A physicist examines the Kennedy assassination film*

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The motion picture film of the Kennedy assassination taken by Abraham Zapruder was one of the most important exhibits examined by the Warren Commission. The author uses the tools of the physicist to draw some conclusions that escaped the notice of the Commission and its expert FBI photointerpreters. Among the subjects treated are (1) the timing of the gun shots, (2) a theoretical and experimental investigation of the "backward snap" of the President's head immediately after he was killed—yielding the surprising result that it was consistent with a shot fired from the rear, (3) the speed at which the camera was running, and (4) a previously undetected deceleration of the President's automobile just before the final shot. The emphasis throughout is not on the assassination but rather on the application of elementary physics principles to the solution of practical problems.

EDITOR'S NOTE

We publish this article by Luis Alvarez for its unique pedagogic usefulness. It brings to bear on a matter of public concern powerful and simple physical arguments that are within the reach of introductory physics students. It shows a physicist at work employing qualitative arguments, estimates, measurements, and calculations appropriate to the problem and to the accuracy of data available.

As always, we welcome readers' responses to this article and will select some for publication according to their appropriateness and the space available. We are interested in comments on procedures which Professor Alvarez uses to reach his conclusions and on the pedagogic uses to which the article can be put. We do not feel that this Journal is an appropriate forum for a discussion of alternative theories of the assassination.

I. INTRODUCTION

In the eleven years since the Warren Commission published its 26-volume report[1] on the assassination of President Kennedy, a controversy has continued over the validity of the Commission's findings. Dozens of books and countless articles have been written to show, for example, that Lee Harvey Oswald had nothing to do with the event, or that he was part of a conspiracy with the CIA or other parties in planning the assassination. Some of the books, such as Mark Lane's *Rush to Judgement*,[2] were best sellers. In December 1966 *Esquire* published an article[3] listing 35 different theories that had been advanced by as many authors, each suggesting a variation on the Warren Commission's official scenario of the assassination. And since then, many more theories have appeared.

In the light of such a long history of unsettled controversy, the reader might well wonder why yet another author would feel moved to write on the subject. The reasons are quite simple; in the first place, I continue to read, and to hear on radio and television that, "The laws of physics require that the President must have been shot from the front, whereas the Warren Commission places his assassin, Lee Harvey Oswald, behind him."

Such statements involve the backward snap of the President's head, immediately after the shot that killed him. I will show, both theoretically and experimentally, that such statements are simply incorrect; the laws of physics are more in accord with the conclusions of the Warren Commission than they are with the theories of the critics.

My second reason for writing this report is to show how an experienced physicist attacks a new problem. Textbooks tend to indicate that problem solving in physics is a straightforward matter; one proceeds step by step from the input data to the final answer. But in real life, as I will show, a physicist makes many mistakes, and backs up to correct them, one by one. (To those who feel the personalized style of this report is an uncorrected error, I apologize; the earliest version was intended only for a few friends, where the liberal use of personal pronouns wouldn't cause offense. When the report was finally finished, the task of squeezing all the first person singular pronouns out of the text seemed too formidable, so the author hopes the reader will accept his apology.)

After a decade of exposure to the various theories of the assassination, I have at least one advantage over the earlier writers. I've watched each new writer in turn criticize the earlier ones for speaking authoritatively in areas in which they weren't experts. I will, therefore, speak with authority only in areas in which a judge would most probably accept me as an "expert witness." For this reason, the reader will be spared any thoughts of mine on conspiracies, medical reports, the CIA, or ballistics. I haven't counted the number of times I have agreed with, or disagreed with the Commission's findings; I've done both in several different instances.

One of the aspects of physics that makes it appealing to those of us who practice it as a profession is that calculations and the results of experiments can be repeated at will. So all of the interesting observations I've made on the Zapruder assassination movie film can be repeated by anyone sufficiently interested in such matters. (And all of them have been duplicated at least once by others.) Most of the conclusions I reach will seem reasonable to physicists, but in one case I will simply give my "best guess," and not try to do any more persuading.

This report will cover my analysis of several events appearing in the assassination film, some theoretical calculations relating to the "head shot," and some firing range experiments that validated the theoretical conclusions based on the laws of physics as I have taught them for the past 40 years. My observations, analyses and conclusions also relate to the timing of the shots, the speed at which the camera was

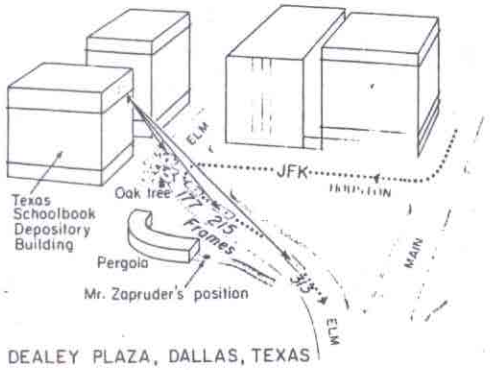

Fig. 1. Dealey Plaza, Dallas, Texas, 22 November 1963. President Kennedy's route is shown down Main Street and Houston Street, turning onto Elm Street, in front of the Book Depository Building, where Lee Harvey Oswald was employed. Mr. Zapruder photographed the President's car throughout its passage along Elm Street, until it disappeared under an overpass. Physical evidence will be presented for three shots, at Zapruder frames 177, 215, and 313.

running—both matters of some dispute, and to a sharp deceleration of the President's car just before the President was killed. To the best of my knowledge, this strange behavior on the part of the President's driver has gone unnoticed by everyone else; I suggest a reason for it.

In pointing out some conclusions that seem persuasive to me as a physicist, I do not wish to give the impression that I think that a physicist's way of arriving at "the truth" is the best way or the only way. It works well in the world of physics and so long as I confine my attention to the physical evidence in the Kennedy assassination, I feel that my conclusions can be of help in elucidating what took place in Dealey Plaza, Dallas, on 22 November 1963 (see Fig. 1).

II. THE FILM, THE COMMISSION, AND THE CRITICS

A remarkable moving picture record of President John F. Kennedy's last living moments was taken by Abraham Zapruder in Dallas on 22 November 1963. The Zapruder film was viewed several times by the Warren Commission, and extensive testimony was presented to the Commission by FBI photoanalysts who had made detailed studies of the film, frame by frame. Nevertheless, a good many substantive observations were missed by the photoanalysts, and some of the information they gave to the Commission was incorrect.

With the publication of the 26-volume series containing the evidence presented to the Warren Commission,[1] together with a transcript of the hearings, a group of "Warren Commission Critics" came into being. These critics, or assassination buffs as they are sometimes called, have gone over the voluminous "exhibits" with fine-toothed combs, and have found many errors and contradictions. The assassination buffs attribute most of the errors to more than the sloppiness of a rapid publishing effort; they feel that the Warren Commission didn't do a thorough enough job in investigating many leads, and some of them take the position that the Commission actually ignored or suppressed evidence that Oswald was part of a conspiracy.

I was quite unaware of the strong criticism of the Warren Commission's actions when I first drew some conclusions from a study of the Zapruder film. A simplified and not too convincing report on my analysis of the timing of the shots was presented in a four-hour CBS documentary television program, "The Warren Report," 25–28 June 1967, the text of which is reproduced in Stephen White's book on that documentary.[4] It is difficult to explain a rather technical matter to a lay audience, and in a short space of time. I hope that the lifting of such limits in this report will permit me to explain the methods I used and the conclusions I drew.

III. HOW MANY SHOTS WERE FIRED, AND WHEN?

Publication of the Warren Commission Report and its supporting documentation initiated an intense controversy involving the timing of the shots. Witnesses testified that as few as two and as many as six shots were fired.

The Commission, noting among other bits of evidence, the presence of three spent cartridge cases on the sixth floor of the Book Depository Building near the abandoned Mannlicher-Carcano rifle, concluded that three shots had been fired by Oswald. They decided that one of the shots missed the car; this missing shot could have been either the first or second one fired, but the Commission favored the hypothesis that the second shot was the one that missed. The Commission decided that of these two early shots, the first one probably passed through the President's body before wounding Governor Connally of Texas, who was riding on a "jump seat" just ahead of the President, and the third one struck and killed the President in frame 313. Governor Connally stated quite positively (in the 25 November 1966 issue of *Life*) that he wasn't wounded by the first shot; his testimony was based on his recollection that he heard a shot, turned around, and was later wounded. His story agrees better with the shot timing to be developed in this section, which in turn is not in conflict with the Commission's "allowed but not favored" conclusions. My reasons for preferring physical evidence to the recollections of even the best witnesses are highlighted by noting that the Governor was not even aware that he had received bullet wounds in his wrist and in his thigh until after he had been admitted to the hospital and operated upon.

Several years after I wrote the previous sentence, I read a fascinating article in *Scientific American* by a man who qualified as an expert on the reliability of "eyewitness testimony." Robert Buckhout wrote[5]:

> "Eyewitness testimony is unreliable. Research and courtroom experience provide ample evidence that an eyewitness to a crime is being asked to be something and do something that a normal human being was not created to be or do. Human perception is sloppy and uneven, albeit remarkably effective in serving our need to create structure out of experience. In an investigation or in court, . . . [the prosecution and the defense], and usually the witness, too, succumb to the fallacy that everything was recorded and can be played back later through questioning."

The above-mentioned issue of *Life* arrived on the day before Thanksgiving, and because of it I got very little sleep that long holiday weekend. It contained a set of reproduc-

tions in color of selected frames from the Zapruder film, illustrating the controversy between the Commission and the Governor. With my many years of experience in analyzing bubble chamber film, plus some moonlighting activities in photographic detective work as a background, I soon found myself completely engrossed in the Zapruder frames. My first observations and their subsequent "explanation" turned out, as I showed later, to be quite incorrect. But by the time I knew my first conclusions were wrong, I had devoted so many hours to a study of the pictures that I was subsequently able to see some things that I do believe have significance.

My attention was drawn to the way the flag, at the left front fender of the President's car, changed its shape from frame to frame in the *Life* photographs. I remembered that at Almagordo, Enrico Fermi had almost instantly measured the explosive yield of the first atomic bomb by observing how far small pieces of paper which he "dribbled" from his hand, were suddenly moved away from "ground zero" by the shock wave. (He had a precomputed table of numbers in his pocket, so he knew the explosive energy of the bomb long before any of the official measurements had been analyzed.) I thought I detected a deformation of the Presidential flag under the influence of the shock wave generated by a nearby bullet. From an elementary calculation involving the known properties of shock waves from bullets, and an assumption as to the surface density of the flag, it seemed to me reasonable to believe that the motions I detected were indeed due to the action of shockwaves. If such a conclusion could be confirmed, the vexing questions concerning the timing of the shots might be solved. (My knowledge of the strength of shock waves from bullets came from an experience I had in World War II, with W. K. H. Panofsky, who had built and was testing a "firing error indicator." This device was towed behind a plane, in a "sleeve," at which gunners fired for practice. It contained two microphones that recorded the shock waves from passing bullets.)

The frames reproduced in *Life* showed a total of only 1.3 sec of the critical moments in Dallas, so I had to wait until the following Monday to examine the sequence of 160 frames in the Law School Library's copy of the Warren Commission "exhibits."[6] When I saw the full set of frames, it was clear that the flag was simply flapping in the breeze. But the thought that effects of the individual bullets might show in the film was still very much in my mind. As I scanned the selected color photographs in *Life* and the full set of black and white copies in the exhibits, I noticed a striking phenomenon in frame 227 (Fig. 2). All of the innumerable pointlike highlights on the irregular shiny surface of the automobile were stretched out into parallel line segments, along the "8 o'clock 2 o'clock" direction. In the plane of the automobile, the parallel streaks appeared to be about 10 in. long.

To appreciate the significance of the streaks, one must remember that each frame of moving picture film is not an instantaneous snapshot, but a time exposure that lasts for about one-thirtieth of a second. For a point of light on the car to be spread out into a streak on the film, the optical axis of the camera must have an angular velocity relative to the line joining the camera and that point of light. If most of the frames had shown streaking, one would simply have concluded that Mr. Zapruder was a "sloppy tracker" who couldn't follow the motion of the President's car as it moved

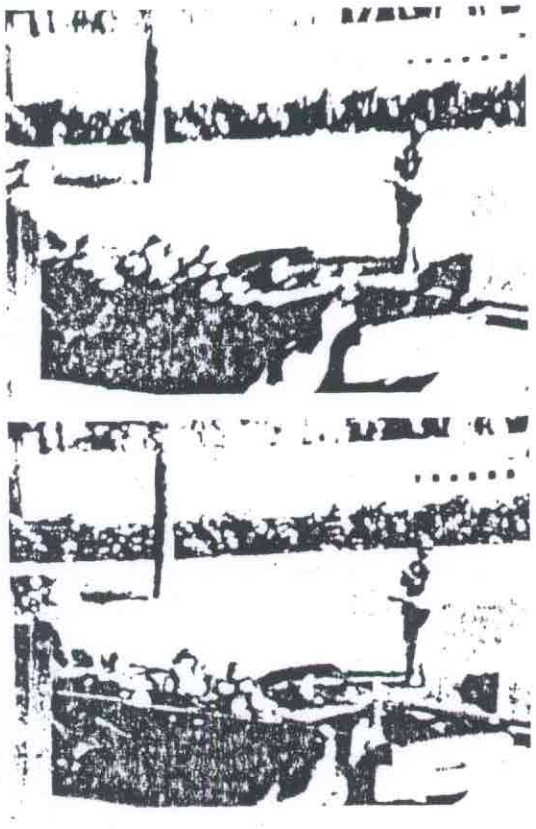

Fig. 2. Zapruder frames 227 (top) and 228 (bottom). Note that the highlights on the car which appear in frame 228 as points, are drawn out into streaks (along the 8 o'clock 2 o'clock direction) in frame 227.

past him, as he "panned" his camera to keep the President in his field of view. But the highlights showed as sharp points of light in most of the frames.

If we "transform" to a rotating coordinate system in which the car and the camera axis are at rest, we can better understand the significance of the streaks. In this system, a streak means that the camera axis has an angular velocity relative to the coordinate axis, and this means that a torque has been applied to the camera to produce the angular acceleration that gave rise to that angular velocity. Such a torque could be produced by a muscle spasm, or by a passing shock wave from a bullet. (I guessed that the frightening crack of a bullet in Dealey Plaza would set Zapruder's neuromuscular system into a temporary spasm. This phenomenon was demonstrated in the CBS documentary series, as we shall see.) For a long time, I thought that I had been the first person to attribute significance to the streaks I've just mentioned. But apparently Harold Weisberg did it first in his book *Whitewash*.[7]

My interest in moving picture camera jitter arose when I was photographing animals in Africa in the summer of 1962. I was bothered by my inability to suppress all visible jitter in a long focal length movie camera used without a tripod, and I started thinking of ways to build optical compensators so that hand-held movie shots would not ex-

hibit the jitter that usually distinguishes amateur movies from those made on tripods by professionals. One night in Nairobi, I invented a solution to the problem. The Bell and Howell Company, which incidentally built Zapruder's camera, was supporting my development of working models of the movie camera stabilizer at the time the President was shot, and my U.S. camera stabilizer patents are owned by Bell and Howell. In the course of my work in movie camera stabilization, I learned that the jitter frequency of a hand-held optical device does not depend to first order upon the weight or the moment of inertia of the device, in spite of what a physicist's intuition would suggest, but instead depends mainly on the time constants of the neuromuscular-feedback system. Most people have a peak in their jitter power spectrum at about 3 cycles/sec. As we shall soon see, this frequency appeared in Zapruder's jitter spectrum when his neuromuscular system was set into oscillation—presumably by the sharp "crack" of the bullets.

Many people who have heard of my observation of "streaks" in the Zapruder film have concluded that the presence of such streaks is the important phenomenon, and that if someone tabulated the frames showing streaking, he would be repeating my observations. Even though CBS presented the data in this highly oversimplified manner, the presence of the streaks simply indicates that the angular velocity of the optical axis of Mr. Zapruder's camera (about a nearly vertical direction) did not match the angular velocity of the President's car, as it drove down Elm Street (Fig. 1). Such a mismatch in the two angular velocities would cause the image of the car on the 8-mm film to move relative to the edges of the "filmgate," during the roughly 30-msec exposure, and this motion would give rise to the streaking of the pointlike highlights. It is obvious that no information of any importance can be attached to such streaking, because no one can perform "hand tracking" accurately enough to avoid all streaking.

My observations involved the measurements of the streaking, but I didn't plot the meaningless streak length—proportional to the mismatch in angular velocity, $\Delta\omega$—but instead, the angular acceleration, α, averaged over two successive frames. Under normal conditions, when $\Delta\omega$ is large enough to give appreciable streaking, the angular acceleration—given by the *difference* in the lengths of the streaks in two successive pictures—is too small to be measured, since the streak lengths in successive frames are almost equal. The plot I made and showed to my friends at CBS is reproduced in Fig. 3. The frame number runs vertically, as on the film itself, and the angular acceleration of the camera axis is plotted horizontally. Since each measure of α involves the subtraction of streak lengths, $\Delta\omega_{n+1}$ and $\Delta\omega_n$ on two successive frames, the value of $\alpha_{n+1/2}$ is plotted at a "half integral frame number," midway between the two frames whose subtracted streak lengths are involved. In order to find α, one needs to know the "sign" of each of the two $\Delta\omega$'s to be subtracted. In other words, we must find out for each streaked frame whether the camera axis was moving toward the back or toward the front of the car. It turns out that the sign of $\Delta\omega_n$ can be found quite unambiguously, simply by observing where the camera was pointing on the $n-1$ and the $n+1$ frames. When I was assigning a plus or minus sign to each of the $\Delta\omega$'s by this technique, I found that the only place this technique didn't work was for frames 314 and 315. A closer examination showed that the numbering of these two frames had simply

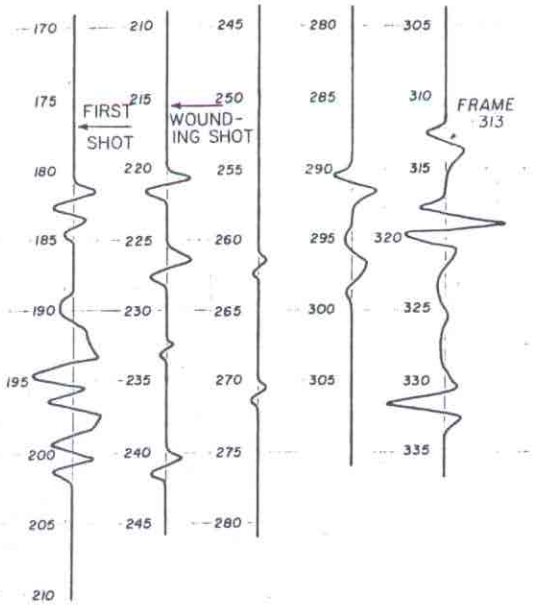

Fig. 3. Angular acceleration of Mr. Zapruder's camera, frame by frame. The frame numbers run vertically from 170 through 334. The angular acceleration for the $n + \frac{1}{2}$ frame is plotted as abscissa, in arbitrary units. Each such acceleration is determined by subtracting the length of the streak in the nth frame from that in the $n + 1$ frame, after assigning an algebraic sign to the streak length in each frame. (See text for details.) Accelerations plotted to the left are "clockwise looking down." Shots are associated (in the text) with pulse trains starting at about 182, 221, and 313.

been interchanged in the "exhibits," and when they were properly labeled, the signs of all $\Delta\omega$ could be determined without ambiguity. Although I later found that the interchange of these two frames was well known to the assassination buffs, the manner in which I detected it convinced me that my determination of the signs of the $\Delta\omega$'s, and therefore the signs and magnitudes of the α's were completely objective.

Figure 3 is a reproduction of my original graph of angular acceleration versus frame number. Angular accelerations plotted to the left correspond to motions of the camera axis that are "clockwise looking down." (The motion of the car and of bullets from the Book Depository are also clockwise looking down, as seen by Mr. Zapruder.) Thus the torque acting on the camera between frames 312 and 313 was "negative," meaning that it could have been caused by a direct interaction of the shock wave from the bullet that hit the President in frame 313, with the left hand side of Mr. Zapruder's camera. (This is important because the impact of the bullet can be seen in frame 313, and there isn't enough time available for the relatively sluggish neuromuscular system to have produced the observed torque on the camera axis.)

When I saw Fig. 3 for the first time, I felt confident that the trains of pulses of angular accelerations were largely the results of the excitation of Zapruder's neuromuscular system, by the sounds of bullets in Dealey Plaza. I had no experimental data to show that a camera would undergo such

violent angular accelerations if held by a person who was startled by the sound of gunfire. But such a test was made for CBS by a firm well known to physicists Edgerton, Germeshausen, and Greer—and films of the test were shown on the CBS program. While the audience watched, cameras held by two separate cameramen shook quite violently in response to gunfire, as Walter Cronkite was saying,[8]

> "Just as a rough check on [the Alvarez] theory, we decided to try it ourselves, using other cameramen holding similar cameras, standing on a rifle range, filming an automobile while a rifleman fired over their heads.
>
> "These two volunteers are aiming their cameras at a parked limousine. Their instructions: 'Hold the cameras as steady as possible, and keep filming no matter what happens.' The shots will come between them and the car. The cameramen are as far from the firing platform as Mr. Zapruder was from the sixth floor of the Book Depository. [Sound of gunfire in background.]
>
> "The reaction was obvious. The film taken by these cameramen showed the effect of the shots, despite instructions to hold steady. Even in steadier hands, motion was always noticeable. This frame shows highlight dots around the car's windshield. In reaction to a shot, the dots changed to crescents. And in the following frame they became streaks, comparable to streaks found in some frames from Mr. Zapruder's film."

In view of these tests, I feel that few persons would now dispute the cause and effect relationship between the shots in Dealey Plaza and at least some of the trains of streaks in Mr. Zapruder's otherwise well-tracked movies. If we accept this relationship, we can use the locations of the trains of streaks to shed useful light on the important question of the timing of the shots. No conclusions of the Warren Report have been so disputed as those concerning the timing of the shots, and the damage done by each bullet. Most observers remembered that three shots were fired, but the recollections embraced a range from two to six. Three spent cartridge cases lay on the floor by Oswald's Mannlicher–Carcano rifle abandoned near the sixth floor window of the Book Depository, overlooking Dealey Plaza. According to the Warren Commission Report, p. 110,

> "... the nearly whole bullet discovered at Parkland Hospital [to which the President was taken directly from Dealey Plaza] and the two larger fragments found in the Presidential automobile, which were identified as coming from the assassination rifle, came from at least two separate bullets and possibly from three."

One of the "boundary conditions" on the timing of the shots (assuming there were three—one from each ejected cartridge) was the FBI's finding that a skilled marksman could not space his shots more closely than 2.3 sec, or 42 frames of Mr. Zapruder's camera, with its measured frame rate of 18.3 per second. (I will discuss the frame rate later in this article.)

No problem was involved in deciding when the third and fatal bullet was fired; the gory photograph labeled frame 313 settled that question quite conclusively. The fates of the first and second bullets were debated at length by the Commission, and the following conclusion emerged: a bullet, fired in a one-second interval between frames 206 and 225, wounded the President by passing through his neck, and then wounded Governor Connally, who was seated just ahead of the President. This so-called "single bullet theory" as we have already learned, was later challenged by Governor and Mrs. Connally.

The Commission decided that the other bullet was never recovered, and after giving reasons to suggest that it could have been fired either before or after the shot that was identified as wounding the two men, the Commission favored the suggestion that the unrecovered bullet was fired after the one that wounded them.

If we now look at Fig. 3 in the light of this background material, we see that the obvious shot in frame 313 is accompanied immediately by an angular acceleration of the camera, in the proper sense of rotation to have been caused directly by shock-wave pressure on the camera body. The human nervous system cannot transmit signals fast enough for the angular acceleration between frames 312 and 313 to have been caused by Mr. Zapruder's muscles reacting to impulses from a brain that had been startled by the shot that killed the President. The expected neuromuscular reaction occurs about one-quarter to one-third of a second later, as shown by the large accelerations near 318. (I'll adopt five frames as Mr. Zapruder's experimentally determined reaction time, for reasons to be discussed later.) Another large acceleration peak occurs about two-thirds of a second after this group, so we observe three out of a possible four pulses spaced very nearly the canonical one-third of a second apart. For those readers who are surprised that the neuromuscular response time is so long, let me recall a common "parlor trick": *A* bets *B* that if *A* drops a vertically held dollar bill without any warning, *B* cannot stop its fall by pinching his fingers together, if his fingers are poised, ready to clamp together, at the bottom edge of the bill. The fact that the bill can almost never be stopped (unless *A* gives a precursor signal with his fingers) indicates that a nervous system "on hair trigger" takes more than one-sixth of a second (3.1 frames) to respond to an optical stimulus.

If we look between frames 206 and 225, the one-second interval in which the Commission suggested the "wounding shot" was fired, we see the start of a one-second-long train of pulses, spaced very nearly one-third of a second apart. We further note that the initial pulse of the series, at 221.5, is not in the proper direction to have been caused by a direct interaction of the shock wave with the camera; the camera turns toward, rather than away from the shock wave. The shock wave from a bullet fired from the Book Depository toward the car in its position at the time of frame 221 would have been considerably weaker at Mr. Zapruder's station than the shock wave in frame 313, so the lack of a direct physical interaction at the time of this earlier shot is not surprising. I therefore conclude that the accelerations at 220.5 and 221.5 were caused by Mr. Zapruder's neuromuscular response to an earlier stimulation. If we use Mr. Zapruder's thereby observed oscillation period of about five frames (which is close to the expected value), we place the "wounding shot" at about 215.5. I find it most interesting

that although the determination of 215.5 as the frame number of this shot was derived directly from the appearance of the streaks, it is exactly halfway between two limits, only one second apart, set by the Warren Commission from very different data.

If we convert the Commission's language into the vernacular of the physicist, their conclusion could be stated: "The bullet that wounded the President and Governor Connally occurred at frame 215 ± 10." Although I would not have expected the conclusions of two such different studies to agree so closely, it is true that my estimated frame number for one of the two disputed shots agrees with the Commission's best estimate to within less than one-tenth of a second. The Commission based its findings largely on an examination of what the people in the car were doing; President Kennedy "seemed to be reacting (in frame 225) to his neck wound by raising his hands to his throat."[9]

I will ignore the two small accelerations between frames 245 and 280; each is caused by a single frame in which I judged that highlights might be smeared slightly more than the normal smearing caused by the imperfections of the half-tone process. I will return later to the short sequence of significant pulses starting at 290 since they require an explanation. They seemed to me to have less intensity, and to last a much shorter time than the three sets of pulses I identified as being triggered by bullets. I eventually found what I think is a reasonable explanation, not only for these angular accelerations, but also for a puzzling deceleration of the President's car at the same time but that is getting a bit ahead of the story.

Because of the quietness of the acceleration graph between the pulse trains starting at 221 and 313 (except for the pulses which I feel have other explanations), and because of the obvious train of pulses starting at 182, I favor the view that the Commission's "missing shot" initiated this first train of pulses. My best estimate of the time of this shot is therefore 182 minus 5 (for Mr. Zapruder's calibrated time delay), or frame 177.

The Commission noted that about that time, the President's car was partially obscured from the sixth floor window, as it passed under a large tree. In a very thorough reenactment session in Dealey Plaza, photographs were taken by the FBI from the window near which the rifle and three spent cartridge cases were found. A limousine was moved along Elm Street, into positions corresponding to known frame numbers, and the Commission report reproduced sample groups of corresponding pictures: (1) from Mr. Zapruder's camera, (2) from the FBI camera in the sixth floor window showing the appearance of the limousine and a man sitting in the President's seat, and (3) from an FBI camera with a field of view equal to that of Mr. Zapruder's movie camera, located at the position from which he photographed the assassination. The FBI pictures corresponding to frames 166 and 186 are reproduced in the Commission's report, and both show that the President was clearly visible through the branches of the intervening tree in both views. It appears that the President had been unobscured before 186, during which time the gunman would have had a good opportunity to track him, and match the angular velocity and angular position of his gun with that of the President's body. The fact that the President's head might have been partially obscured by branches for one-half a second, at frame 177, would not, in my opinion, have had any appreciable effect on the gunman's tracking ability, or feeling of confidence that his aim was good. Anyone who has ever driven a car in a heavy rainstorm, with a slow windshield wiper will realize that a partial loss of visual acuity for a half-second would not seriously affect a gunman's ability to perform good tracking, particularly when most of the car was still clearly visible through the holes in the trees. And if we remember that the decision to squeeze the trigger must have been made a few tenths of a second before the bullet was fired, the effect of the obscuring tree should have been negligible on the actions of the gunman, for a shot fired at frame 177.

I find it strange, on reading the testimony of experts on firearms (which I certainly am not), that they all looked at the photographs taken through the trees and testified whether or not a gunman could have fired at particular frame numbers. They treated the subject as though it was static—as though the gunman was presented with a stationary target behind a tree. They looked at the still photographs taken from the window in this static way, and decided that the gunman could have fired at certain frame numbers (when the President's body showed through a hole), but not at other times, when it was eclipsed. I can appreciate how they could have said such things under the stress of the investigation, when asked to comment on a set of still pictures, but I am surprised that no one mentioned what the real situation was like, with a large moving object containing a specific target fixed in its moving frame, that had a very nearly constant angular velocity with respect to the gunman. I don't believe a gunman would have been deterred from firing at frame 177, and I consider it most likely that the shot fired at that time was the one the Commission concluded missed the car and was unrecovered.

To return to the FBI's (assumed) minimum possible firing interval of 2.3 sec, we should compare this time with my best estimate of the time interval between what I identified as the first two shots. From frame 177 to frame 216 is 2.13 sec. To make this conform to the 2.3-sec limit, it is only necessary to change the timing of the two shots by one and a half frames each; if the first occurred at 175.5 and the second at 217.5, the time interval would be 42/18.3 = 2.3 sec. Such a procedure of altering estimated numbers within their known errors is a standard technique in my own physics specialty of bubble chamber event analysis. We have complicated computer programs that alter measured angles and measured momenta of tracks (within the known errors) to match the constraints imposed by the laws of conservation of energy and momentum. Just as a bubble chamber physicist uses a "fitting routine" to make his events match a known constraint, I have shown that I can fit the 2.3-sec time interval constraint by two small adjustments in estimated frame number. Since the two changes of ±1.5 frames are small compared to the extrapolation of five frames each, made to arrive at the two unfitted estimates, and since no one would really believe that such extrapolations were more accurate than 1.5 frames, I believe that the fitting procedure is justified. However, if the reader dislikes this fitting procedure, he can still accept my "unfitted estimates," by learning that the CBS tests turned up a "technician who had one hit and two misses" (at a moving car, in a three-dimensional mockup of the Dealey Plaza) "in 4.1 sec."[10] This is remarkably like the apparent performance of the marksman identified by the Commission as Lee Harvey Oswald and reduces the permissible time interval to 2.05 sec, which is within my unfitted estimate of 2.13 sec.

Let me now summarize the conclusions of this section. By an analysis of "streaks" in the Zapruder film, I identified the precise timing of two shots that had been pinpointed by other means by the Warren Commission. So far as I know, there is no real controversy concerning the timing of these two shots. I found evidence that convinced me that a third shot was fired at about frame 177. This firing time is allowed by the findings of the Warren Commission, even though they favored the idea that the "third shot" was fired between the two that they identified as surely hitting President Kennedy. And finally, this firing sequence is consistent with the memories of Governor and Mrs. Connally.

What limitations can be placed on these observations? If, as many people have suggested – and continue to suggest – two shots hit the President almost simultaneously from opposite directions, at frame 313 and very shortly thereafter, could I have detected this multiple firing? The answer to that question is "no." To be detected by the "streak method," two shots must be spaced by about 2 sec to be resolved as two separate shots, rather than a single shot followed by a slower than normal recovery time for Mr. Zapruder's neuromuscular system. But in the next section, I will be able to shed some light on the question of the "shot from the front."

I was bothered for some time by the weaker set of pulses lasting a shorter time, that show in Fig. 3, from frames 290 through 298. They don't look like the ones that seemed clearly associated with bullets. But obviously they required an explanation. I'll give my best explanation for them in the final section of this report, but I don't feel as certain about that explanation as I do about the other three cases.

IV. WHY DID THE PRESIDENT'S HEAD SNAP BACKWARD AFTER THE FATAL SHOT?

I must apologize for the tone of the following section, which may sound cold blooded and devoid of human feeling. My long delay in publishing this analysis derives largely from my feelings of inadequacy after many attempts to soften its impact. But I am finally convinced that the conclusions I reach in this section are important, and I have therefore done my best to make the text as free from emotional content as possible. John Kennedy was one of my personal heroes, and I had the pleasure of talking with him on two occasions. His death touched me deeply, and I hope the reader will bear that in mind as he studies this section.

Paul Hoch, who was then a graduate student at Berkeley, tried to interest me in one of the hottest and longest surviving controversies arising from a study of the Zapruder film. (It was the subject of several radio and television shows in April 1975, and testimony concerning it was taken during the Congressional Hearings on the CIA, in June 1975.) This controversy involves the unexpected behavior of the President's head immediately after it received the final and mortal shot. Everyone who studied the behavior of the people in the Zapruder film agreed that immediately after this shot, the President's head and body moved suddenly backward. The sixth floor window of the Texas Book Depository Building was behind the car, and the Warren Commission concluded that Lee Harvey Oswald shot the President from that window. Why then did the President's head recoil toward, rather than away from the gun as the laws of physics would seem to demand? The assassination buffs argued at length about this action. I shall mention only three persons out of a great many who concluded in writing that the President was shot from the front. In his *Rush to Judgment*,[2] Mark Lane said, "So long as the Commission maintained the bullet came almost directly from the rear, it implied that the laws of physics vacated in this instance, for the President did not fall forward." Josiah Thompson, Professor of Philosophy at Haverford College, wrote a book that devoted a good deal of space to this problem.[11] He concluded that immediately after the President was wounded in the head from behind, another bullet fired from in front of the car hit his head and drove it back, by momentum conservation, toward the rear of the car. District Attorney James Garrison of New Orleans made similar claims in the highly publicized trial of Clay Shaw, in 1969. The thrust of all these arguments is that if the President was shot from two directions, almost simultaneously, there must have been a conspiracy, in contradiction to the Warren Commission's basic conclusion that Oswald acted as an independent agent.

Paul Hoch often pressed me for an explanation of the odd behavior of the President's head, and although I hadn't observed it myself, I usually suggested that the head had probably been held erect by muscles controlled by the brain, and that when the controls were suddenly damaged, the head fell back. I was finally convinced that this explanation was incorrect after Paul Hoch handed me a copy of Thompson's book as I was leaving Berkeley for the February 1969 meeting of the American Physical Society in St. Louis. On the plane I had time to study the book carefully. It is beautifully printed, with excellent photographs and carefully prepared graphs. When I studied the graph showing the changing position of the President's head relative to the moving car's coordinate system, I was finally convinced that the assassination buffs were right; there had to be a real explanation of the fact that the President's head did *not fall* back, but was *driven* back by some real force.

And the answer turned out to be simpler than I had expected. I solved the problem (to my own satisfaction, and in a one-dimensional fashion) on the back of an envelope, as I sat in solitary splendor in the beautiful suite that the St. Louis hotel management supplied me in my capacity as president of the APS.

I concluded that the retrograde motion of the President's head, in response to the rifle bullet shot, is consistent with the law of conservation of momentum, if one pays attention to the law of conservation of energy as well, and includes the momentum of *all* the material in the problem. The simplest way to see where I differ from most of the critics is to note that they treat the problem as though it involved only two interacting masses: the bullet and the head. My analysis involves three interacting masses, the bullet, the jet of brain matter observable in frame 313, and the remaining part of the head. It will turn out that the jet can carry forward more momentum than was brought in by the bullet, and the head recoils backward, as a rocket recoils when its jet fuel is ejected. (Col. William H. Hanson came to the same conclusion, independently.[12])

If a block of wood is suspended by strings from the ceiling, it is called a ballistic pendulum, and physicists or gunsmiths can calculate the velocity of a bullet shot into it to be

$$v_B = v_W M_W / M_B, \quad (1)$$

where v_M is the velocity of the wooden block after it stops the bullet, and M_W and M_B are the masses of the wooden block and bullet. Equation (1) follows directly from the law of conservation of momentum:

$$v_B M_B = v_W M_W. \quad (2)$$

In using a ballistic pendulum, we normally forget that the collision of bullet and wooden block is very inelastic. Of the incoming kinetic energy of the bullet, only a small fraction f appears as kinetic energy of the moving wooden block; the remaining fraction $(1 - f)$ goes into heating the wood. If $M_B \ll M_W$,

$$\mathrm{KE}_W = f\,(\mathrm{KE}_B),$$
$$M_W v_W^2/2 = f \times M_B v_B^2/2. \quad (3)$$

From (3) and (2),

$$f = M_B/M_W. \quad (4)$$

For the case of a 10-g bullet, and a block weighing 10 kg, it can be seen that 99.9% of the incoming kinetic energy goes into heating the block, and only 0.1% appears as mechanical energy. Ballistic pendulums are designed so that they contain the inelastically dissipated energy. Unfortunately, the human head is not able to contain the major fraction of the energy carried in by the bullet. This tragic aspect of the assassination is clearly visible in frame 313 of the Zapruder film, and is discussed in detail in the reports of the autopsy surgeons.

The mechanism of the retrograde recoil turns out to be rather simple, if one remembers that 99.9% of the incoming energy must be accounted for. The momentum associated with a given amount of kinetic energy varies as the square root of the mass of the object carrying that kinetic energy:

$$p = (2MK)^{1/2}, \quad (5)$$

where p is the momentum, and K is the kinetic energy of the object with a mass M.

Figure 4 shows what happened when my friends and I fired bullets at melons that had been wrapped with Scotch glass filament tape, to mock up the tensile strength of the cranium. Under the influence of the bullet, some of the material making up the melon breaks through the reinforcement, and carries momentum in the forward direction. (Frame 313 of the Zapruder film shows this same phenomenon.) As we shall now see, the momentum carried forward in this way can be much larger than the momentum brought in by the bullet. For example, if the bullet weighed 0.1% of the melon weight, and if 10% of the incoming kinetic energy was used to propel 10% of the mass of the melon forward, then the momentum of the jet expelled forward would be $(10)^{1/2}$ times that of the incoming bullet. (I will use subscripts, b for bullet, j for forward moving jet, and m for melon.)

$$p_j = (2M_j K_j)^{1/2} = (2 \times 100 M_b \times 0.1 K_b)^{1/2}$$
$$= (10)^{1/2}\,(2M_b K_b)^{1/2} = (10)^{1/2} p_b. \quad (6)$$

since $M_j = 0.1 M_m = 100 M_b$, $K_j = 0.1 K_b$. The melon would then recoil backward with about twice the velocity it would have been expected to go forward, assuming it were made of wood. This is because the melon, acting at first as a ballistic pendulum, acquires a forward velocity equal to $v_m|_{BP}$

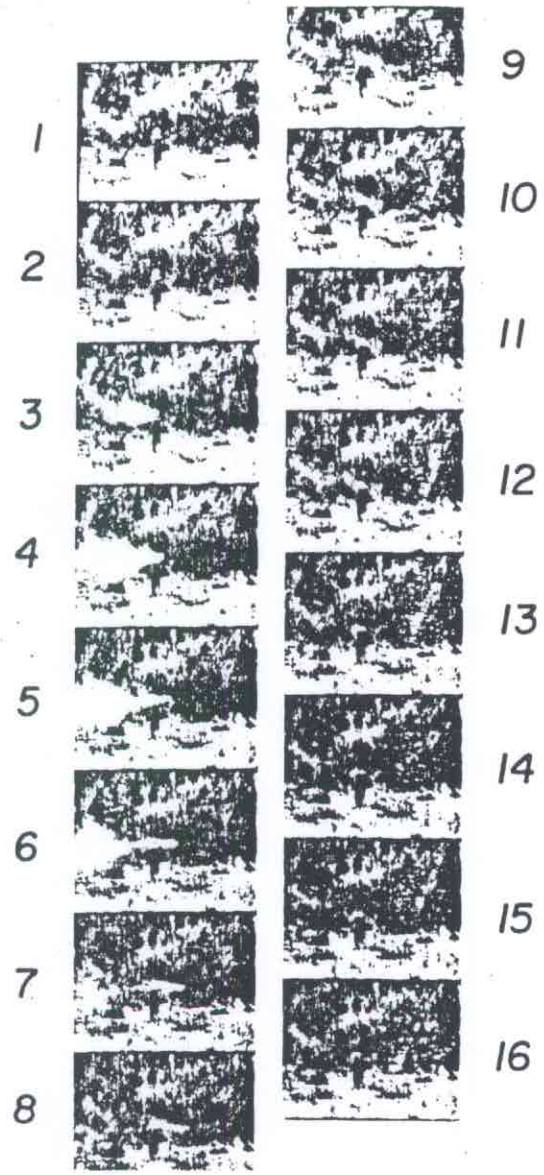

Fig. 4. Retrorecoil in a tape-reinforced melon hit by a high-velocity bullet. The bullet came from a rifle off the right-hand side of the frames. The forward jet (to the left) propelled the melon "backwards." (See text.)

$= p_b/M_m$. (The notation $v_m|_{BP}$ means the velocity one would expect the melon to have if it contained all the kinetic energy of the bullet, as a ballistic pendulum does.) But in the center of mass system of the melon, which is moving "forward" with the expected velocity, a jet moves forward with momentum equal to $(10)^{1/2} p_b$—as we have just seen. It gives the melon an equal and opposite momentum, in the moving (CM) system; in that system, $p_m = -(10)^{1/2} p_b$. If we neglect the 10% loss of mass by the melon to the jet, the recoil velocity of the melon (in the CM system) is

$-(10)^{1/2}$ times the "expected value." Since velocities add vectorally, the final velocity of the melon (in the laboratory system) is $[1-(10)^{1/2}]\,v_m|_{BP}$. Since the square root of 10 is close to 3.16, the observed velocity of the melon is about $-2v_m|_{BP}$.

If one wants to know more about the details of the transfer mechanism of kinetic energy from the bullet to kinetic energy of the fragments thrown forward, he will have to ask someone more knowledgeable in the theory of fluid mechanics than I am. My intuitive feeling is that the conical shape of the interaction zone is the key to the nonnegligible efficiency of energy transfer. (It is clear that an appreciable mechanical energy transfer is only possible if the incoming energy can avoid "being thermalized.") The conical region is defined by the small entrance hole and the much larger exit hole in the melon. Transmission lines with tapered internal conductors are efficient transformers of electrical energy, and a tapered bullwhip can smoothly transform the energy given to a large mass, by the flick of the wrist, into roughly the same energy of a much smaller mass at the tip of the whip. The "crack" of the whip occurs when the tip of the whip goes supersonic. I believe that in a somewhat analogous manner, but of course in the opposite direction, the kinetic energy of the bullet is given in a "tapered region" to a progressively larger mass in the melon, to achieve the modestly efficient energy transfer that is demonstrated in our experiments.

Now that I've given the theory of the "jet recoil mechanism," I'll describe the experiments that gave rise to Fig. 4. When I showed my simple calculations to Paul Hoch, he said that no one would believe my conclusions (including himself) unless we could demonstrate the retrograde recoil on a rifle range, using a reasonable facsimile of a human head as a target. I discussed my theory with my longtime friend and associate at the Laboratory, Sharon "Buck" Buckingham. Buck is an enthusiastic deer hunter, and he offered his services if I would buy the melons into which he would fire the shots.

Buck did his first experiments in June 1969 at the San Leandro Municipal firing range. Before he started shooting, all the expert marksmen in attendance told him that he was wasting his time—one said, "I've been around guns all my life, and you must be out of your mind to believe something you hit with a bullet will come back toward you." Most of the targets were melons that Buck had reinforced by wrapping with 1-in. Scotch "filament tape," as mentioned earlier.

The results of the first test shootings were encouraging in that most of the reinforced melons were driven by their shots toward the gun as I expected, rather than away from the gun "as the laws of physics require."

Paul Hoch expressed an interest in the results of this test, but said that he wouldn't ask his fellow buffs to believe them unless he had photographic evidence to document the case. Paul enlisted the help of Don Olson, another physics graduate student and assassination buff, who had a remotely controlled Super 8 movie camera, and I was present as an observer. We were all impressed to find that Buck's early results could be duplicated before the camera. The performances were now more uniform, with six out of seven reinforced melons clearly recoiling in a retrograde manner toward the gun. (According to Paul Hoch, the other one "just rolled around a bit.")

Figure 4 is an enlargement of a section of the film showing shot number 4. The frame rate is 24 per second. The gun, a 30.06 rifle, is about 30 m out of sight on the right-hand side of the photographs. Its 150 grain hand-loaded soft-nosed[13] bullet hit the melon with a velocity of about 3000 ft/sec; the 6.5 Mannlicher-Carcano rifle found near the sixth floor window of the Book Depository building fired a 160-grain bullet at about 2165 ft/sec. (I am told that at a distance of 265 ft, the measured slant range from the Book Depository window to the President in frame 313, the bullet would have slowed down to about 1800 ft/sec.)

To relate these experiments to the melancholy affair in Dallas, we can use Thompson's[11] carefully measured velocity of the backward motion of the President's head. He finds that it was about 1.6 ft/sec, averaged over eight frames. In Fig. 4, the measured retrograde velocity of the melon is 4.5 ft/sec. It is obvious that if the melon had been hit by a slower bullet, and had been connected to a large mass, simulating a torso, rather than being free of restraint, it would also have moved back more slowly. But in spite of what appears to me to be a good semiquantitative match in velocities, we must remember that the important question at issue here is not the *magnitude* of the velocity, but its *direction!*

I believe that our experimental demonstration of retrograde recoil in head-like objects will convince most people that the laws of physics do not require a second assassin to have been firing at the President from the "grassy knoll," ahead of the car. It is important to stress the fact that a taped melon was our *a priori* best mockup of a head, and it showed retrograde recoil in the first test. If we had used the "Edison technique" and shot at a large collection of objects, and finally found one which gave retrograde recoil, then our firing experiments could reasonably be criticized. But as the tests were actually conducted, I believe they show it is most probable that the shot in frame 313 came from behind the car; after all, the jets visible in frame 313 were what suggested this mechanism to me.

Many of the assassination buffs wrote to Hoch to say that neither my "back of the envelope" numbers nor the experimental results agreed with Professor Thompson's measured head velocities. So, in case any readers of this article may be similarly bothered, I should point out that the three numbers I used in my analysis (two mass ratios and an efficiency) were each assumed to have the value of 10^i, where i is a positive or negative integer. In spite of this highly quantized nature of the input data, the calculated and observed velocities differ by only a factor of 3. The assassination buffs who argued with Paul Hoch in a quantitative way (neglecting the important sign of the velocity) usually suggested that I was assuming that the mass of the jet (10%) was too high. But they missed the fact that, if either this assumed mass ratio or the assumed efficiency of energy transfer were *reduced* by a combined factor of almost 10, the calculated and observed velocities would be equal. In addition, frame 313 shows that the event wasn't one dimensional, as the model was; the two jets visible in frame 313 have vertical components that would lower the longitudinal component of momentum, bringing the theory closer to the actual event. I don't want to be that quantitative; the theory wasn't designed to calculate the velocities to high accuracies—but to show qualitatively that the head could jerk backwards.

I will end this section by saying what I think can be concluded from our experiments. It is possible to disprove

a theory, but never to prove one; no matter how often a theory has given correct predictions in the past, a single (repeatable) counterexample invalidates that particular theory. (Newton's theory of gravitation was disproved in this manner.) For these reasons, I believe that those arguments for a second assassin that derive from President Kennedy's head movements after frame 313 are now clearly invalid; a documented counterexample is now available to disprove the assertions of many writers concerning the consequences of Newton's laws of motion. I am convinced that everything that is known about the motion of the President's body in that short time interval is consistent with a shot from above and behind, where the sixth floor window of the Book Depository building was situated. But by the argument given earlier in this paragraph, I obviously can't prove that the bullet came from that window.

Dr. John K. Lattimer recently published an article[14] entitled "Observations Based on a Review of the Autopsy Photographs, X-rays and Related Materials of the Late President John F. Kennedy." Dr. Lattimer was apparently the first physician without governmental credentials to be given access to this material, which had been restricted for more than eight years, at the request of the President's family. Dr. Lattimer's article, published several years after the shooting experiments described above, says

> "These observations, made possible by actually seeing the autopsy photographs and the clothing, (and added to the previous laboratory and autopsy findings) have answered some of the questions that were in the mind of the author and have revealed no incompatibilities with the concept that two high-speed bullets hit the President, both fired downward and from the rear, as from the sixth floor of the Book Depository Building;—There were no signs of bullets or bullet wounds or bullet fragment tracks through the President's body running in any other location or direction, such as transversely, or from the front, to indicate bullet "hits" from any of these directions upon the President's head, body or limbs."

Several critics of the Warren report had predicted that when a "nonestablishment" expert on bullet wounds, such as Dr. Lattimer (with his "questions") was finally permitted to see the autopsy films, the "head shot from the front" would be confirmed. But Dr. Lattimer has ruled it out quite unequivocally.

Although Dr. Lattimer is now classified as a urologist, his biographical sketch[14] shows that he is an expert in the relevant fields:

> "In World War II, Dr. Lattimer was a military surgeon in the European Theater of Operations and had experience with military missle wounds of all types, almost always using X-rays for their localization. He served as a firearms range officer and also did experimental work on the wounding capabilities of various missiles on human tissues."

V. HOW FAST WAS THE CAMERA RUNNING?

Everyone who has watched football on TV knows that it is easy to distinguish a slow motion "instant replay" from the real thing, even when the play-back rate is not much slower than the normal rate. The clues come largely from our memorized knowledge of the oscillation frequency of the legs of runners moving at their fastest possible rates, and from our memory of the way objects fall in a "one g" gravitational environment.

But Mr. Zapruder's camera showed an automobile in which the occupants were for the most part sitting still, together with images of two motorcycle policemen who sat immobile on their seats all the while. The background comprised fixed structures, plus a few spectators who appeared to be standing still as the camera panned past them as it followed the President's car. So the clues we see in "instant replay football" on TV seem to be denied us in the Zapruder film.

If one accepted the FBI's subsequently measured frame rate of 18.3 per second for Mr. Zapruder's camera, the car was moving at a speed of approximately 12 mph. But an FBI report stated that, "The camera was set to take normal speed movie film or 24 frames/sec." Had the camera actually been operating at that rate, it would have been exceedingly difficult—if not impossible—to devise a sequence of Mannlicher-Carcano rifle shots that would have been within human capability, and therefore the multiple gunmen theories—so popular with many of the Warren Commission critics—could not have been ignored. (The higher the frame rate, the shorter is the time between any pair of numbered frames.) The Bell and Howell camera used by Mr. Zapruder had a "normal" button position, and a "slow motion" position, and I believe the intent of the FBI report was simply to answer the question, "Did Mr. Zapruder use normal or slow motion speed in taking his pictures?" Since the normal speed of 16- or 35-mm *sound* moving pictures is well known to be 24 frames/sec, I believe that the FBI was in turn saying, in effect, "He used normal speed." (I am now using my legally acceptable status as a "camera expert" to give an opinion outside the field of physics; I was for several years a salaried consultant to the Photoproducts Division of the Bell and Howell Company.) Actually the "slow motion frame rate" on the Zapruder camera was closer to 48 frames/sec.

I tried for some time to find a way to convince myself that the frame rate was 18.3 per second, and not the much higher "slow motion rate." But as I looked at the pictures again and again, I couldn't find a clue that could distinguish pictures of a car moving at 10 mph, together with some people who moved slowly, from pictures of a car moving at about 30 mph, with the same people still moving slowly, but not quite so slowly. I was about to give this problem up as hopeless when I noticed the action of a man standing beyond the car, as seen by the camera. He was clapping as the President drove by—a gesture that was common in the Kennedy era.

An elementary analysis of the muscle power involved in clapping shows that the power required, for a given maximum hand spacing, varies as the cube of the clapping frequency. The average velocity of the hands varies directly with the frequency, so the energy expended per cycle varies as the square of the frequency. Power is the time rate of expenditure of energy, so it involves an additional factor proportional to the frequency. It turns out that we can use the spectator's apparent clapping frequency, together with his observed and very natural maximum hand separation of about 1 ft, in the same way we use a running back's leg rate, to decide if we are watching live action, or slow motion "instant replay."

The spectator appears to move smoothly across the film from the right-hand edge, and about 1 (assumed) sec later (18 frames) disappears out of view beyond the left-hand edge. His apparent motion is of course due to Mr. Zapruder's panning action to follow the car. The clapping is shown in Frames 278 through 296 (Fig. 5), and even though the man's image is blurred because of the panning, it is evident that he has executed between 3½ and 4 full clapping cycles. I will assume that his apparent clapping frequency is 3.7 cycles/sec, and will ask how much greater this could be—due to a higher frame rate—and still be within reasonable human limits. The key to this particular analysis is the existence of the aforementioned cube law relating clapping frequency and muscle power. If a person doubles his clapping frequency, at constant amplitude, he must expend eight times as much power. The "steepness" of the cube law is what gives one the ability to distinguish film speeds by observations of clapping behavior, but only if normal clapping behavior is not too far from the "power barrier."

To answer this question, I clapped in synchronism with a metronome set at the assumed rate of 220 beats/min. I found I could clap quite comfortably at this rate of 3.7 per second, but I couldn't do so at twice the rate, with the same amplitude; to make 7.4 cycles/sec, which was an obviously unnaturally high rate, I had to reduce my amplitude considerably. I could just make it at 1.5 times 3.7 cycles/sec, but the effort felt quite unnatural. I am confident that anyone who repeats these experiments, as I have just done after a hiatus of several years, will be convinced that Mr. Zapruder's camera was running at very nearly 18 frames/sec. (It was certainly not running at 48 frames/sec, and I believe that 24 frames/sec can be ruled out, as well.) Although there is apparently no longer a serious controversy relative to frame rates, I wanted to share with my physicist readers the pleasure I had in discovering a "cube law clock" in the film.

VI. WHY DID THE PRESIDENT'S CAR SLOW DOWN ABRUPTLY JUST BEFORE THE FATAL SHOT?

The Commission was aided in its interpretation of the films by an FBI photoanalyst, Mr. Lyndal L. Shaneyfelt. My first disagreement with his testimony comes on p. 155 of Vol. V, where he was running the Zapruder film for Allen W. Dulles and John J. McCloy, members of the Commission. After the expert had made a comment relative to frame 222, the following conversation took place:

> *Mr. Dulles:* Jerky motion in Connally in the film.
>
> *Mr. Shaneyfelt:* There is—it may be merely where he stopped turning and started turning this way. It is hard to analyze.
>
> *Mr. Dulles:* What I wanted to get at—whether it was Connally who made the jerky motion or there was something in the film that was jerky. You can't tell.
>
> *Mr. Sheneyfelt:* You can't tell that.

Since Fig. 3 shows some "jerky motion" immediately after frame 222, it is a reasonable assumption that this is what had caught Mr. Dulles's attention. It was too bad that Mr. Dulles answered his own question concerning the possibility of distinguishing between the motion of a man in the car, and a movement of the film (camera) as a whole. Mr. Dulles was an experienced intelligence agent, and his practiced eye caught an important clue, but he too quickly dismissed it as undecipherable, which, of course, we now know it wasn't. The expert photoanalyst put the lid on the matter by his polite endorsement of Mr. Dulles's error.

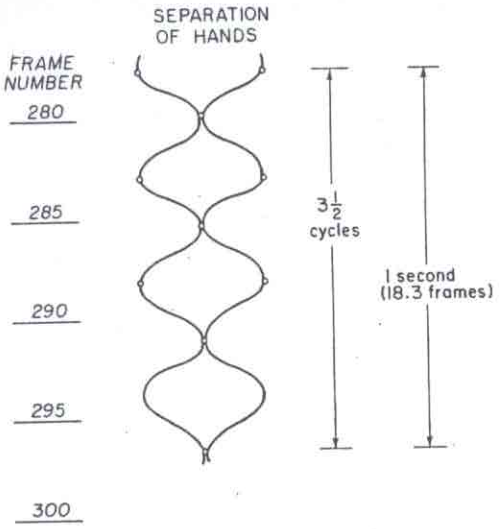

Fig. 5. Hand clapping at 3½ cycles/sec by a spectator allows film speed to be determined, within important limits. (See text.)

My second disagreement with this same FBI photoanalyst came when he testified concerning his inability to pinpoint the President's car, at frame 313, by examining the Zapruder film. He had this to say[15]:

> "Yes, I might state first that all of the other (reenactment) photographs were reestablished on the basis of the Zapruder film, using reference points in the background of the pictures.
>
> "As is apparent here from the photograph of the Zapruder frame 313, there are no reference points. There is just a grassy plot. So there is no reference point on which we can reestablish the position of the car in the roadway.
>
> "For this reason it was necessary to use the Nix film of the head shot and the Muchmore film of the head shot to establish this position in the road." [These films were shot from amateur movie cameras located on the opposite side of the street; one of them showed some identifiable background close to Mr. Zapruder's position, including Mr. Zapruder himself, instead of the plain grass that showed at that time in the Zapruder film.]

Mr. Shaneyfelt pinpointed the location of the car in 13 (or perhaps more) frames from 161 to 255, in which interval, there were architectural background features that were easily identifiable in the Zapruder frames. And as he said, the position of the car in frame 313 was determined from the two other films. These data were used in the FBI reenactment studies in Dealey Plaza. An open automobile, similar to the one in which the President rode, was moved in turn to the 14 (or more) positions as determined in the

films. At each position, it was photographed (1) by a still camera with the same angular field as Mr. Zapruder's movie camera, from his original location, and (2) from the sixth floor window of the Book Depository building, through the rifle scope of the rifle found at that location immediately after the assassination. For each of these 14 selected frames, the Exhibits[16] show photographs (1) and (2), together with the original Zapruder frames; in the case of frame 313, the corresponding frames from the Nix and Muchmore films are shown, together with still shots of the stationary car from the Nix and Muchmore locations.

In addition to the several pictures corresponding to each of the 14 locations, the exhibits also tabulate various measurements made at the 14 locations. These include the distance of the car from a benchmark on Elm Street ("station C"), the distance between the rear seat of the car and the sixth floor window of the Book Depository building, and the angle of depression of the rifle sight in that window. The distances are given to the nearest tenth of a foot; they are probably accurate to somewhat better than 1 ft.

As any physicist would do, I plotted the tabulated distance of the car (from "station C") against frame number for these 14 selected frames. This graph is shown in Fig. 6, and all the points except that for frame 313 lie on a line with a slope equal to 11.8 mph. It is clear from the dispersion of the (Zapruder) points from a straight line that the final point (determined from the Nix and Muchmore films) does not lie on the extrapolated line. Two explanations are possible; the position of the car at frame 313 was incorrectly determined, or the car slowed down somewhere between frames 255 and 313. Neither of these possibilities seemed reasonable to me when I first saw Fig. 6, so I set myself the task of finding out which explanation was correct. (I did this work, and the analysis of the clapping, during the Christmas vacation following the publication of the November 26, 1966 issue of *Life*.)

The first relevant observation I made was that contrary to what Mr. Shaneyfelt said in his testimony, it was a trivial exercise to determine precisely where the car was at *each* of the 79 frames from where his "Zapruder data" stopped (at frame 255) to the final published frame, number 344. What he apparently failed to realize was that the approximately ten persons who were standing on the featureless background were "reference points" exactly as useful as if they were set in concrete. Their usefulness comes from two independent considerations. There is a linear relationship between any horizontal interval on the original film (or on the half-tone reproductions in the Exhibits) and the corresponding angular interval subtended at Mr. Zapruder's camera. In other words, every time the camera panned through an angle θ, a fixed object in the field of view moved to the left in the picture, a distance of $k\theta$. The value of the constant k (the focal length of the camera lens) could be determined with the aid of an accurate plan of Dealey Plaza, showing Mr. Zapruder's station. (The camera had a zoom lens of variable focal length, which I found had been used at very nearly its longest value.) From such a plan, one can measure the angles subtended by many architectural features, visible in the frames. Those angles, which can be measured with a high degree of precision, can be divided by the accurately measureable corresponding intervals on the film (or on the halftone reproduction) to give the corresponding value of k^{-1}. From then on, we can immediately tell through what angle the camera is being panned, frame

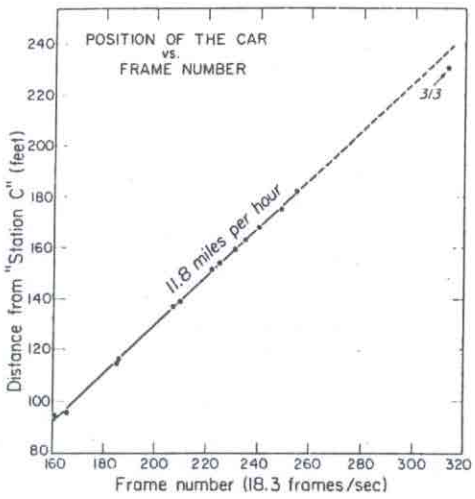

Fig. 6. Position of the President's car as determined by the FBI. Note that point 313 does not lie on extrapolated line.

by frame, by simply measuring the displacement of *any* stationary object in the field of view. That stationary object can be a concrete pole, or equally usefully, a person's foot that is temporarily bearing his weight, and is therefore fixed to the ground.

Since I didn't have an accurate enough plan of Dealey Plaza, I couldn't evaluate k with an absolute uncertainty as small as the relative uncertainty with which measurements could be made on the halftone reproductions. (The FBI could have done that with the theodolite they used in the reenactment session.) But that minor lack of absolute precision will have no effect on the very accurate measurements of the relative speed of the car before and after the strange and previously unseen deceleration I am about to describe. But before describing that event, I should mention that in one sequence, when no spectators are in the background, another interesting reference mark is available on the plain grass behind the car, in frames 313-334, the last ones reproduced in the exhibits. This mark is a white streak, whose position can be seen to move progressively across the film gate, in that sequence of 22 frames. It is clear that the white streak is really the image of a small shiny object that is reflecting sunlight into the camera lens. In this sense, it corresponds directly to one of the highlights on the car; it is "streaked" in every frame because the camera axis is moving relative to it in all frames.

Figure 7 shows the angular position of the car as a function of frame number, from frame 260 to the end of the sequence—a 4-sec interval of time in which the President was fatally wounded. This figure could have been drawn as an extension of the Commission-derived Fig. 6, which ends at frame 255, but I wanted the scale enlarged because the new individual points are now more precisely known. And all of this is in a region where the background

> ". . . is just a grassy plot. So there is no reference point on which we can reestablish the position of the car in the roadway."[15][!]

The extreme smoothness of the curve comes from the fact

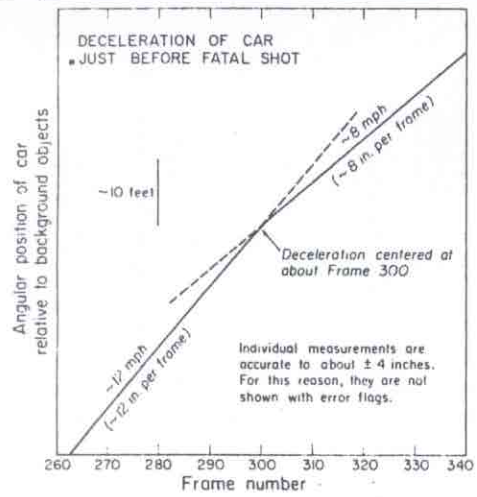

Fig. 7. Position of the President's car as determined in this paper. (See text.) Note the sudden deceleration of the car about one second before the President was fatally wounded (in frame 313). Error flags not shown; the 75 separate points have errors comparable to the width of the two straight lines.

that the smearing due to the camera accelerations (see in Fig. 3) cancels out; the measurements are made from a highlight on the car, to one of the reference points on the (featureless) "grassy plot" that I've just discussed. Any "jiggle" of the camera axis moves both of these reference points (on the car and on the ground) by the same distance on the film, leaving the distance between the two images on the film unchanged. These distances are plotted against frame number in Fig. 7, and I estimate that each point has a relative uncertainty of about 4 in. "in real space." The car had an average velocity of about 12 mph or about 12 in./frame interval. I would normally show all the measured points on a curve such as this, but the scatter of the 75 points about the "best fit" two line segments is less than the width of the lines.

The car was moving almost exactly at 90° to the camera axis for these few seconds; one can easily check this by noting that the image of the horizontal strip separating the front and back compartments of the open car appears as a vertical stripe in one of these frames from Mr. Zapruder's downward-looking camera. For this reason we can translate relative positions of a car highlight and the background object on a frame-by-frame basis directly into the velocity of the car, simply by measuring the slope of the graph in Fig. 7.

The heavy car decelerated suddenly for about 0.5 sec (10 frames), centered at about frame 299, reducing its speed from about 12 mph to about 8 mph. Since the car was certainly being operated in some low gear ratio, the deceleration was no doubt caused by the driver reducing his foot pressure on the accelerator pedal. The question is then, "Why did the driver suddenly slow down at a time when a more natural reaction would be to speed up and weave to left and right, to avoid being hit again." I worried about this for some time, without finding any satisfactory answer. But then I found some testimony concerning a police siren that was remembered to have come just after the President was killed (in frame 313). The many inconsistencies in the various witnesses' remembrances of exact times in this critical period made me feel that it was permissible to suggest that the siren, from an escorting police vehicle behind the President's car, had come a few seconds *before* the fatal shot. It would be most probable that an escorting officer, having heard one shot, and seeing the President wounded by a second shot, would hit the siren button when I'm suggesting he did. If the siren sound became apparent to Mr. Zapruder at frame 285, we would expect him to respond at frame 290, where we see the "unexplained and relatively weak angular accelerations" starting. We don't know the reaction time of the driver, but if it was 0.5 sec (9 frames), then he would lift his foot from the accelerator at frame 294, as Fig. 7 shows he did. Everyone will recognize that such a reaction on the part of the driver would be an unavoidable conditioned reflex; we all learn that when we hear a siren suddenly turned on, just behind our car, we lift our foot from the accelerator pedal. I haven't been able to think of any other reason why the driver of a car that has just stopped one or two high velocity rifle bullets would suddenly *slow down* his rate of travel.

The driver of the car, Agent William R. Greer, recalls that he speeded up the car in this period[17]:

> *Mr. Arlen Specter:* Do you recollect whether you accelerated before or at the same time or after the third shot?
>
> *Mr. Greer:* I couldn't really say. Just as soon as I turned my head back from the second shot, right away, I accelerated right then. It was a matter of my reflexes to the accelerator.
>
> *Mr. Specter:* Was it at about that time that you heard the third shot?
>
> *Mr. Greer:* Yes, sir; just as soon as I turned my head.
>
> *Mr. Specter:* What is your best estimate of the speed of the car at the time of the first, second, or third shots?
>
> *Mr. Greer:* I would estimate my speed was between 12 and 15 mph.
>
> *Mr. Specter:* At the time all of the shots occurred?
>
> *Mr. Greer:* At the time the shots occurred.

But since Fig. 7 shows that the car was still moving at the slower rate through the last of the published Zapruder frame number 334 it is apparent that Mr. Greer's memory doesn't jibe with the recorded facts. This is what Professor Buckhout pointed out in his article on the reliability of eyewitness testimony[5]; all past events aren't recorded in a person's memory as on a magnetic tape, to be recalled later. That is why I find the photographic record so interesting; it doesn't have the normal human failings.

Certainly, the car eventually speeded up, and this is doubtless what Agent Greer recalled. In view of the disparity of several seconds between what the agent remembered of this terrible event and what actually happened, the reader may come to accept my conclusion that memories of the siren were similarly off by a few seconds. That's all it takes to turn the otherwise fantastically absurd deceler-

why does he reverse direction?

ation of the car into a reasonable conditioned reflex on the part of the driver to the sound of a siren going off in his ear, and to shake up Mr. Zapruder at the same time. But as I said in the introduction, I can't prove that this is the way it happened.

As stated earlier, the streaks in the "grassy plot" were doubtless made by a small object reflecting light from the sun into the lens of Mr. Zapruder's camera. Figure 8 shows how this streak moved across the film gate in the camera (frames 313–334). This particular interval of just more than 1 sec coincides exactly with the climax of the events in Dealey Plaza. The President has just been fatally shot as the streak appears in the background, labeled 313. In the following second, Mr. Zapruder experiences great difficulty in continuing his earlier smooth tracking. He sees clearly in his view finder what has happened to his President, and it is a traumatic experience for him:

> *Mr. Zapruder:* . . . I heard a second shot and then I saw his head opened up and the blood and everything came out and I started—I can hardly talk about it. [The witness crying.][18]

But to return to the streaks in Fig. 8, let us first realize what that figure would have looked like if the shots had not been fired. Mr. Zapruder's tracking ability has been checked during the quiet periods of Fig. 3; a given highlight on the car, in those periods, stays pointlike, and at a fixed location in the film gate. Under such circumstances, a point of light in the background, such as that shown in Fig. 8, would move across the film gate on a straight line, at constant velocity. But because the camera shutter closes between exposures, while the film is being "pulled down," the straight line just mentioned would appear as a "dashed line" drawn by a draftsman using a straightedge.

Contrast the evenly spaced dashes on a straight line that Zapruder was capable of "drawing," with the dashes of Fig. 8 which appear to have been drawn by a spastic; that might even be the correct word to describe Mr. Zapruder's condition in that ghastly second after frame 313. (Until I realized that the labels on frames 314 and 315 had been interchanged in the exhibits, I thought Mr. Zapruder had lost even more control of his muscles than he actually had.)

Starting at frame 331, we see the streaks move up to the right and then back quite rapidly to the left. This phenomenon might be related to the "crescent"-like streaks seen in the CBS tests.[8] In Fig. 3, I couldn't plot this two-dimensional excursion of the camera axis, but one can see from that figure, at frame 332, that something pretty violent is happening. If I'd had access to the enlarged color prints that Governor Connally is shown viewing in *Life*, it would have been worthwhile plotting tracking curves like Fig. 8, for the whole sequence of frames. My reason for saying this is that such a curve complements an acceleration graph, such as Fig. 3. Ideally, the two should yield the same information, but in practice, the tracking curve shows more. This can be seen by comparing Fig. 8 with Fig. 3, in the vicinity of frame 325. From Mr. Zapruder's measured oscillation time of five frames, I expected to see an acceleration peak in Fig. 3, near this frame. But I've already mentioned the fact that of all the expected ones, a third of a second apart, only this peak was missing. However, a glance at Fig. 8 shows that there was quite a space in Mr. Zapruder's relatively smooth tracking curves at this point. This

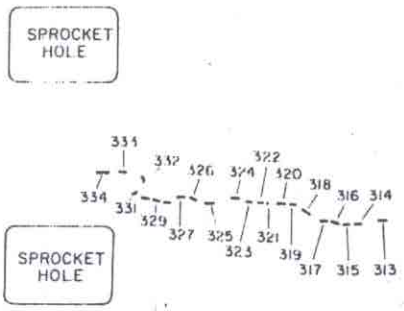

Fig. 8. "Streak" in the grass. The motion of Mr. Zapruder's camera axis is shown in two dimensions during the 1.2-sec period immediately following the fatal shot. (See text.)

example illustrates the fact that tracking curves are more sensitive than the angular acceleration graphs that derive from subtracted streak lengths.

I'll close this section by recalling that the wealth of data shown in Fig. 8, encompassing the climactic second in Dealey Plaza, involves a time period when an FBI photointerpreter told the members of the Warren Commission that from those pictures alone, there was no way to tell where the car was. I hope that this section will demonstrate what I've long felt that the testimony of a physicist could have been of help to the Warren Commission, as it searched for the truth in early 1964.

ACKNOWLEDGMENTS

As I've indicated in the body of this paper, I've had help from several friends in the shooting experiments, particularly "Buck" Buckingham and Don Olson. Paul Hoch was for a long time my most knowledgeable and severest critic. In the absence of his always friendly but persistent criticism, this report of my study of the Zapruder film would have been much less convincing that I now hope it is. His vast store of knowledge concerning all aspects of the assassination was of great help to me, in my position of having read almost nothing of the literature critical of the Warren Commission's Report. His help in such matters is clearly evident in the text, where I acknowledge the work of others who anticipated conclusions that I reached later, but independently. Paul made many suggestions for improvements in a 1970 draft of this report, almost every one of which I incorporated. I don't believe we've discussed the assassination more than once or twice since then, and I haven't talked to Paul since I started the final rewriting a few months ago. He is now writing a book on the assassination, and we are agreed that although we each learn from the other, when final versions are being written, only one person can be responsible. And finally, I would like to acknowledge a great deal of constructive editorial criticism and help from Richard A. Muller.

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[1]*Hearings Before the President's Commission on the Assassination of President Kennedy* (U.S. GPO, Washington, DC, 1964).
[2]M. Lane, *Rush to Judgement* (Holt, Rinehart and Winston, New York, 1966), p. 55.
[3]Esquire, 205 (December 1966).
[4]S. White, *Shall We Now Believe the Warren Report?* (Macmillan, New York, 1968).
[5]R. Buckhout, Sci. Am. **231**, 23 (December 1974).
[6]Reference 1, Vol. XVIII, pp. 1–80.
[7]I. Weisberg, *Whitewash* (Weisberg, Hyattsville, MD, 1966; reissued by Dell, New York, 1966).
[8]Reference 4, p. 228.
[9]Reference 1, Report, p. 98.
[10]Reference 4, p. 82.
[11]J. Thompson, *Six Seconds in Dallas* (Geis, 1967).
[12]W. H. Hanson, *The Shooting of John F. Kennedy: One Assassin; Three Hits, No Misses* (Naylor, San Antonio, 1969).
[13]The fact that the bullets were soft nosed, rather than fully jacketed (as the Mannlicher–Carcano bullets were), was apparently important in intensifying the explosive jet effect. Dr. John K. Lattimer tells me that when he repeated our melon experiments with a duplicate of Oswald's weapon and jacketed cartridges, the effect was not as vigorous nor as dependable, even though it did occur about half the time. When he repeated it on skull models, however, the effect was still *more* violent than ours, even with the jacketed bullets.
[14]Dr. J. K. Lattimer, Resident and Staff Physician, 34 (May 1972).
[15]Reference 1, Vol. V, p. 159.
[16]Reference 1, Vol. XVIII, pp. 86–313.
[17]Reference 1, Vol. II, p. 119.
[18]Reference 1, Vol. VII, p. 571.