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Time-Line of the Evolution to the End of the 20th Century of Units, Quantities & Measurements for X-Ray Diagnosis, X-Ray Therapy & X-Ray Protection

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A time-line is presented of the evolution of X-ray units & quantities and X-ray measurements to the end of the 20th century. It is given chronologically in the form of a list which makes for easy reading. It is an extensive time-line, albeit a selected one, and will provide a useful starting point for authors writing historical introductions to research and review papers.

Introduction

This time-line is based on a series of conference exhibition posters, books, reports and review articles. Selected names & organisations are quoted in this time-line at the end of each entry. For full references the reader is referred to the bibliographies in publications by Glasser, Grigg, ICRP, ICRU, Jennings, Mossman, Mould, NBS, NCRP and Webb [1–17].

Time-Line

■ **1896.** Intensity of X-rays measured using a fluorescent screen. [Röntgen]

■ **1896.** Description of the principle of the 'free-air' ionisation chamber. [Perrin]

■ **1898.** Röntgen Society, London, Committee on X-ray Injuries. Formed because of the importance of Röntgen-ray dermatitis. Survey proposed with a list of 'medical questions' and 'electrical questions'.

■ **1900.** Quality description: soft & hard X-rays. [Kienböck]

■ **1902.** Unit based on a fused mixture of potassium chloride and sodium carbonate. [Holzknecht]

■ **1902–1910.** Penetrameters and quality meter designed to measured the X-ray beam quality. [Benoist, Wehnelt, Walter, Bauer]

■ **1904.** Unit based on platino-barium cyanide, the pastille dose, where the dosimeter was a small capsule which changed colour after irradiation. [Sabouraud, Noiré]

■ **1904–1930s.** Biological dose units of which the most well known was the skin erythema dose [Holfelder, Schall, Quimby, Solomon, Seitz, Wintz]

■ **1905.** Unit based on photographic film blackening. The dosimeter was a small piece of silver bromide photographic paper, called a Kienböck strip [Kienböck]

■ **1906.** Unit based on ionising power of X-rays. [Belot]

■ **1907.** Personnel monitoring using a small photographic plate. [Wagner]

■ **1907.** Unit based on quantity of electricity across unit spark gap. [Phillips, Lenard]

■ **1907.** Unit based on fluorescence. [Guilleminot]

■ **1908.** Technique outline for 'e' unit, liberation of 1 esu of charge per cc. [Villard]

■ **1912.** Unit proposed as energy deposited per unit mass. [Christen]

■ **1913.** Principal of half-value-layer as a measure of X-ray beam absorption. [Kristen]

■ **1915.** Unit based on selenium resistance. [Fürstenau]

■ **1915.** Dose-time fractionation of importance in clinical practice. [Colwell, Russ]

■ **1918.** Comprehensive study of ionisation measurement techniques. Use of phantoms and small ion chambers for clinical dosimetry. [Krönig & Friedrich]

■ **1920s.** Skin erythema dose. Widely used, but was abandoned when in **1937** the roentgen unit was introduced for both X and gamma rays. [Failla, Solomon, Seitz, Wintz, Béclère]

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■ **1920s.** Establishment of the concept of a quantitative tolerance dose for operators of X-ray tubes for roentgenology, roentgenoscopy and therapy. [Mutscheller]

■ **1920s.** Treatment planning based on central axis depth dose tables & isodose curves. [Mayneord, Quimby, Glasser, Voltz Failla]

■ **1921.** British X-Ray Protection Committee.

■ **1921.** Isodose charts used for clinical dosimetry. [Dessauer]

■ **1920s** & **1930s.** Dose fractionation. [Regaud, Coutard]

■ **1923.** Physical Society British X-ray Units Committee.

■ **1923.** Recognition of the need to avoid wall effects when using ion chambers to measure X-ray dose.

■ **1923**–**1950s.** Measurements with cavity chambers and condenser chambers. [Failla, Fricke, Sievert, Holthusen, Meyer, Glasser, Mayneord, Gray]

■ **1923.** Röntgen Society becomes the British Institute of Radiology.

■ **1924.** Hammer dosimeter for routine ionisation measurement of X-ray therapy doses. [Physikalische Technische Werkstätte GmbH, Freiburg, Germany]

■ **1925.** Development of a portable ion chamber, the 'iontoquantimeter'. [Landauer, Standard X-ray Company, USA]

■ **1925.** 1st International Congress of Radiology (ICR), London, where the need for a definition if an X-ray unit was deferred.

■ **1925.** Creation of the International X-Ray Units Committee (IXRUC), which in **1950** became the ICRU.

■ **1926.** Proposal of a film badge for personnel monitoring, with a system of filters to take into account greater sensitivity of the film to low energy X-rays. [Quimby, Landauer]

■ **1926.** Mekapion dosimeter using triode electronic valves. [Laboratorium Strauss GmbH, Vienna, Austria]

■ **1927.** British Committee on Radiological Units, which in **1967** became the BCRU.

■ **1927.** Ferrous sulphate dosimetry. [Fricke, Morse]

■ **1927.** Likelihood of the absence of a threshold dose for radiation induced mutations. [Muller]

■ **1927.** Victoreen dosimeter for routine measurement of X-ray therapy doses, using a condenser ionisation chamber. [Victoreen Instrument Company, Cleveland, USA]

■ **1928.** 2nd ICR, Stockholm, when the röntgen unit was defined as a unit of quantity of radiation. 'That this international unit [the roentgen] be the quantity of X radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produced in one cubic centimetre of atmospheric air at 0°C and 76 cm mercury pressure, such a degree of conductivity that one electrostatic unit of charge is measured at saturation current.'

■ **1928.** Creation of the International Advisory Committee on X-ray & Radium Protection (ICXRP) which was the forerunner of the ICRP.

■ **1928–1930.** X-ray measurement standards. Free-air chamber developed at NPL so that the roentgen unit could be measured. [Kaye & Binks]

■ **1929.** Creation in the USA of the Advisory Committee on X-ray & Radium Protection (ACXRP).

■ **1930**–**1934.** Treatment machines operating at 500 kV and above. [Trump, Van de Graaff]

■ **1931.** International comparison measurements made with standard chambers from the United Kingdom, Germany and USA. [Behnken, Taylor, Wyckoff]

■ **1931.** Cavity chambers also developed as standard chambers.

■ **1931.** 3rd ICR, Paris, definition of the röntgen unit remains unchanged.

■ **1934.** 4th ICR, Zurich. Recognition of the need to include gamma-rays in a unit of measurement.

■ **1937.** 5th ICR, Chicago. Definition of the röntgen unit revised. 'The roentgen shall be the quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 e.s.u. of quantity of electricity of either sign.'

■ **1940.** Concept of 'integral dose'. [Mayneord, Happey, Grimmett, Meredith, Neary]

■ **1940s**-onwards. After World War II there was a big expansion in all aspects of radiation dosimetry. Problems therefore had to be solved based on the new availability of much wider ranges of generating energy, absorbed dose rate and absorbed doses. Discussion points included the following criteria. Is an absolute method of measurement required? What accuracy and precision are required? Whether total absorbed dose or absorbed dose rate is required. Range of absorbed dose to be measured? Range of absorbed dose rate to be measured? Type and energy of radiation to be measured? The need to match the dosimeter to the medium. Size of detector required? Spatial resolution required? Other relevant factors included convenience of measurement, cost and ruggedness of the apparatus.

■ **1940s.** Dosimetric systems available during these years included those based on calorimetry, ionisation, chemical, thermoluminescence, photographic, scintillation, silicon, plastics and the vacuum chamber. All had different, with some overlaps, ranges of absorbed dose rate measurement and of absorbed dose measurement.

■ **1940s.** Analogue computing techniques developed for X-ray isodose curve production for treatment planning. [Clarkson, Martin, Mayneord, Lamerton, Meredith, Neary]

■ **1944.** Iso-effect curves relating total dose to number of fractions in terms of skin reaction or tumour control. [Strandqvist]

■ **1945.** Proposal that 'biological dose = physical dose x relative biological effectiveness (RBE)'. When physical dose is in rads, the RBE dose is in rems (roentgen equivalent man). [Parker]

■ **1948.** Proposal that the quantity 'dose' should be defined for general use as 'the energy absorbed in irradiated material', with the unit roentgen equivalent physical, rep. [Parker]

■ **1950s.** Thermoluminescence used to make quantitative measurements of radiation exposure. Several materials have been used for TLD dosimeters but lithium fluoride is the most successful as a TLD phosphor. [McKinlay]

■ **1950s.** Computerised treatment planning. [Tsien, Bentley, Laughlin]

■ **1950s.** Wedge filters to modify the X-ray beam in external beam therapy. [Groom, Tranter, Tulley]

■ **1950.** Concept of 'equivalent fields'. Tables given of the side lengths of square fields equivalent to rectangular fields, which provide the same central axis depth dose data and tissue-air ratios. [Day]

■ **1950.** 6^{th} ICR, London, Absorbed dose defined as 'the quantity of energy absorbed per unit mass at the point of interest', expressed in erg/g. [ICRU]

■ **1950s** & **1960s.** RBE related to linear energy transfer (LT) and RBE dose expressed as the sum of absorbed dose in rads x RBE, with RBE-LET relationships established for reference radiation. Next RBE was replaced by the term quality factor (QF), and the quantity dose equivalent (DE) introduced, where DE = absorbed dose D × (QF × DF), where DF is the dose distribution factor expressed in rems. [ICRU, ICRP]

■ **1953.** 7^{th} ICR, Copenhagen. Absorbed dose redefined as 'the amount of energy imparted by ionising particles per unit mass of irradiated material at the point of interest' and the unit rad introduced, the acronym for radiation absorbed dose equal to 100 erg/g. [ICRU]

■ **1956.** Survival fraction curve: in tissue cultures the same proportion, not the same number, of mammalian cells is killed with each incremental dose of radiation. The corollary is that higher doses are needed to eradicate a tumour cell population as the number of clonogens increases. [Puck, Marcus]

■ **1956.** 8^{th} ICR, Mexico City. Exposure dose defined as 'the ability of X or gamma rays to produce ionisation' measured in roentgens. [ICRU]

■ **1958.** Quantity KERM proposed, 'the energy released per unit mass', expressed in erg/g. [Roesh]

■ **1959.** Use of compensators for variation in tissue thickness for high-energy radiotherapy beams. [Ellis, Hall, Oliver]

■ **1960s.** Importance of fraction size recognised. [Fowler]

■ **1962.** Absorbed dose defined as '$D = \Delta E_D/\Delta m$ where ΔE_D is the energy imparted by ionising radiation to the matter in a volume element, and Δm is the mass in that volume element.' The special unit of absorbed dose is the rad. [ICRU]

■ **1962.** The quantity kerma introduced. $K = \Delta E_K/\Delta m$ where ΔE_K is the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionising particles in a volume element of the specified material, and Δm is the mass of this volume element. The unit is erg/g. [ICRU]

■ **1962.** Exposure X replaces exposure dose and is defined as '$X = \Delta Q/\Delta m$ where ΔQ is the sum of the electric charges on all ions of one sign produced in air when all the electrons liberated by photons in a volume element of air of mass Δm are completely stopped in air.' [ICRU]

■ **1965.** Concept of tissue-phantom ratio. TPR is formed by the radio of the dose at point X to the dose at point X" where X" is at a standard or reference depth d_r in a phantom, but all other conditions of radiation are the same. [Karzmark]

■ **1971** & **1973.** Dose equivalent, H, defined as 'H=DQN at the point of interest where D is the absorbed dose, Q is the quality factor, and N the produce of other modifying factors'. Its special unit was the rem when D is in rads. [ICRU]

■ **1971.** Concept of stochastic quantities introduced to take account of statistical fluctuations in the interaction of radiation and matter. This entailed the introduction of a stochastic quantity of energy imparted, ε, which in **1998** was expressed in terms of energy deposit for a single interaction. [ICRU]

■ **1976.** The backscatter factor (BSF) defined as 'Exposure due to primary and scattered photons/Exposure due to primary photons' was in use from the **1950s** for energies up to deep therapy X-rays of ~ 400 kV. BSF defines the contribution due to scatter at the point of intersection between the central axis and the skin surface. However, in **1976** ICRU recommended the term peak scatter factor (PSF) as a replacement for BSF for photon energies above 400 kV, and for telecaesium and telecobalt machines. [ICRU, British Institute of Radiology]

■ **1978.** For dose specification for reporting external beam therapy with photons and electrons, ICRU defined target volume, treatment volume, irradiated volume and organs at risk. In addition for the absorbed dose pattern, ICRU defined maximum target, minimum target, mean target, median target and modal target absorbed doses: and also hot spots. [ICRU]

■ **1980.** Definitions of absorbed dose, D, kerma, K, and exposure, X, remained unchanged, but SI units were recommended for use, namely the gray (Gy) = 1 J/kg for both absorbed dose and for kerma, and the C/kg for exposure. [ICRU]

■ **1980.** Definition of dose equivalent, H, remained unchanged but the SI unit was recommended for its use, namely the sievert (Sv) = 1 J/kg. [ICRU]

■ **1980s.** Radiotherapy treatment planning incorporates imaging such as CT and MR. For example contiguous CT slices are used to define anatomical structures and tumour volumes. Non-coplanar dose distributions and 3D dose distributions become standard, as does the beam's eye view (BEV) in which patient contours are viewed as if the observer's eye is placed at the source of radiation looking out along the axis of the X-ray beam. [Goitein, Purdy, Wong, Almond, Cunningham & many others]

■ **1980s** & **1990s.** MR imaging of dose-sensitive gels. Studies showing that ferrous sulphate ions held in a gel can be used as a radiation dosemeter with MR readout to give a 3D map of the delivered dose. [Appleby, Gore, Hazle, Johansson, Podgorsak]

■ **1990s.** Transit dosimetry developed. The dose distribution actually delivered to the patient is computed from a transmission portal image taken at the time of treatment. It can then be determined if this matches the dose distribution computed at the planning stage. [Evans, Hansen]

■ **1991.** Two new quantities introduced for dose limitation purposes, namely (organ) equivalent dose, H_T, and effective dose, E. In addition, quality factors were replaced by radiation weighting factors, w_R, and updated human evidence provided new tissue weighting factors w_T. This was modified in 2001 by a proposal to use the term 'weighted average absorbed dose' instead of 'equivalent dose' in order to avoid confusion with 'dose equivalent'. [ICRP]

■ **1993.** For prescribing, recording and reporting photon beam therapy, ICRU defined gross tumour volume (GTV), clinical target volume (CTV) and planning target volume (PTV). [ICRU]

■ **1999.** New concept of 'controllable dose'. This is an individual-based doses as against a population-based philosophy and included the abandonment of the concept of collective dose on the grounds that it aggregates information excessively. [Clarke, ICRP]

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