# EFFECTS OF APPLIED VOLTAGE-WAVEFORMS AND CURRENT-WAVEFORMS OF X-RAY TUBES ON EMISSION AND TRANSMISSION OF RADIATION

By

Hitoshi KANAMORI

Radiation Apparatus Division Shimadzu Seisakusho Ltd., Kyoto, Japan

(Received 3 August, 1964)

# X線管電圧および管電流波形がX線特性におよぼす効果

島津製作所

金 森 仁 志

(昭和39年8月3日受付)

単相および3相診断用X線装置の管電圧・管電流波形は，単純な正弦波整流波形ではない．しかも，kVp, mA が変れば複雑に変化する．管電流が少い時は定電圧波形に近づく．しかし，管球フイルタ，被写体を通過したあとのX線の特性は，実用上は，kVp 値のほかに，管電圧の脈動と mA ピーク値によつてきまる．普通は mA 平均値が表示されているが，ピーク値で表示する方がよい．コンデンサ式装置では少し異つたデータが得られる．定電圧，3相，単相，コンデンサ放電の4種の波形について，アルミニウム，アクリライトを透過した時のデータを比較した．このデータを使えば，波形がX線特性と最適撮影条件におよぼす効果を，簡単に比較する事ができる．

**SUMMARY**

Applied voltage and tube-current waveforms using a single-phase or a three-phase X-ray unit were not simple rectified sine-waves but varied with applied voltage peak (*kVp*), and tube current (***mA-mean***) in complexity, but transmitted X-ray properties through tube-filters and objects were able to be determined by applied voltage-pulsation, and ***mA-peak*** not ***mA-mean*** value, in addition to applied voltage-peak, while the data on condenser-discharged waveforms were slightly different. The data of aluminium and acrylite-absorbers, for comparing 4 kinds of waveforms, *i.e.*, constant, single-phase, 3-phase, and condenser discharged waveforms, were given. From the data, the effects of waveforms to emission, transmission of radiation, and the optimum exposure-factors for radiography can be easily compared.

## §1 Introduction

Medical radiographic X-ray units require higher electric power, but for a shorter duration, than other X-ray units. Due to the difficulty of high-voltage pulse measurement, properties of the medical units were not investigated in detail, before the development of higher-voltage and smaller-size units. This development was commenced from 1953. For this purpose, electrical factors, *i.e.*, applied high-voltage peaks (*kVp*) and waveforms, tube-current mean values (mA) and waveforms, abnormal voltages, etc., have been measured in detail[1], and these results have been explained theoretically[1] by an electric circuit theory[2]. Following the above investigations, following problems, which motivated the investigations of this paper, were introduced: It was well known from radiographic experience that the quality and quantity of X-rays were different, even if the same factors of $kVp$ and $mA \cdot sec$ were used with different units having the same type of high-voltage sources. Moreover, even if one X-ray unit was used with the same $kVp$ and same $mA \cdot sec$ setting, the properties of X-ray sometimes change with the setting of $mA$.

It will be explained in this paper that not only inaccuracy of $kVp$ nor nonniformity of X-ray generation cause these phenomena, but also that applied voltage and tube-current waveform vary with $kVp$ and $mA$ also. The above mentioned problems are those of single-phase units and three-phase units. In addition, since condenser-units are used in medical radiography, this paper also treats effects of waveforms of condenser-units. These problems have been important since radiographic quality-control, automatization of radiography, and information-radiography were introduced.

This kind of work became possible since accurate $kVp$ as well as waveforms were obtained by theoretical and experimental means[1]. Accurate $kVp$ was desired because a small error in $kVp$ results in a large deviation in quantity of radiation.

The data of this paper will give a standard for comparing the effects of waveforms to emission and transmission of radiation. From the data, radiographic effects can also be obtained by using the method which was stated in a previous paper[3].

## §2 Applied Voltage and Tube-Current Waveforms[1]

First, we consider single-phase and 3-phase units. In these units, commercial a.c. voltages (single phase or three phase) are built up by high-voltage transformers, rectified into d.c. high-voltages, and applied to X-ray tubes. Hitherto, applied voltage and tube-current waveforms from these types of units were considered to be simple rectified sine-waves, whereas, some experiments confirmed that the waveforms vary with $kVp$ and $mA$ in complexity. Typical measured waveforms are shown in Fig. 1 and Fig. 2 regarding one cycle of electric supply. From the figures it follows that:

1. They distort from sine-wave,
2. Parasitic oscillations sometimes appear. These two phenomena have been theoretically confirmed using the saturating properties of tube-current to tube-voltage, and $L,C,R$ in the electric circuit of the units.
3. If $mA$ is small, voltage pulsation decreases by the condenser action of the cables between the high-voltage generator and the X-ray tube.

Fig. 3 shows tube-current waveforms in addition to applied voltage waveforms with low $kVp$ of a single-phase unit. With large $mA$, tube-current saturation is little or nothing to applied voltages, therefore current-waveform is sharp at the top forming a triangle similar to the voltage waveform. In other cases, current saturation increases as voltage increases, therefore current-waveform becomes flatter at the top than voltage-waveform. In Fig. 3, areas under the current-waveforms were made identical in the same $kVp$ waveforms. Therefore, the ratios of current-peak ($mAp$) to current-mean ($mA$) values may be

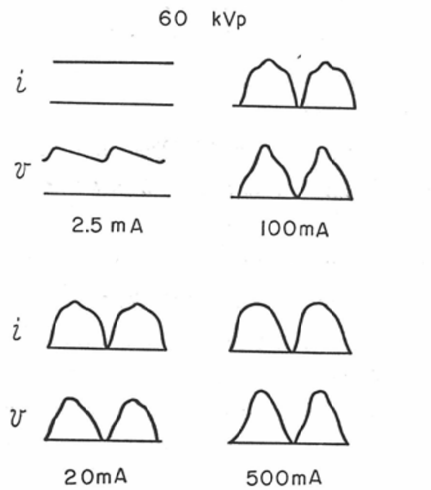


Fig. 1 Typical applied voltage waveforms of a single-phase unit

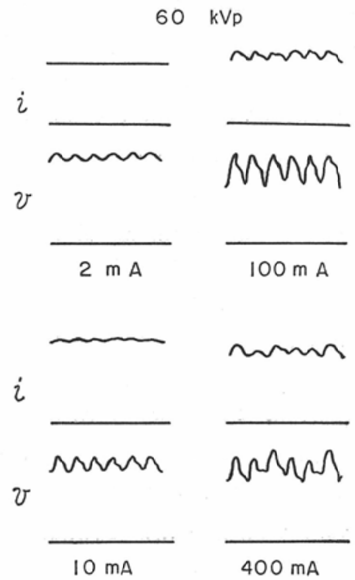


Fig. 2 Typical applied voltage waveforms of a 3-phase unit

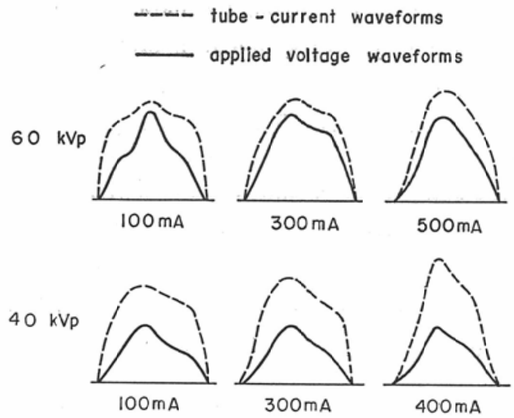


Fig. 3 Applied voltage waveforms and tube-current wave forms of a single-phase unit with low *kVp*: With large *mA*, current saturation is little or nothing to voltage, due to tube property. Therefore current is steep at the top, and the ratios of current-peak to current-mean valuse become larger than other cases.

compared by measuring the peak-heights. By this means, we see that the ratio of *mAp* to *mA* increases more in the unsaturated cases than in the saturated cases. Therefore, the ratio becomes larger especially with lower *kVp* and larger *mA*. Whereas with a 3-phase unit, current and voltage pulsations are less than those of a single-phase unit. Therefore, *mAp*/*mA* changes little whether or not there is current saturation.

Besides the above two types of units, simple condenser-units are utilized. In this type, electric charges are stored in high-voltage condensers through small-capacity electric sources, transformers, and rectifiers. Then, the stored charges are discharged through X-ray tubes instantaneously when X-ray generation is desired.

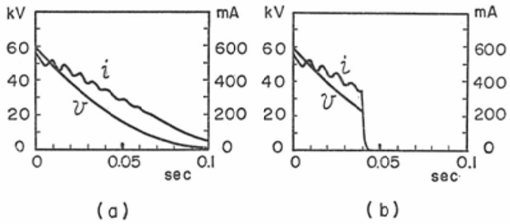


Fig. 4 Typical applied voltage and tube-current waveforms of a condenser-unit: Perfectly discharged waveforms(a), and chopped waveforms (b)

An applied voltage waveform and a tube-current waveform with a condenser unit are shown in Fig. 4. Applied voltage decreases as tube-current flows from condensers. Pulsation of a current-waveform is caused by the X-ray tube filament heated with a.c. current. In Fig. 4, (a) and (b) show perfectly discharged waveforms and chopped waveforms, respectively. Exposure-factors for radiography are expressed by *charged kV*, instead of *kVp* when using perfectly discharged waveforms, and in addition, *chopped kV* or difference of charged and chopped *kV* when using chopped waveforms. With a condenser-unit, the range of *mA • sec* is limited by the relation

$$mA.\ sec = C\ (charged\ kV—chopped\ kV),$$

where $C$ is condenser capacity in $\mu$F. This relation is independent of the discharging process. With a perfectly discharged waveform, *kVp* and *mA • sec* are in one to one correspondence.

## §3 Effects of the Changes of *mA*-Settings under the Same *kVp*-Setting

One X-ray tube was connected to a typical single-phase unit or 3-phase unit alternately in order to compare the effects of different units without change of geometrical factors. The single-phase unit, 3-phase unit, and tube used were SHIMADZU KD-150-L (150 kVp, 500 mA), HD-125-G (125 kVp, 1000 mA), and CIRCLEX-2 (rotary anode tube, 2-mm focus) respectively. A primary filter of 1.4-mm aluminium was attached to the tube. Waveforms in Fig. 1 and Fig. 2 were measured with the same units. The peak voltage that was applied to the tube was measured by means of sphere-gaps and an oscilloscope. The results coincided with results calculated from electric circuit theory[1]. Thus, *kVp* was accurately determined. Exposure was measured by a Victoreen's Radocon with a 613-type probe or Condenser-R-Meter with a 130-type probe. Their readings must be calibrated when effective *kV* of radiation is less than 35. This calibration was done using the data of calibration coefficients to effective *kV*, which was annexed to chambers, *i.e.*, effective *kV* were obtained from aluminium half-value-layers and correctiong the measured absorption curves repeatingly. Focus-chamber distance was 1.8 m. Phantoms instead of objects were placed at the mid-point between focus and chamber to remove the effects of secondary radiation[4]. Aluminium-plates and acrylite-plates were selected as objects. Because aluminium and acrylite have similar absorption properties to bone and tissue respectively.

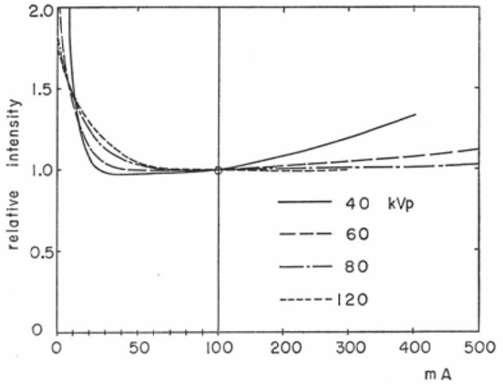


Fig. 5 Relative exposure using a single-phase unit to various *mA*: With small *mA*, exposure increases due to the smoothing effect of applied voltage. With large *mA* of low *kVp* curves, intensity increases due to increasing *mAp*/*mA*.

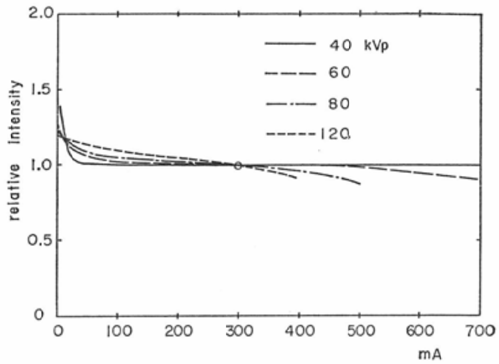


Fig. 6 Relative exposure using a 3-phase unit for various *mA*: Exposure decaeases as *mA* increases due to increasing applied voltage-pulsation rates

At first, effects of change in *mA* with same *kVp* and with same *mA*• *sec* were checked. Exposure due to transmission through the 10-cm acrylite phantom, which was usually used as a chest-equivalent phantom, was measured with a typical intensifying screen, SHIMADZU FD. Its fluorescence-brightness was measured by means of integrating photo-current in a photo-multiplier 931A. Fig. 5 and Fig. 6 show the results of a single-phase and a 3-phase unit respectively. In the two figures, brightness per *mA* for each *kVp* was put at unity at 100 and 300 mA respectively. Since radiation quality changes little or nothing with the same *kVp*, screcen-brightness is proportional to the exposure in air in each curve. The ordinates in the figures, therefore, show relative exposure/*mAs*. From the two figures it follows that:

1. In the two figures, exposure/*mAs* increases when a small *mA* is used. This may be caused by decrease in voltage pulsation.

2. With a large *mA* and a low *kVp* of a single-phase unit, *i.e.*, when tube-current saturation is little or nothing exposure/*mAs* increases when *mA* increases, as can be seen in Fig. 5. This may be caused by the effect of increasing the *mA-peak* value.

3. Exposure/*mAs* of single-phase unit does not change in other cases. In these cases, applied voltage falls to zero every half-cycle and tube-current saturates.

4. With a three-phase unit, exposure/*mAs* decreases as *mA* increases. This is caused by applied voltage-pulsation rate increasing with *mA*.

Factor number 2 was examined in detail. Exposure due to emission and transmission for various *mA* were measured and plotted in Fig. 7. From the figure it follows that,

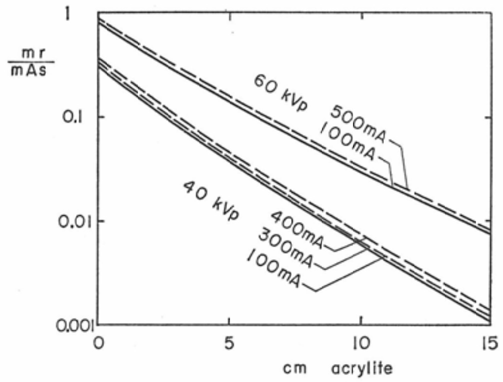


Fig. 7 Measured exposure due to transmitted rays as a function of tube-current

with a low *kVp* of the single-phase unit, exposure in air increases with *mA*. This change is evident with 40 kVp, whereas little change is evident with 60 kVp. The exposure/*mAs* is almost proportional to the ratio of *mAp*/*mA* over the entire thickness range. While with 60 kVp, the exposure/*mAs* increases with *mA* but less than proportional to *mAp*/*mA*. The reason for this may be as follows: When *kVp* is low e. g. 40 kVp, even if applied voltage-waveform and current-waveform change the property of X-rays, soft-ray components may be absorbed by primary filter and object, transmitting only the hardest rays generated at applied voltage-peak. Whereas, current reaches its peak value when voltage reaches peak-value. Therefore, with low *kVp*, exposure due to transmitted rays are proportional to *mAp* value, even if only primary-filter-transmission is measured. When *kVp* increases, effects of the rays from other part of voltage-peak become larger, therefore the increasing of transmission become less than proportional to *mAp*/*mA*.

Then we can conclude that exposure due to transmission through an object depends upon the *kVp* values, applied voltage-pulsation rates, and *mA-peak* values. It should be noted that *mA-mean* values were hitherto used, but improperly. From a practical view, waveform-distortion from a sine-wave and parasitic oscillation have no effect.

## §4 Emission and Transmission Produced by Constant, Single-Phase, 3-Phase, and Condenser-Discharged Waveforms

According to the conclusions of the last section, with a single-phase or three-phase unit, exposure due to emission and transmission may be obtained when the data of various *kVp* and applied voltage-pulsation rates are performed, if the calibration for *mA-peak* effects is added. Therefore, experiments on the emission and transmission of radiation were made such as: Data on single-phase and 3-phase waveforms were obtained from the two units used above. In addition to these, smoothing capacitors were connected to the 3-phase unit for producing constant waveforms in addition to the smoothing effects of the cable-capacitors. One value of *mA* was so selected for each *kVp* that the applied voltage-pulsation rate in the three kinds of waveforms were 1, 0.3, and 0 respectively. Data on saturating cases with low *kVp* of the single-phase unit were used.

Moreover, experiments on a condenser-unit were made, using a SHIMADZU SM-125 generator with a grid-controlled X-ray tube, CIRCLEX 2GB, and a tube-filter of 2-mm aluminium. This X-ray tube was also connected to the single-phase unit used above, and experiments were performed without geometric change in front of the X-ray tube. These data were so modified that the two sets of data on the single-phase unit, with two different X-ray tubes, coincided. With this modification, data on the condenser-unit could be added to the data on the 3-phase and the single-phase unit. According to these data, it has been confirmed that the data of chopped waveforms of a condenser-unit can be derived from the above mentioned data, by replacing charged voltage with *kVp*, and chopped voltage with pulsation-rate, while the data of perfectly discharged waveforms were smaller than the data of single-phase waveforms of the same *kVp*. The reason for this may be that a perfectly discharged waveform is sharp at its peak, while a single-phase waveform is round at its peak. Therefore only the data on perfectly discharged waveform were added.

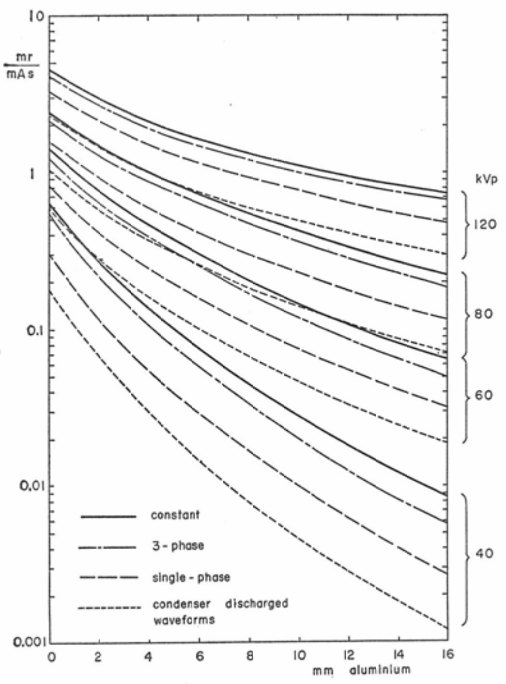


Fig. 8 Measured exposure due to transmitted rays through aluminium-phantom for constant, 3-phase, and single-phase waveforms

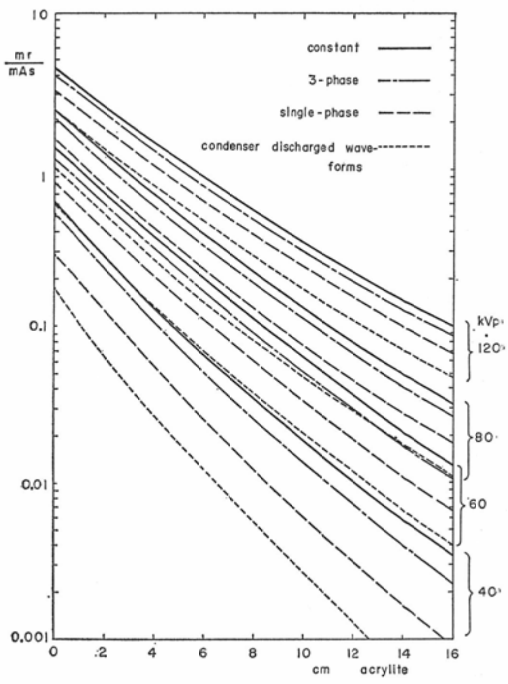


Fig. 9 Measured exposure due to transmitted rays through acrylite-phantom for constant, 3-phase, and single-phase waveforms

Fig. 8 and Fig. 9 show exposure in air thus obtained from the four kinds of waveforms using aluminium-phantoms and acrylite-phantoms respectively. The ordinates in the figures are logarithmic exposure, milli-roentgen/second, per *mA*. The figures facilitate investigation of radiographic effects when using the method of the previous paper[3]. From the figures it follows that:

1. Using the same $kVp$, constant waveforms generate harder quality and larger quantity of radiation than single-phase waveforms. Condenser-discharged waveforms generate the softest and the smallest amount of radiation. This is well known but has not been measured accurately.

2. Using 40 kVp for instance, the first and the second half-value-layers of aluminium from a constant waveform are 1.52 and 1.78 mm, those from a single-phase waveform are 1.45 and 1.66 mm, and those from a condenser-discharged waveform are 1.40 and 1.15 mm, respectively. The difference in hardness, however, decreases as $kVp$ increases, and it becomes identical when $kVp$ exceeds 80. This is true also when acrylite phantoms are used.

3. The ratio of intensity from a constant waveform to that from a single-phase waveform increases as $kVp$ decreases and as object-thickness increases. For instance, the ratio with 40 kVp through 10-cm acrylite is 3.16, while with 60, 80 and 120 kVp, the ratios decrease to 2.14, 2.00 and 1.77 respectively.

The above properties may be caused by the soft radiation absorption rates of objects. The radiation produced by a single-phase waveform may have greater rate of soft radiation than constant waveform radiation. This difference is remarkably evident as $kVp$ decreases.

4. Transmitted radiation is hardened as thickness of objects increases. This appears more remarkably on aluminium than on acaylite. Absorption coefficient characteristics of acrylite to photon-energy are more constant than those of aluminum, so that soft radiation may absorbed more rapidly by aluminium than by acrylite.

## §5 Conclusion

Precise measurements of emission and transmission of X-ray radiation were performed on 4 kinds of applied voltage waveforms, *i.e.*, constant, 3-phase, single-phase, and condenser-discharged waveforms. Comparisons of the effects of the four waveforms were performed. These experiments were made possible, since applied voltage-peak, applied voltage waveforms, and tube-current waveforms were measured in detail, with units having various kinds of high-voltage generators.

From the experiments, it was found that, properties of X-rays were determined by the factors of applied voltage-peaks ($kVp$), applied voltage pulsation-rates, and the porducts of tube-current *peaks* and exposure-durations, whereas, hitherto, the factors of $kVp$'s and *mA-mean•seconds* were used. Complex change in waveforms should not be considered in practice.

### References

1) H. Kanamori: To be published in the Jour. Franklin Inst. in 1965.
2) S. Hayashi: *Periodically Interrupted Electric Circuits,* Denki-Shoin Book Co., Kyoto (1961).
3) H. Kanamori: Japanese Journal of Applied Physics, 3 (1964) 286.
4) D.E. Trout et al.: American Journal of Roentgenology 84 (1960), 729.