv/h) than from mediolateral images (0.1 ± 0 mSv/h; Table 2).

**Part 3** - From the 5 examinations observed of each joint, the mean imaging times were 75 ± 9 s for fetlocks, 84 ± 16 s for tarsi, and 173 ± 26 s for carpi. Review of the practice records indicated that an average of 6 fetlock, 6 carpal and 3 tarsal examinations were performed each week. Using mean exposure rates determined in Part 2, estimated radiation exposure to personnel from each of these routine examinations and on a 40-week annual basis is presented in Table 2.

**2.5 - Discussion**

It is assumed that all exposure to ionizing radiation is harmful, making it impossible to determine a level below which no injury will occur. Detrimental health effects of ionizing radiation are classified as either deterministic (nonstochastic) or stochastic. Deterministic effects result from the killing of cells, which, if the radiation dose is large enough, causes sufficient cell loss to impair tissue or organ function. Above this threshold dose, the severity of damage increases directly with additional exposure. Highly radiosensitive tissues, such as cells of the gonads, bone marrow and lens of the eye, are most likely to be affected. For fluoroscopists, however, high exposures to the head, neck and hands make cataract formation, thyroid dysfunction and skin cancers the most common deterministic effects.
Stochastic effects, unlike deterministic effects, have no defined threshold level for occurrence. They result when an irradiated cell is modified, but not killed. Although the probability of a stochastic change is proportional to the radiation dose, the severity of that change is not necessarily dose-related. Clinical disease from stochastically modified cells may not surface for long periods, but the potential for its development cannot be ignored. Leukemia, the most common neoplasia resulting from radiation exposure, has a median latent period of 8 to 10 years.

The hand-held portable fluoroscopic unit described in this study is intended to augment or to replace standard radiography in equine practice. While many veterinarians follow excellent radiation-safety procedures when using portable x-ray units in the field, a large number fail to do so. Unfortunately, there appears to be a general misconception that such safety methods are not required when using portable fluoroscopic systems.

In the current study, fluoroscopy of the equine lower limbs resulted in significant radiation exposure to personnel, greater than that previously reported for standard radiography. During routine fluoroscopic examination of the carpus, the fluoroscopist received approximately 0.1 mSv to the collar/thyroid region, 0.3 mSv to the image-intensifier hand, and 2.8 mSv to the tube hand. The assistant acquired 0.03 mSv at the collar (Table 2). In a comparable 7-view radiographic examination of the carpus, exposure to the person holding cassettes was approximately 25 times less to the thyroid region (0.004 mSv) and up to 40 times less to the hands (0.07 mSv). Exposure to the assistant was approximately 30 times less (0.001 mSv) than during fluoroscopy.

To avoid the deterministic effects described above, the National Council on Radiation Protection and Measurement (NCRP) recommends an annual maximum
permissible dose (MPD) of 500 mSv to the extremities.\textsuperscript{7} If fluoroscopic imaging, as performed in Part 3 of this study, was limited solely to carpal examinations (6 per week), the estimated 40-week annual dose to the fluoroscopist's tube hand (664 mSv) would exceed the 500-mSv MPD (Table 2). If all examinations (fetlock, carpus and tarsus) were included, the estimated annual tube-hand dose (1082 mSv) would be over twice the recommended MPD. A previous study similarly evaluated radiation exposure to the hands of human orthopedic surgeons during fluoroscopically guided procedures. Even the surgeon performing the greatest number of operations did not approach the annual MPD.\textsuperscript{12} Unlike orthopedic surgery, in which fluoroscopy is used for short bursts or "spot films", the routine examination of an equine joint by an experienced fluoroscopist required up to 2.9 minutes. Imaging times and associated radiation exposure would obviously increase in the hands of a novice or infrequent user, or if the fluoroscope was commonly used to survey multiple sites, such as during prepurchase examinations.

Measurements of radiation exposure in the collar region are representative of doses received by the thyroid and the lens of the eye, as well as providing a practical estimate of average total-body exposure. It is usually assumed that the eye and collar/thyroid region receive similar exposure, but doses to the eye can actually be up to 2 times greater.\textsuperscript{13} For example, exposure can increase by 21% due to scattered radiation from the fluoroscopist's head.\textsuperscript{14} Although exposure rates to the fluoroscopist's collar area (2.3 mSv/h) were 4 to 24 times lower than to the image-intensifier (9.9 mSv/h) and tube (56.2 mSv/h) hands, they still represent a significant radiation dose (Table 2). To avoid stochastic effects, the NCRP recommends a total-body MPD of 20 mSv/year, averaged over 5 years and not exceeding 50 mSv in any given year. It also recommends a maximum
lifetime cumulative exposure of 10 times the individual's age in years. The experienced fluoroscopist in Part 3 of this study received approximately 47 mSv to the collar region annually. If no radioprotective clothing was worn, not only would the recommended annual MPD be exceeded, but the fluoroscopist's lifetime limit would be reached relatively rapidly. Exposure rates to the assistant's collar region (0.5 mSv/h) were almost 5 times lower than to the fluoroscopist (2.3 mSv/h; Table 2). Although the assistant's estimated annual exposure (11 mSv) is unlikely to approach the MPD described above, attempts should still be made to keep exposure to ionizing radiation "as low as reasonably achievable".15

Fluoroscopic imaging of equine lower limbs clearly represents a significant radiation-safety hazard which must not be ignored. Since it is impossible to determine a safe level of exposure to ionizing radiation, all reasonable precautions should be taken to minimize exposure to involved personnel. Such precautions are particularly important in preventing stochastic effects, for which there are no known dose thresholds. Radiation exposure can be reduced by a combination of 3 methods: increasing distance from the primary beam, reducing the time of exposure, and the use of barriers.10

Radiation exposure is inversely proportional to the square of the distance from the source ("inverse square law").10 In Part 1, distance had the predominating effect (P < 0.01) on radiation exposure rates among all joints, views and meter positions; and as expected, this effect mimicked the inverse square law (Fig 2). However, exposure rates did not approach background level until distance from the primary x-ray beam reached over 4 m (Table 1, Fig 2). In Part 2, differences in exposure rates between the meter positions (P < 0.01) were influenced by their direct but usually fixed link with distance. Exposure to the
assistant's collar (0.5 mSv/h) was 5 to 112 times less than at any other location (2.3 to 56.2 mSv/h), due largely to its distance from the primary beam (173 cm) being 3 to 12 times greater than at any other location (15 to 62 cm; Table 2, Fig 3). Therefore, increasing distance from the source of radiation would seem to be a simple method of reducing exposure during equine fluoroscopy. Any assistants could be positioned as far away from the c-arm as possible. Unfortunately, the fluoroscopist, who receives a much greater exposure from actually holding the c-arm, has limited opportunities to move away from the x-ray source.

Unlike standard radiography, in which the time for each exposure is measured in fractions of a second, routine real-time fluoroscopic examinations required 1.3 to 2.9 minutes per joint. Imaging times appeared to be directly related to the practical difficulties and the complexity of the examination. Carpal studies had the greatest imaging times, and resulted in the greatest exposure to personnel at 3 of the 4 meter locations (Table 2). However, carpal studies also included more fluoroscopic projections (7 standard views) than did fetlock or tarsal examinations. Therefore, the principle of decreasing radiation exposure by reducing exposure time$^{10}$ may have limited practical application. Only by changing the general format of the examinations, from nearly continuous real-time imaging to a multiple spot-film technique, could significant reductions in imaging time be achieved.

Barriers, mainly those protecting against scatter radiation, are important in reducing exposure during fluoroscopic imaging.$^{10}$ The results of both Parts 1 and 2 reflect the influence of various forms of barriers. The body of the fluoroscopic c-arm, itself, particularly the receptor plate on the image-intensifier side, appeared to significantly attenuate scatter radiation. Exposure rates recorded in Part 1 were highly dependent on
the meter's directional position relative to the c-arm ($P < 0.01$). Readings were usually highest at meter 2, which had the least amount of c-arm between it and the primary x-ray beam. The largest section of c-arm stood between the primary beam and meter 4, which consistently had the lowest exposure-rate readings (Table 1, Fig 1 and 2). It would seem that maximum exposure rates for all meters should have occurred at the shortest direct distance from the joint (30 cm). In meters 1 and 4, maximum values were recorded at the shortest distance from the limb, but usually in a plane above or below the level of the c-arm, resulting in a direct distance of 42 cm. If positioned at 30 cm on the same plane as the c-arm, both meters were close enough to be shielded by the c-arm body (Table 1, Fig 1). In Part 2, radiation exposure to the fluoroscopist's tube hand (56.2 mSv/h) was almost 6 times that of the image-intensifier hand (9.9 mSv/h), despite a consistently greater distance between the tube hand and the joint (23 versus 15 cm; Table 2, Fig 3). The tube hand was subjected to more back-scatter radiation from the horse's limb, and similar to meter 2 above, it received little or no shielding from the c-arm (Fig 1). A small amount of leakage radiation from the tube housing may have also contributed to the greater tube-hand exposure.\(^{10}\) Although not formally investigated during this study, leakage radiation was reported to be $\leq 0.04$ mSv/h at any point around the c-arm tube.\(^{f}\)

Significant barrier effects were also exhibited by the fluoroscopist and the patient. During mediolateral images in Part 2, the fluoroscopist was positioned directly between the c-arm and the assistant. Exposure to the assistant (0.1 mSv/h) decreased to 10% of that during dorsopalmar/plantar images (1.0 mSv/h). During all examinations, radiation to the fluoroscopist's image-intensifier hand was attenuated by a portion of the c-arm, similar to meter 4 in Part 1, and by a portion of the limb being imaged. As diameter of the limb
increased, from fetlock to carpus and tarsus, exposure rates decreased markedly (21.2, 6.5 and 2.2 mSv/h, respectively; Table 2).

Knowledge of the above intrinsic barrier effects can be used to reduce radiation exposure to both the fluoroscopist and any assistants. Previous studies examining radiation exposure to orthopedic surgeons and cardiologists during fluoroscopic procedures also found that exposure rates were highly dependent on position relative to the c-arm.\textsuperscript{4,16} Whenever possible, personnel should try to position themselves toward the image-intensifier side of the unit. For example, a mediolateral projection may provide more shielding than the more common lateromedial projection.

When using a portable fluoroscopic system to perform routine examinations on equine limbs, opportunities to increase the fluoroscopist's distance from the primary x-ray beam, reduce exposure time, or utilize existing barriers appear relatively limited. An additional barrier, radioprotective clothing, is required. All personnel present during a fluoroscopic examination should wear an apron or gown and a thyroid collar equivalent to at least 0.5 mm of lead.\textsuperscript{17} Given the high exposure rates to the hands, especially on the tube side of the unit, lead-containing gloves or mittens are indicated for the fluoroscopist. Unfortunately, standard 0.5-mm lead-equivalent gloves and mittens made grasping the c-arm cumbersome and operating the 8.4-kg unit for prolonged periods almost impossible. Alloys of lead and related elements, such as tin, have been used to decrease the weight of aprons and gowns by up to 30%, without sacrificing radioprotection.\textsuperscript{18,19} However, gloves or mittens containing these alloys are presently not commercially available. Lighter more-flexible gloves and mittens, not equivalent to 0.5 mm of lead, can be obtained, but do not comply with current radiation-safety legislation. Although these gloves cannot be
recommended, their reduced radioprotection would perhaps be offset by increased use, and would certainly afford more protection than no gloves at all. The most practical method of protecting the fluoroscopist's hands and forearms from scatter radiation may be the addition of light-weight shielding at appropriate locations on the c-arm.

Since exposure rates to the fluoroscopist's head are also relatively high, radioprotective eyewear is recommended. Purpose-manufactured lead-containing glasses or goggles reduce radiation transmission to 3 to 10%. Regular eyeglasses with glass lenses may provide some protection, since lead or barium are sometimes added to increase the refractive index of the glass. Conversely, plastic or polycarbonate lenses in regular eyeglasses allow 95 to 98% transmission of radiation.\textsuperscript{14}

From the results of this study, personnel are exposed to significant levels of scatter radiation during portable fluoroscopic examination of equine lower limbs. Since radiation levels remain significantly above background until approximately 4.7 m from the source (range, up to 9.9 m), there is no "safe" distance from the c-arm for personnel within the same room. Radiation-safety procedures during fluoroscopy are just as, if not more, important than during standard radiography.
2.6 - Footnotes

a Equiscan, Model 1000-1, Manufactured October 1997, XiTec Inc, East Windsor, CT

b Model 471 General Survey Meter, Victoreen Inc, Cleveland, OH


d Sedivet, Boehringer Ingelheim Ltd, Burlington, Ontario, Canada


f Personal communication. XiTec Inc, East Windsor, CT

g Personal communication. Infab Corp, Camarillo, CA
2.7 - References


### 2.8 - Tables

Table 1 - Maximum radiation exposure rates (mean ± SEM) and associated direct distances from the joint, for each meter while imaging the fetlock, carpus and tarsus of cadaver limbs in Part 1. Calculated from regression-fit curves (Fig 2), exposure rates for each meter at 0.5, 1 and 2 m from the joint, and the distance at which exposure rates = 0.1 mSv/h (background level).

<table>
<thead>
<tr>
<th>Joint-view</th>
<th>Meter</th>
<th>Maximum exposure</th>
<th>Calculated from regression equations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mSv/h</td>
<td>Distance (cm)</td>
</tr>
<tr>
<td>Fetlock -DP</td>
<td>1</td>
<td>10.8 ± 5.1</td>
<td>42 ± 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.3 ± 1.3</td>
<td>32 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9.9 ± 2.7</td>
<td>32 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.5 ± 1.5</td>
<td>37 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Lat 1</td>
<td>26.2 ± 12.7</td>
<td>42 ± 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12.7 ± 0.7</td>
<td>30 ± 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>13.3 ± 3.4</td>
<td>32 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8.2 ± 2.2</td>
<td>35 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Lat 1</td>
<td>15.1 ± 3.4</td>
<td>35 ± 1.4</td>
</tr>
<tr>
<td>Carpus - DP</td>
<td>1</td>
<td>9.1 ± 0.4</td>
<td>42 ± 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17.6 ± 0.7</td>
<td>30 ± 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15.1 ± 3.0</td>
<td>30 ± 0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.5 ± 0.9</td>
<td>37 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Lat 1</td>
<td>11.8 ± 1.3</td>
<td>35 ± 1.4</td>
</tr>
<tr>
<td>Tarsus - DP</td>
<td>1</td>
<td>6.6 ± 1.6</td>
<td>42 ± 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16.3 ± 1.6</td>
<td>30 ± 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>14.5 ± 2.0</td>
<td>30 ± 0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.5 ± 0.6</td>
<td>37 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Lat 1</td>
<td>11.6 ± 0.7</td>
<td>36 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.5 ± 1.4</td>
<td>35 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9.0 ± 0.5</td>
<td>42 ± 0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>17.8 ± 1.5</td>
<td>30 ± 0</td>
</tr>
<tr>
<td>Overall mean</td>
<td>Lat 1</td>
<td>11.4 ± 0.7</td>
<td>36 ± 0.6</td>
</tr>
</tbody>
</table>

DP = dorsopalmar/plantar view; Lat = lateromedial view.
Table 2 - Radiation exposure rates (mean ± SEM) for the fluoroscopist and the assistant while imaging the fetlock, carpus and tarsus of live horses in Part 2. Distance (mean ± SEM) from the center of the joint to each meter position. Estimated radiation exposure acquired by the fluoroscopist and the assistant during routine real-time multiple-view examinations of live horses in Part 3, and over a 40-week year.

<table>
<thead>
<tr>
<th>Joint-view</th>
<th>Assistant</th>
<th>Fluoroscopist</th>
<th>Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>collar</td>
<td>Collar</td>
<td>Image-intensifier</td>
</tr>
<tr>
<td>Distance (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall mean</td>
<td>173 ± 6</td>
<td>62 ± 1.0</td>
<td>15 ± 0.2</td>
</tr>
<tr>
<td>Exposure rate (mSv/h)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fetlock - DP</td>
<td>0.9 ± 0.1</td>
<td>3.2 ± 0.1</td>
<td>21.0 ± 1.7</td>
</tr>
<tr>
<td>Lat</td>
<td>0.0 ± 0</td>
<td>1.9 ± 0.1</td>
<td>21.3 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>0.4 ± 0.1</td>
<td>2.6 ± 0.2</td>
<td>21.2 ± 1.2</td>
</tr>
<tr>
<td>Carpus - DP</td>
<td>1.3 ± 0.1</td>
<td>3.0 ± 0.2</td>
<td>6.8 ± 1.3</td>
</tr>
<tr>
<td>Lat</td>
<td>0.1 ± 0</td>
<td>2.0 ± 0.2</td>
<td>6.1 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>0.7 ± 0.1</td>
<td>2.5 ± 0.2</td>
<td>6.5 ± 0.8</td>
</tr>
<tr>
<td>Tarsus - DP</td>
<td>0.7 ± 0.1</td>
<td>1.9 ± 0.3</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>Lat</td>
<td>0.1 ± 0.1</td>
<td>1.6 ± 0.2</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>0.4 ± 0.1</td>
<td>1.7 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>Overall mean</td>
<td>0.5 ± 0.1</td>
<td>2.3 ± 0.1</td>
<td>9.9 ± 1.0</td>
</tr>
</tbody>
</table>

Estimated exposure per exam (mSv)*

Fetlock | 0.01 | 0.05 | 0.4 | 1.0
Carpus | 0.03 | 0.12 | 0.3 | 2.8
Tarsus | 0.01 | 0.04 | 0.05 | 1.5

Estimated exposure per 40-week year (mSv)†

Fetlock | 2 | 13 | 106 | 242
Carpus | 8 | 29 | 75 | 664
Tarsus | 1 | 5 | 6 | 176

Total | 11 | 47 | 187 | 1082

DP = dorsopalmar/plantar view; Lat = mediolateral view.
*Based on mean imaging time: fetlock = 75 s, carpus = 173 s, tarsus = 84 s.
†Based on mean exams per week: fetlock = 6, carpus = 6, tarsus = 3.
2.9 - Figures

Figure 1 - Overhead view of the limb (A), c-arm (B), survey-meter positions (M1 to M4), and representative horizontal distance measurements during Part-1 data collection.
Figure 2A - Radiation exposure rate (mean) for each meter versus direct distance from the fetlock of cadaver limbs in Part 1, with the associated quadratic-regression fit of each data set. For this figure, data were pooled from dorsopalmar/plantar and lateromedial views.
Figure 2B - Radiation exposure rate (mean) for each meter versus direct distance from the carpus of cadaver limbs in Part 1, with the associated quadratic-regression fit of each data set. For this figure, data were pooled from dorsopalmar/plantar and lateromedial views.
Figure 2C - Radiation exposure rate (mean) for each meter versus direct distance from the tarsus of cadaver limbs in Part 1, with the associated quadratic-regression fit of each data set. For this figure, data were pooled from dorsopalmar/plantar and lateromedial views.
Figure 3 - Radiation exposure rates (mean ± SEM) for the fluoroscopist and the assistant while imaging the fetlock, carpus and tarsus of live horses in Part 2. For this figure, data were pooled from dorsopalmar/plantar and mediolateral views. Distance (mean) from the center of the joint to each meter position.
2.10 - Addendum

Americium-241 (\(^{241}\text{Am}\)) standard: Calculation of the exposure rate

\[
N = N_0 \cdot 2^{-\frac{t}{t_{\text{th}}}}
\]

\[
= 5 \cdot 2^{-\frac{8.27}{433}}
\]

\[
= 4.93 \text{ mCi}
\]

where, \(N_0\) = initial activity of \(^{241}\text{Am}\) source (mCi)

\(t\) = time elapsed since source manufactured (8.27 y)

\(t_{\text{th}}\) = half-life of \(^{241}\text{Am}\) (433 y)

\[
X/t = \Gamma \cdot A / d^2
\]

\[
= 13 \cdot 4.93 / 1^2
\]

\[
= 0.06412 \text{ mR/h}
\]

where, \(X/t\) = exposure rate (mR/h)

\(A\) = activity of \(^{241}\text{Am}\) source (mCi)

\(d\) = distance (m)

\(\Gamma\) = exposure rate constant (Johns & Cunningham 1983)

Exposure rate 1 m from the \(^{241}\text{Am}\) source was measured daily with each survey meter and compared with the calculated exposure rate of 0.06412 mR/h.
Addendum: Figure A - C-arm (large arrow) of the portable fluoroscopy unit suspended from the aluminum frame for Part-1 data collection. Survey meters (small arrows) suspended from polyvinyl chloride pipes radiating at 90° intervals from the center of the frame. The limb is positioned for lateromedial imaging of the fetlock.
Addendum: Figure B - C-arm and survey meters positioned for lateromedial imaging of the fetlock during Part-1 data collection.
Addendum: Figure C - Positioning of the survey meter for measurement of the radiation exposure rate at the fluoroscopist's image-intensifier hand during Part 2. The c-arm is positioned for mediolateral imaging of carpus.
Addendum: Figure D - Positioning of the survey meter for measurement of the radiation exposure rate at the fluoroscopist's collar during Part 2. The c-arm is positioned for mediolateral imaging of carpus.
Addendum: Figure E - Positioning of the survey meter for measurement of the radiation exposure rate at the assistant's collar during Part 2. The c-arm is positioned for mediolateral imaging of carpus.
3.0 - LIMITATIONS AND FUTURE AREAS OF STUDY

Two potential limitations were identified after completion of this project. 1) The contribution of tube-leakage radiation to the measured exposure rates, especially at the tube-hand position, was not formally investigated. During personal communication with the manufacturer, however, leakage radiation was reported to be $\leq 0.04$ mSv/h at any point around the c-arm tube. A short informal follow-up investigation with the Radiation Protection Service, Ontario Ministry of Labour, supported the manufacturer's report. 2) The exposure rates measured from this c-arm were not compared with those from other similar fluoroscopy units. It is possible that the amount and energy of radiation emitted from this c-arm was not representative of that from other units marketed as identical. Before beginning and after completing data collection, however, the unit used in this study was evaluated by the manufacturer as performing within specifications. The results of this study should, therefore, be applicable to any comparable hand-held portable fluoroscopic system.

Any persistent questions associated with the above limitations could be addressed in a future study. However, evaluating possible design modifications to improve the inherent shielding of the unit would probably be a much more useful investigation. For example, lightweight tin or aluminum shields could be added to the body of the unit, particularly on the tube side, to reduce exposure to the hands and forearms. A comparison of the diagnostic quality of images obtained from this portable fluoroscopy unit with those obtained from a portable x-ray unit would also have significant practical application. Do portable fluoroscopy systems produce images which are of sufficient
quality to replace standard radiography, or should they be used only as an adjunct to radiographs in specific circumstances?
3.1 - GENERAL CONCLUSIONS

From the results of this study, it is clear that portable fluoroscopic imaging of equine lower limbs represents a serious radiation safety hazard. There is a significant amount of scatter radiation produced by the unit, the magnitude of which varies with distance and directional position relative to the c-arm. The levels of scatter radiation measured around the unit are sufficiently high that recommended maximum permissible dose limits will be rapidly exceeded if no radioprotective clothing, which is required by law, is worn. Radiation exposure significantly greater than background levels is present for approximately 4.7 m from the primary x-ray beam, with a range of up to 9.9 m.

Based on these results, we accept both hypotheses of the study: 1) all personnel directly involved with portable fluoroscopic imaging of equine limbs receive radiation exposure significantly greater than background level, and 2) for all practical purposes, there is no “safe” distance from the c-arm for these personnel.
4.0 - MASTER REFERENCE LIST


IMAGE EVALUATION
TEST TARGET (QA-3)

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Phone: 716/482-0300
Fax: 716/288-5988

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