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NOTE

AFRRI TN73-1
JANUARY 1973

DESIGN CONSIDERATIONS FOR STOP-MOTION CINEFLUOROGRAPHY AT 500 FRAMES PER SECOND

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AFRRI TN73-1
January 1973

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ABSTRACT

A prototype cinefluorographic system operable to 500 frames per second was assembled to test the feasibility of high-speed x-ray cinematography. The stop-motion capability of the device is absolute for biomedical research and is based upon a repetitively pulsing flash x-ray source with a 30-nsec exposure time. A discussion of repetition rate and resolution-limiting factors is presented in depth.

I. INTRODUCTION

Many areas of research have a real need for stop-motion cineradiography. Traumatology, high-speed angiography, mechanical motion analysis, and transitional ballistics all require such systems. The design and assembly of the necessary equipment is now feasible, and a unique prototype operating at up to 500 frames per second has been assembled. The stop-motion capability is adequate for in-flight ballistics and therefore is almost absolute for biomedical research. The framing rate is sufficient to study events with maximum periodicities of 250 Hz, and the x-ray beam intensity is sufficient for positive contrast radiography in the smaller primates.

The prototype represents a mating of "state of the art" technologies in ballistic radiology,[1,4,5,11] image intensifier design,[7,8,13,20,21,23,28] and high-speed photography.[16,18] It consists of four basic components: a repetitively pulsing flash x-ray source, an x-ray image intensifier, a 16-mm pin register camera, and the necessary synchronization circuitry. Figure 1 is a block diagram of this system. Figure 2 shows the components arranged during testing.

The x-ray generating unit is a modified Fexitron 846B with a beam intensity of 500 microroentgens per pulse which is independent of repetition rate to its maximum 1200 pulses per second.[1] The detector is a Machlett 9TZ x-ray image intensifier with a 5000 brightness gain and 2.9 line pair per millimeter resolution.[21] The final image is recorded on 16-mm cinefilm by a high-speed Photo-Sonics 1P camera operating at up to 500 frames per second.[16] The camera shutter is electronically synchronized to trigger the x-ray pulser circuit.

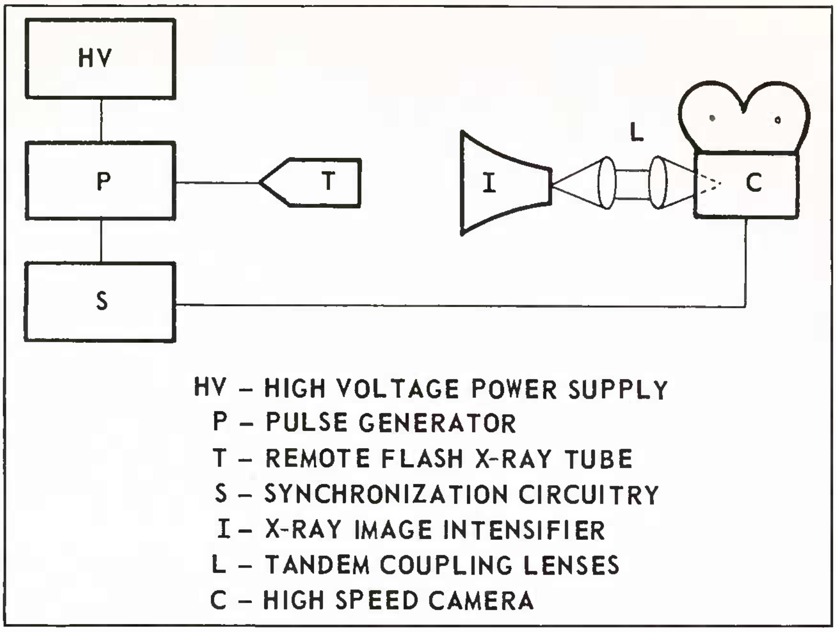

Figure 1. Prototype 500 frames per second cinefluorographic system

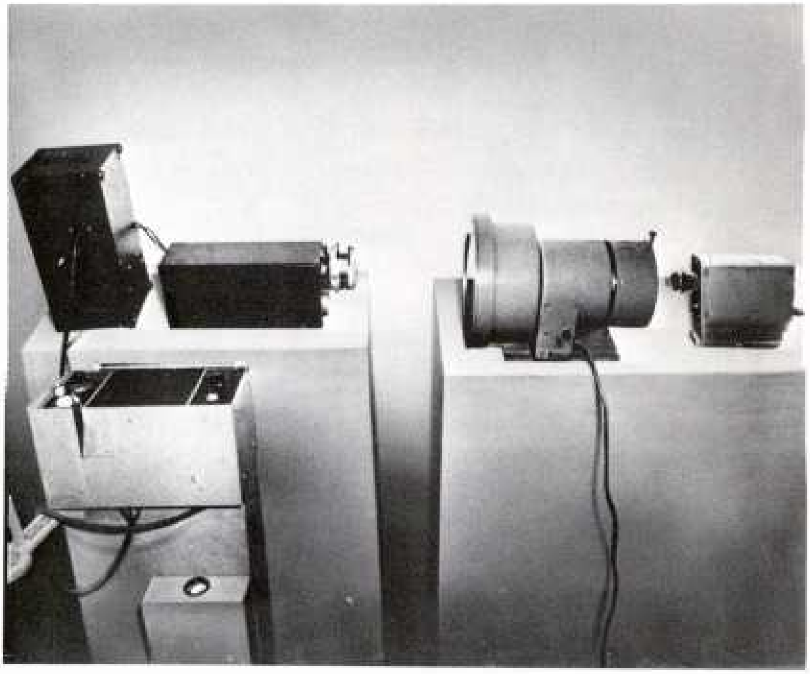

Figure 2. Assembled components of prototype high frame rate cinefluorographic system. From left: high voltage rectifier; 150 kVp flash x-ray tube; Machlett 9TZ image intensifier; Photo-Sonics 16-mm-1P camera; and at bottom, Field Emission modified 846B high repetition pulse generator.

II. STOP MOTION

The stop-motion capability of this design is entirely a function of x-ray pulse width. This is in the submicrosecond range; 30 nsec (30×10^{-9}) in this system, 10 - 100 nsec in other interchangeable units.

The ability to achieve the high x-ray beam intensities necessary for radiographic exposures in ultrashort time intervals is a property of field emission.[4,5,11] This differs from thermionic, Schottky, and T-F emission in that electron production is from a cold cathode in a high vacuum and at high kilovoltage. Large current densities, the order of 10^3 amperes, produce high x-ray beam intensities in nanosecond intervals and therefore yield high information rates.

Figure 3 demonstrates the motion-stopping capability of a flash x-ray beam. The impact of a .45-caliber bullet is stopped as it deforms at target, while the shell casing is discharged from the chamber and the pistol recoils upward.

III. REPETITION RATE

Several factors limit the rate at which this cinefluorographic system can produce sequential frames of usable information. The x-ray pulser, image intensifier and camera each impose separate restrictions.[1,13,18]

The Field Emission x-ray pulser uses a multiple stage Marx surge circuit.[11] These generators are limited by characteristics of the spark gap to recharge rates of a few hundred microseconds. As a result, the maximum achievable pulse repetition rate is approximately 5000 per second; however, the maximum for operational systems is 1200 per second.[1] If more rapid rates are necessary, separate Marx surge circuits with blocking diodes could pulse a single x-ray tube as fast as a 10-μsec repetition rate for short sequences.

Figure 3. Stop action effect of flash x-ray beam. All motions of a hand held .45-caliber automatic pistol are stopped 12 msec after firing. The shell casing ejects from the chamber as the weapon recoils upward. The lead bullet is seen at right undergoing impact deformation.

The x-ray image intensifier is presently a major rate-limiting component in high-speed cinefluorography. During high repetition operation, both input and output screens, but not the photocathodes, can become rate limiting.

The most efficient input screens are CsI or Gd_2O_2S:Tb. Both phosphors excite or "turn on", rapidly, but differ in their decay or "turn off" characteristics. CsI has a short decay (1 - 10 μsec)[14, 32] and Gd_2O_2S:Tb, a medium decay (100 μsec - 10 msec).[29]

The commonly used P-20 output phosphor ZnCdS:Ag is intermediate, with a medium-short to medium persistence (10 μsec - 10 msec).[9, 26]

Figure 4 shows the overall excitation and decay characteristics of the Machlett 9TZ image amplifier, as measured by a rapid reacting photodiode and displayed on a storage oscilloscope. This image tube utilizes a Gd_2O_2S:Tb input, and P-20 output screen. The x-ray source was a modified Fexitron 846B pulser, 350 pulses per second, 1.5 mR/pulse at 65 cm. The excitation or "turn on" time is very short. However, at 1 msec, 20 percent of the initial brightness remains. At 3 msec, the second pulse reaches a higher brightness level than the first, indicating storage phenomena are occurring.

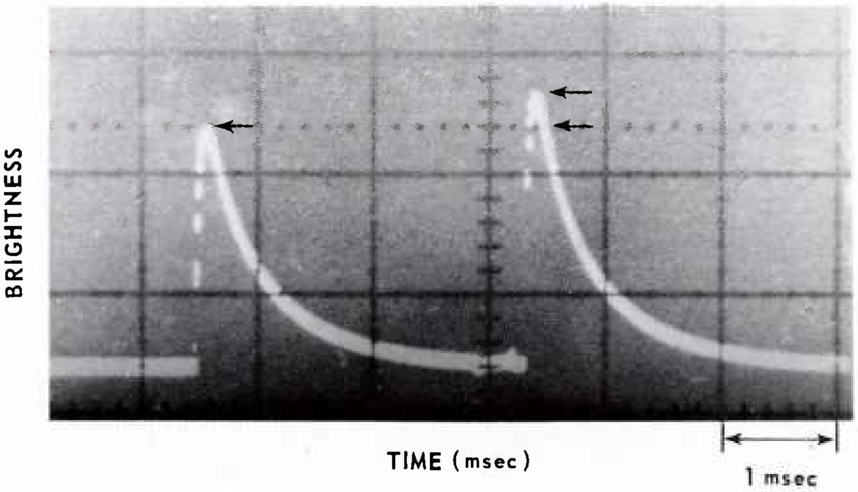

Figure 4. Excitation and decay characteristics of the Machlett 9TZ image amplifier during intermittent flash x-ray irradiation, 1.5 mR/pulse. The excitation or "turn on" time is very short, followed by a slow decay or "turn off" of the phosphors. At 3 msec, decay is incomplete, and a second x-ray pulse produces a higher image tube brightness, indicating additive storage phenomena are occurring.

The long phosphor persistence observed means the image tube will fail to erase rapidly enough to prevent "stacking" of sequential images. Figure 5 demonstrates this phenomenon at a cine-rate of 500 frames per second. A foam and aluminum phantom is stopped twice on a single frame while traveling from right to left at 5 m/sec. The black arrows show its initial position, and the arrowheads show its position 2 msec later. The double exposure was produced by the failure of the phosphor screens to fully decay before accepting successive images.

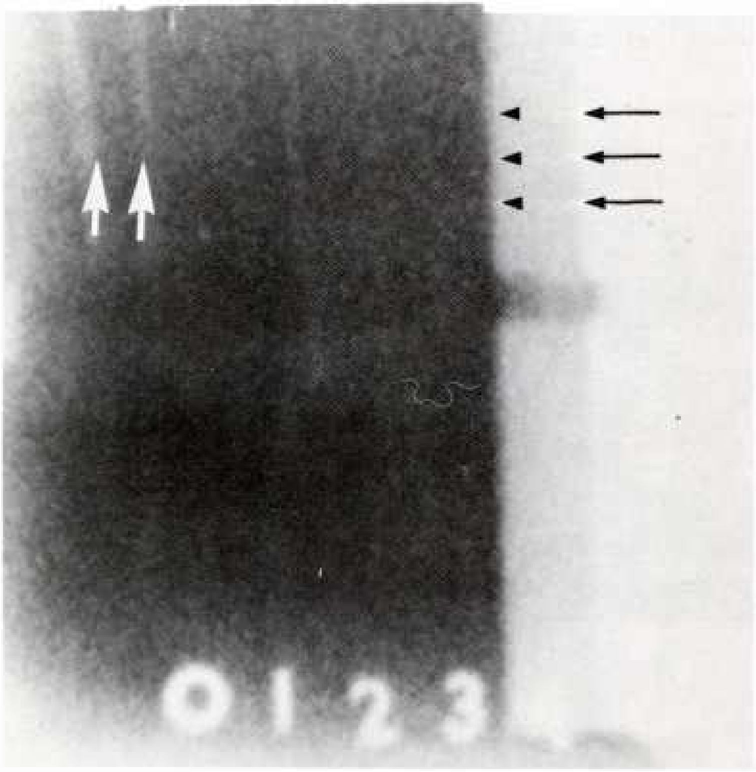

Figure 5. Severe image stacking occurring at 500 fps in absence of motion blur. An aluminum and foam phantom is moving from right to left at 5 m/sec. Black arrows indicate the initial position, arrowheads, position 2 msec later. White arrows show double images of a 1-mm aluminum needle. Scale at bottom is in centimeters.

Cinefluorography above 200 fps requires the use of image amplifiers with input and output screens of short persistence. At the 1000-fps rate, the overall image tube persistence should be less than 1 percent of the initial brightness at 1 msec without storage phenomena. The specific phosphor selection will depend upon the highest frame rates and film spectral sensitivity desired. CsI[14, 32] and RbI[29] are both usable input screens at rates to 10,000 fps, if the effect of their slow "tail" decay components is minimized by electronically gating the image tube. P-15, P-16,[26] P-36, P-37[9] and G-350[26] are all acceptable alternate output phosphors at this rate, although none have been used extensively for this purpose.

The final limiting factor in high-speed cinefluorography is the camera design. Two alternate shutter systems and three film transport mechanisms are feasible.

All current commercial cinefluorographic systems utilize intermittent pin register cameras.[24] These are versatile, efficient, and provide good resolution characteristics. The fastest existing camera of this type, the Photo-Sonics 16-mm-1W,[16, 18] is operable to 1000 fps. The fastest 35-mm pin register cameras, the Flight Research 705[10] and Photo-Sonics 4E,[16] are operable to 360 fps. For higher rates, 35-mm rotary prism cameras, the Fastax WF8A[27] and Photo-Sonics 4B,[16] have maximum rates of 2500 fps. Above this, the Super Dynafax 317[2] rotary drum camera is capable of 16,000 fps for short sequences. If the smaller 16-mm format is acceptable, multiple high-speed rotary prism cameras are available. The Fastax,[27] Hycam,[27] Nova[25] and Photo-Sonics[16] are all operable to approximately 10,000 fps at full frame size. This speed is doubled at half, and quadrupled during quarter frame operation.

IV. RESOLUTION

Many separate resolution-limiting factors are present in this cinefluorographic apparatus. These are (1) x-ray source size,[11,30] (2) x-ray light conversion,[12,20,23,31,33] (3) image amplification,[8,13,21,23,36] (4) demagnification,[5,28,34] (5) optical coupling,[19,28,36] (6) camera selection,[12,20,24] and (7) film grain size.[3,20,25]

The Fexitron 150 kV x-ray tube has a source size of 2.5 mm.[1] This places a geometric limit on the resolving power of the overall system due to this finite size.[11,30] The resolving power, R, or smallest spacing two objects can have without overlapping penumbra, is equal to OF, the object to film distance, divided by SF, the source to film distance, times the source size (see Figure 6). By diminishing OF or increasing SF, the resolving power is improved. Practical values of OF = 3 cm and SF = 75 cm allow resolution of 0.1-mm structures.

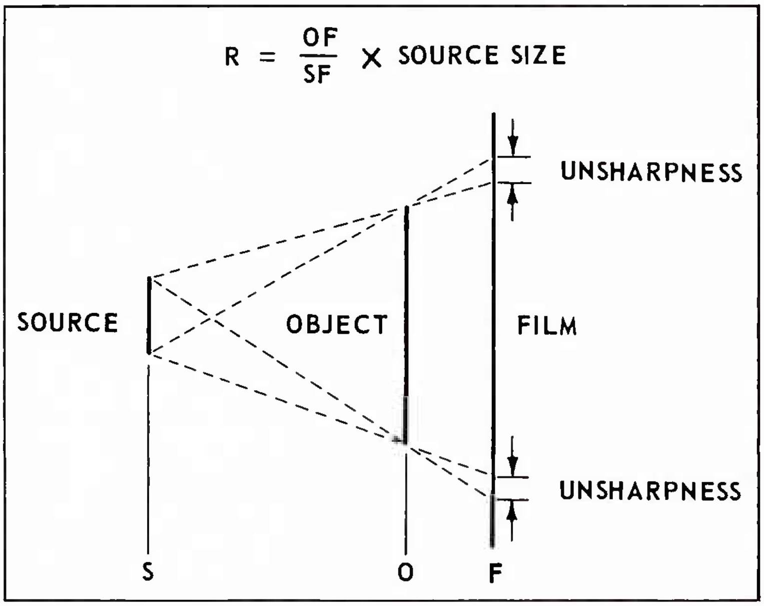

Figure 6. Diagram illustrating geometric principles of resolution

The conversion of x-ray photons to light is an inefficient process,[31, 32] and is a major resolution-limiting parameter of the overall system.[13] The maximal resolution of medical fluoroscopic screens (CB-2) is 3 line pairs (lp) per millimeter.[12, 31, 33] Industrial fluoroscopic screens can yield 15 lp/mm,[15] whereas the maximum for the input screens of x-ray image intensifiers is 5.0 lp/mm.[35] Simple light image amplifiers, both magnetic and electrostatic, have resolutions an order of magnitude higher,[17, 23] and the electron optics of x-ray image amplifiers are nearly equal.[23]

Minification of a 225-mm image on the input screen of an intensifier tube to 25 mm results in image degradation;[7, 28, 34] however, this is accompanied by a large brightness gain not achieved by simple optical demagnification. This minifying design is no longer required to achieve acceptable brightness gain, but has proven excellent for adapting the vidicon pickups of video systems. Since the commercial television raster scan rate is a slow 1/60 second,[20] such a modification was not possible for our system, and there is then no major need for such image minification.

The degree of demagnification here is acceptable for both 16- and 35-mm frame sizes, but for optimal photographic purposes a larger diameter phosphor is superior. The latter provides an increased area and total number of output phosphor particles for information storage and reprojection.[7, 34]

Direct fiber optic coupling of image intensifier to film is the most efficient design optically. Cinefluorography, however, requires the less efficient use of motion camera recording. A tandem lens arrangement of a fast collimating lens and camera lens set to infinity is the most widely used system. This decreases vignetting and allows image reduction in the ratio of the focal lengths of the lenses.[8, 19, 28, 34]

These latter are selected for high resolution, high efficiency and low reflectance at the spectrum of the specific output phosphor.

Two interchangeable camera designs are usable for frame rates of 400-1200 per second.[16] Pin register 16-mm and rotary prism 35-mm cameras are alternate feasible systems and can be synchronized to the x-ray pulser. The optical efficiency of the rotary prism is approximately 20-30 percent that of the shutter design, with poorer resolution, peripheral image degradation and decreased image steadiness. However, a 4.5 - 5.8 times larger area for information storage is present on the 35-mm cine-negative, allowing approximately a twofold increase in resolution (16 x 22-mm Academy or 18.5 x 25-mm full screen format versus 7.5 x 10.5-mm standard 16).[6, 20, 22, 36] Therefore, the 16-mm pin register and 35-mm rotary prism cameras are design alternates in spite of a 15- to 30-fold difference in their required film illuminations.

At any given level of film technology, there is a trade off in three factors: film sensitivity, granularity, and contrast.[3, 36] Use with image intensifiers tends to minimize the film speed requirements and maximize the need for contrast.[28] The latter is often obtained at the expense of increased granularity and decreased resolution when fast, high-gamma films are selected. Use of larger film formats,[6, 20, 36] fine-grain slower films, and fine-grain development techniques tends to diminish this problem. Acceptable films for high-speed applications include Dupont Cronex SF-2; Kodak high-speed Ektachrome 7241; Linagraph Shellburst 2476; and RAR 2498, reversal processed.

V. DISCUSSION

The cinesystem presented was assembled using components loaned by the manufacturers, modified to interface with one another. Its purpose was to demonstrate the feasibility of stop-motion cineangiography for neurosurgical traumatology studies. Undoubtedly, later generations of this equipment design will find more extensive uses in other areas. Specifically, high-speed motion analysis, general traumatology, orthopedic joint motion studies, stop-motion contrast radiography and transitional ballistics are areas in which such an instrument would be of great value.

The present prototype minimizes subject irradiation and scatter. Alternate feasible designs, utilizing either a dc x-ray source and gated image amplifier or a pulsed source and rotating film drum, would require extensive shielding and still would not possess equivalent stop-motion capability. Certainly their radiation outputs would rapidly become hazardous as they achieved good stop-motion effect. The present design, however, offers an inherently simpler and lower x-ray dose approach to high-speed radiography. It has its greatest potential value in the study of a multitude of internal human physiologic events with the complete absence of motion blur.

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Armed Forces Radiobiology Research Institute Defense Nuclear Agency Bethesda, Maryland 20014	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

DESIGN CONSIDERATIONS FOR STOP-MOTION CINEFLUOROGRAPHY
AT 500 FRAMES PER SECOND

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

S. A. Shatsky and S. H. Jacobson

6. REPORT DATE January 1973	7a. TOTAL NO. OF PAGES 16	7b. NO. OF REFS 36

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) AFRRI TN73-1
b. PROJECT NO. NWED QAXM	
c. Task and Subtask Q 999	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Director Defense Nuclear Agency Washington, D. C. 20305

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DD FORM 1 NOV 65 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT