

Computational ballistic analysis of the cranial shot to John F. Kennedy

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Abstract

Almost 60 years after the assassination of John F. Kennedy in 1963 the majority of Americans are still reluctant to believe the official reports of commissions from 1964 and again in 1976 that determined the direction of the shot resulting in the fatal head injury. Long-withheld, confidential government files released in 2017 reignited the controversy.

The present investigation computationally simulated projectile-skull impacts from the direction specified in official reports and from three other directions. Detailed geometric models of the human head and ammunition, as well as known parameters from the assassination site served as the supportive base for analysis. Constitutive mathematical models for the impact of projectile material with skull tissues at supersonic speed were employed to analyze bone and bullet fragmentation mechanics.

Simulated fracture characteristics of the bone and the bullet were compared with photographic and X-ray evidence. The most likely origin of the fatal shot was determined based on the degree of corresponding deformation and fragmentation between simulation and documented evidence. Computational corroboration could be established as physically consistent with high-speed impact from the rear, as established by the official commissions. Simulations of three other speculative shot origins did not correspond to the documented evidence.

Keywords: Cranial gunshot, bone and bullet fracture mechanics, finite element simulation

1 Introduction

The President's Commission on the Assassination of President Kennedy, unofficially the *Warren Commission*, released its final report in 1964 and attributed the assassination of President John F. Kennedy (JFK) to three shots fired from a single marksman behind the presidential limousine with two bullets striking the president from the rear. While the first shot missed, the second shot caused a neck wound to Kennedy. The third and fatal shot hit Kennedy in the head [1].

Controversy concerning the commission report arose due to a physician in the overall disarray describing the neck wound from the second shot as a bullet entrance from the front throat [2-5]. Considerable doubt regarding the shot direction was further raised by the testimony of over 40 eye witnesses, including treating doctors, who unanimously reported a large wound in the right back of Kennedy's head [5-9], contradicting the official version of a large wound in the temple region of the right frontal bone [6]. Further contradiction was added by the film from a civilian bystander [10], known as the *Zapruder Film*, showing the president's head snapping violently backward upon impact with the third shot. Intuitive interpretation of this backward movement led to a lay verdict that the projectile must have come from the front.

Due to diminishing public trust in the 1964 report and to resolve controversy, the United States House of Representatives Select Committee on Assassinations (HSCA) was convened as a second official panel in 1976. The HSCA confirmed the main findings of the Warren Commission and concluded that JFK was hit by two shots from behind him. However, it was also concluded that with "high probability" at least two gunmen were involved [11]. Intense controversy thus remained and conspiracy theories still linger, many of them involving other or multiple possible shot directions as considered likely by the HSCA report [12]. In opposition to both official commissions that located the 6th floor of the Texas School Book Depository building to the rear of President Kennedy as the origin of the fatal shot, various conspiracy theories claim different sites as shooter locations [6,7,13-17]. The disagreement about the exact circumstances of the assassination, including possible shot directions, is reflected to date in over 40,000 published books and articles [18].

The present investigation compares the official findings related to the fatal shot origin to conspiracy related hypotheses by using state-of-the-art numerical software simulating the complex scenario of high-dynamic three-dimensional nonlinear bullet-skull penetration. Various shot origins were simulated using detailed models of the head and the bullet and these were compared with photographic and forensic evidence, particularly the documented

sharp skull bone defect in Kennedy's right temple and the deformed and fragmented bullet jacket. Also, the mechanical cause of the non-intuitive violent post-impact retrograde head snap is elucidated.

2 Methods

2.1 Potential shot origins

At time of the fatal shot John F. Kennedy was situated in the presidential limousine on Elm Street in Dallas, Texas, cf. Fig.1 position (L). While the official report states that the Texas School Book Depository (TSBD) behind the presidential limousine was the origin of the fatal shot, conspiracy related hypotheses propose the following other locations as possible shot origins [6,7,13-17]: 1. the Grassy Knoll (GK), an elevated site to the right of the limousine, 2. the South Knoll (SK) to the front/slight left and 3. a storm drain (SD) to the slight right front of the limousine. The SK-site included three potential shooter locations, Fig1. labels (1), (2), (3). Traces from these locations to the current position of Kennedy's

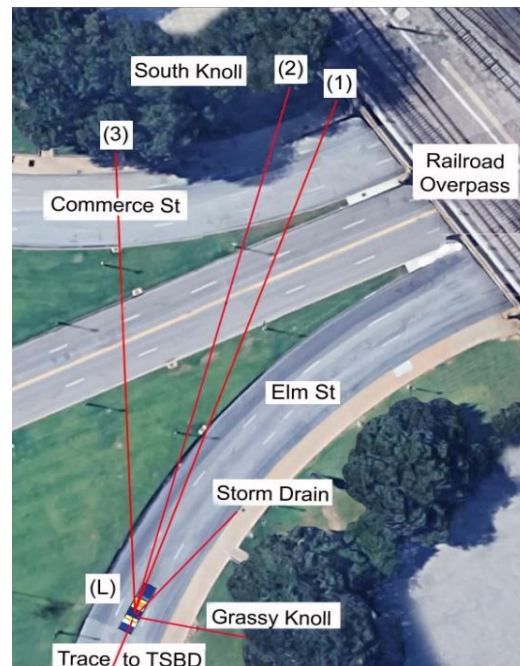


Fig.1 True to scale top view photo with superimposed limousine model (L) and potential shot directions/traces to various sites at time of the fatal shot (Credit: 2021 Google Inc.)

head are depicted to scale in Fig.1 and, also to scale but enlarged in Fig.2. Geometric details of Fig.1 and Fig.2 including traces from the potential shot origins were generated using schematic scale drawings together with a true to scale top view picture of the assassination site [12,19,20]. Data of the presidential limousine was based on a commercially available digital model as well as scale drawings [5,12].

All drawings were digitalized employing CreoParametric (PTC, MA, USA). Digitalized data was assembled in one model using HyperWorks software package (Altair, MI, USA). Trace lengths and declinations were deduced from the assembled model. They are listed in section 2.2.

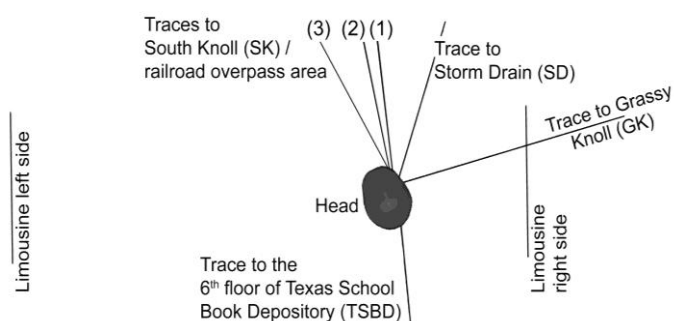


Fig.2 True to scale schematic: Kennedy's head position relative to potential shot directions at time of the fatal shot

Shot traces were also used to spatially orient the bullet model relative to the head model in the simulation.

2.2 Initial conditions prior to bullet impact

The Carcano projectile, officially identified as the assassination ammunition [5,12], was determined to have an average muzzle velocity of 670 m/s with a clockwise twist rate of 1 x 21.5 cm [21]. The velocity is 638 m/s after travelling 24 m, which was the distance between JFK's head and the location of the SD, 633 m/s at a distance of 30 m from the fence on the GK, and approximately 590 m/s at a distance of 82 m from the 6th floor window of the TSBD, and an average 574 m/s for a distance of 80 - 90 m for the SK-area [5,19,21,22]. The trajectory declination angles were approximately 0.2°- 5°, 5°, 8°, and 15° from the SK, GK, SD, and TSBD, respectively, to the position of Kennedy's head. The ground distance to the 6th floor of the TSBD was assumed 18.5 m, the approximate vertical distance from the GK fence to street level 2.5 m, 0 m from the SD and 4 - 5 m from the SK area. These distances and angles determine spatial bullet position and orientation to the head.

Approximate spatial orientation of the head relative to the limousine was based on Frame #312 of the *Zapruder Film*, [Figs.3a](#), depicting the scene immediately prior to the fatal head shot. Based on [Fig.3b](#) - a blow-up of [Fig.3a](#) - Kennedy's head and the head model used for simulation were digitally superimposed, aligned and orientated.



Fig.3a Frame #312: Limousine passengers immediately prior to the fatal head shot: fond right: JFK



Fig.3b Blow-up detail: superposition and image alignment with the head model (white)

Credit: *Zapruder Film* (Renewed 1995) The Sixth Floor Museum at Dealey Plaza

Positioning of the bullet and head model with respect to a shot from the TSBD was based on the digitalized trajectory as well as on information from the Clark and HSCA forensic panel report stating that the wound on the back of JFK's head was located about 100 mm above the external occipital protuberance, and between 18 - 25 mm to the right of the head midline [12,23]. Bullet positioning for the other potential shot origins - SK, SD and GK - was based on trace/trajectory geometries as previously delineated.

2.3 Projectile geometry and mass distribution

To obtain CAD data of the Carcano projectile (6.5×52 mm "Parravicini-Carcano"), scale drawings [24] were digitalized. In addition, bullets samples were milled to obtain section cut samples, Fig.4a. Using a 3D-digital microscope bullet dimensions were verified: jacket outer length and diameter at the bearing surface were 30.4 ± 0.2 mm and $\varnothing = 6.6\pm 0.2$ mm, respectively.



Fig.4a Parravicini-Carcano bullet: mid plane section cut of jacket and lead core



Fig.4b Bullet nose detail: lead core with copper-alloy jacket

Jacket thickness varied over the length: 0.42 ± 0.2 mm (bearing surface) to 0.85 ± 0.2 mm (nose), Fig.4b. After digital model generation, the mean volumes of the jacket and core were found to be 260 mm^3 and 714 mm^3 , respectively, and the bullet's mass was 10.4 g, in accordance with official specifications [5]. Digital volumes together with the densities listed in Tables 3,4 yielded a lead core mass of 8.1 g and a jacket mass of 2.3 g.

Contact surfaces of jacket and core are loosely connected. The jacket is open at the base, Fig.4a-bottom. Mechanically, this design is described as a "single cell, one-end closed tube structure with closed thin wall section". This is important to comprehend bullet stability and deformation behavior.

2.4 Skull geometry

Precise data specifically pertaining to Kennedy's head anatomy do not exist. Thus, a human skull exhibit, as well as a plastinated brain, were scanned using computed tomography (CT) to acquire digitalized anatomical data. Scan images were reconstructed using MIMICS software (Materialise, Leuven, Belgium) providing digital data used for finite element (FE) head modeling including cortical and cancellous bone, cerebrospinal fluid (CSF) volume, brain and skin tissue. Thickness of the parietal/ occipital bone was estimated from Kennedy's autopsy X-ray photographs together with his head circumference, i.e. 61 cm [12,25]. The FE model was scaled accordingly to fit these values.

3 Constitutive modeling and FE representation

The peak strain rate corresponding to a typical defense-related ballistic impacts is in the order of 10^5 - 10^6 s^{-1} . Material data in that range is sparse. Bullet, scalp skin, bone, and brain tissue material properties thus were deduced based on the literature.

3.1 Projectile model

Substantial controversy surrounds the bullet's alloy composition [12,26,27]. In this report it was assumed that the bullet jacket consisted of 90% copper and 10% zinc, and the soft core consisted of common lead [12].

To realistically simulate bullet fragmentation behavior, adequate material modeling is essential. Jacket material was modeled using a modified version of the Johnson-Cook constitutive relation [28]. This model expresses the equivalent flow stress σ_y , Eq.(1), considering the effects of rate-independent strain hardening represented by a power law together with strain-rate dependence and thermal softening:

$$\sigma_y = (A + B\varepsilon_p^n)(1 + \bar{\varepsilon}_p)^C (1 - \bar{T}^m) \quad (1)$$

with A , B , C , m , and n being experimentally determined constants, ε_p is the effective plastic strain, $\bar{\varepsilon}_p$ is a dimensionless effective strain rate with $\bar{\varepsilon}_p = \dot{\varepsilon}_p/\dot{\varepsilon}_0$ where $\dot{\varepsilon}_0$ is the reference strain rate used in underlying material tests. $\bar{T} = (T - T_0)/(T_M - T_0)$ with T_0 being the initial temperature of the material during testing. T_M is the material's melting temperature, T the current temperature. In the model, two material failure criteria combined with the FE erosion method were used: the Cockcroft-Latham criteria [29] as well as a temperature limit, assuming a strength limit at 90% of the material's melting temperature.

Lead core material behavior was represented by the Steinberg-Lund constitutive model [30] where the shear modulus G and the yield strength σ_y are given by

$$G = G_0 \left[1 + G'_p/G_0 pV^{\frac{1}{3}} + G'_T/G_0 \left(\frac{E_i - E_c}{R'} - 300 \right) \right] e^{-\frac{fE_i}{E_m - E_i}}, \quad (2)$$

$$\sigma_y = \sigma_0 [1 + \beta(\gamma_i + \bar{\varepsilon}_p)]^n \left[1 + b'pV^{\frac{1}{3}} + G'_T/G_0 \left(\frac{E_i - E_c}{R'} - 300 \right) \right] e^{-\frac{fE_i}{E_m - E_i}}. \quad (3)$$

The volumetric pressure response was represented by the Mie-Gruneisen EOS,

$$p = \frac{c^2 \rho_0 \mu [1 + (1 - \gamma_0/2)\mu - b/2\mu^2]}{[1 - (S_1 - 1)\mu - S_2\mu^2 / (\mu + 1) - S_3\mu^3 / (\mu + 1)^2]} + (\gamma_0 + b\mu)E. \quad (4)$$

In Eqs.(2,3) G'_p/G_0 and G'_T/G_0 represent pressure and temperature dependence on the shear modulus and are, together with the initial shear modulus G_0 and f , experimentally determined

constants. σ_0 is the initial yield stress, $b' = \sigma'_p/\sigma_0 \approx G'_p/G_0$ where σ'_p is the partial differential of σ_y with respect to pressure. $V = v_0/v$ is the relative volume with v_0 and v being the initial and the specific volume, respectively; p is the pressure and β and n are work-hardening parameters. E_i , E_m and E_c are the internal, melting, and cold compression energy per unit volume, respectively. R' is defined as $R' = R\rho/A$ with R being the gas constant and A the atomic weight, γ_i and $\bar{\epsilon}_p$ are the initial and equivalent plastic strain, respectively. In Eq.(4), E is the internal energy, γ_0 is the Gruneisen coefficient with b the volume correction to γ_0 . C is the bulk sound speed. S_1 , S_2 , S_3 are the Hugoniot slope coefficients and $\mu = \rho/\rho_0 - 1$ is the compression coefficient.

Employed material parameters were adopted from the literature [31-35] and listed in Tables 1-5.

Table 1. Bullet jacket material constants for Johnson-Cook model (A , B and W_{cr} in MPa; T , T_m in K; $\dot{\epsilon}_0$ in s^{-1})

Material	A	B	n	$\dot{\epsilon}_0$	C	T	T_m	m	W_c	D_c	β
90/10 Brass	206	505	0.42	5.0E-04	0.01	293	1189	1.68	914	1.0	0.0

Table 2. Bullet lead core material constants for the Steinberg model

Material	$b' \approx G'_p/G_0$ [mm ² /N]	G'_T/G_0 [K ⁻¹]	R' [NK ⁻¹ mm ²]	β	n	γ_0	f	a
Lead	11.63E-05	1.16E-03	0.455	110	0.52	2.74	0	2.2

Table 3. Bullet jacket material properties

Material	ρ [t/mm ³]	E [MPa]	ν	C_p [J/tK]	α [K ⁻¹]
90/10 Brass	8.95E-09	123.0E03	0.3	418.0E06	1.9E-05

Table 4. Bullet lead core material properties

Material	ρ [t/mm ³]	G_0 [MPa]	σ_0 [MPa]	σ_{max} [MPa]	T_{m0} [K]	A [t/mol]
Lead	11.34E-09	8600	8	100	760	207.2E-06

Table 5. Mie-Gruneisen EOS parameters for lead material

Material	C_0 [mm/s]	S_1 [-]	S_2 [-]	S_3 [-]	γ_0 [-]	b [-]
Lead	2.0E-06	1.429	0.8506	-1.64	2.74	0.54

During high-speed impact severe deformation/fragmentation of the bullet may occur. To avoid drawbacks of standard Lagrangian elements under extreme distortion, bullets, Figs.5a,b, were modeled using smoothed-particle hydrodynamics (SPH) elements with a renormalized

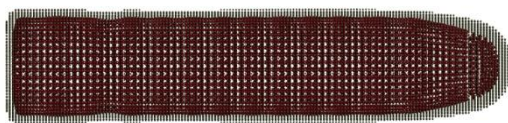


Fig.5a Bullet model: SPH elements used for jacket and core representation (section cut view)

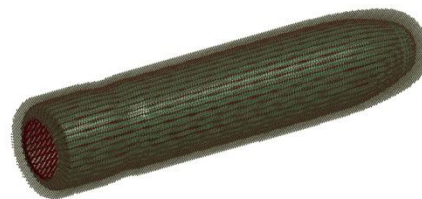


Fig.5b Bullet model: uncut (perspective view)

Lagrangian formulation, to account for excessive deformation during bone/brain contact. Since bullet jacket and core materials are only loosely connected, a penalty-based contact was defined between both constituents.

3.2 Head model

Based on digitalized CT-scan data the head model includes: scalp skin, cortical bone, cancellous bone, CSF, and brain, [Figs.6a-c](#).

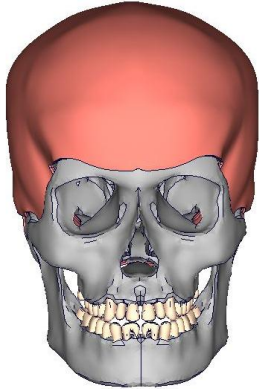


Fig.6a FE head model

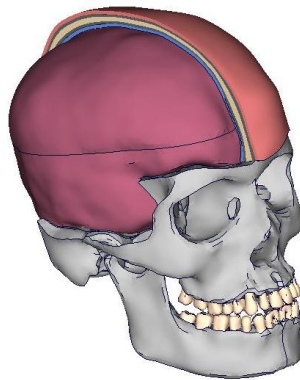


Fig.6b Section cut view: scalp skin, cranial bone, CSF, brain (from exterior to interior)

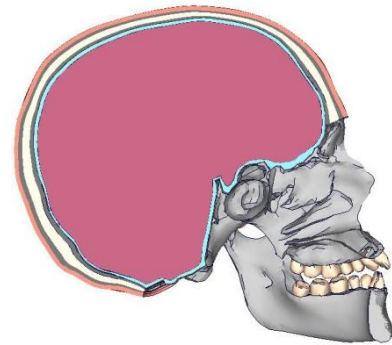


Fig.6c Side section cut view

Scalp skin

Scalp skin was included since, in general, skin stiffens significantly at increasing loading rates [36,37]. Experimental human skin data collected under tension at a strain rate of 167 s^{-1} was used for tissue representation [37]. The isotropic Ogden form was employed to define tissue behavior [38,39], skin anisotropy was neglected. An algorithm based on the simplex strategy was used to optimize model parameters constraining Poisson's ratio to $\nu = 0.497$. Employed values are shown in [Table 6](#). Effective failure strain was estimated at 0.25, based on strain at peak stress [37]. Scalp skin tissue was modeled using thick shell elements with two elements over the thickness. Skin thickness was assumed to average 6.5 mm [40,41].

Table 6. Parameters for scalp skin tissue

μ_1 [MPa]	μ_2 [MPa]	α_1 [-]	α_2 [-]
0.30279	0.12096	21.26804	0.40587

Skull bone

Data used in this report for human cortical and cancellous bone were adopted [42-56]. In contrast to dry bone, wet bone can pass through a plastic phase [57]. Thus, a rate-dependent elasto-plastic material model with plastic strain to failure criteria was used, based on both tension and compression yield stress versus effective plastic strain. Failure strain was estimated based on findings for cranial cortical bone and for femoral cortical bone [45,56]. A factor of 1.4 between the response in mechanical strength to tension and compression of

cancellous bone was deduced [58,59] as well as for cortical bone [60,61]. Employed bone material data is shown in Table 7, including Young's modulus for tension/ compression, E_t/E_c , Poisson's ratio ν , yield stress during tension/compression $\sigma_{y,t}/\sigma_{y,c}$, and plastic failure strain during tension/compression, $\epsilon_{p,t}^f/\epsilon_{p,c}^f$ (assumed equal).

Table 7. Employed wet bone material constants for $\dot{\epsilon} = 10^5 - 10^6 \text{ s}^{-1}$ (σ in MPa)

Material	ρ [t/mm ³]	E_t [MPa]	E_c [MPa]	ν	$\sigma_{y,t}$	$\sigma_{y,c}$	$\epsilon_{p,t}^f = \epsilon_{p,c}^f$
Cortical	1.9E-09	26000	36000	0.22	36	68	0.0075
Cancellous	1.7E-09	10200	7300	0.10	28	21	0.0055

Volumetric densities were adopted from Sharma and Fry et al. [62,63]. Cranial suture structures were not included in the model since findings are mixed regarding suture strength in adults compared to adjacent bone [64-66]. Stacked thick shell elements with two elements over the thickness were used to model cortical and cancellous bone layers.

Cerebrospinal fluid

CSF was considered a Newtonian fluid with properties close to water. It was modeled with tetrahedral continuum elements employing zero-stiffness material definition in addition to a linear polynomial EOS to accommodate for high-pressure shock loading. Coefficients were $C_1 = 2190 \text{ MPa}$, $C_2 = 9224 \text{ MPa}$ and $C_3 = 8767 \text{ MPa}$ fitting Hugoniot data for water [67-70]. The subarachnoid space was set to a constant thickness of 2 mm. A penalty contact between outer and inner CSF surface to inner skull bone and outer brain surface was assigned. A dynamic shear viscosity coefficient of $\mu = 3.5\text{E-}09 \text{ [MPa}\cdot\text{s]}$ was used.

Brain tissue

Based on the similarities of human and porcine brain tissue, porcine brain is often used for testing. Based on tests with varying strain rate in porcine brain tissue samples during compression ($\leq 90 \text{ s}^{-1}$), shear ($\leq 120 \text{ s}^{-1}$) and tension ($\leq 90 \text{ s}^{-1}$) instantaneous shear moduli in the range of 12-27 kPa were deduced [71-75]. Similarly, based on tests including porcine brain at shear rates up to 800 s^{-1} , a mean instantaneous shear modulus of 14 kPa was derived [76]. Shear tests on bovine brain tissue at a shear strain rate of 700 s^{-1} led to an instantaneous shear modulus of 54 kPa [77]. In this report, a viscoelastic Maxwell model was used to describe brain tissue mechanical properties:

$$G(t) = \sum_{i=1}^n G_i \exp(-\beta_i t) . \quad (5)$$

The deviatoric response was modeled based on experimental data of white matter tested in shear up to 6300 Hz [72]. From this data, instantaneous and long-term shear moduli of 62 kPa

and 0.27 kPa, respectively, can be deduced. Employed Prony series shear relaxation moduli and shear decay constants are provided in [Table 8](#).

Table 8. Employed brain material parameters

i	1	2	3	4	5	∞
G_i [kPa]	50.0	6.22	2.49	1.23	1.62	0.27
β_i [s ⁻¹]	1.0E+05	4350.0	200.0	5.3	0.0051	1.0E-25

Brain tissue was assumed isotropic and modeled with under-integrated constant stress hexahedral continuum elements with hourglass stabilization. The element erosion method was defined to account for material failure, assuming principal failure strain to be in the range of 40% [79]. To conserve mass and momentum, Lagrangian solid elements used for brain modeling and exceeding the failure strain were eroded from the mesh and defined to transform to freely-moving SPH particles. These in turn were set in contact definition to adjacent Lagrangian elements of brain and skull to continue their contribution to the fragmentation process.

4 Forensic evidence

4.1 Bullet fragments

Following the assassination, three small bullet lead fragments and two larger jacket fragments, [Figs.7,8](#), were found in the limousine (exhibits CE567 and CE569, [5]).



Fig.7a Exhibit CE569

Fig.7b Exhibit CE569

Fig.8a Exhibit CE567

Fig.8b Exhibit CE567

Credit: National Archives and Records Administration

[Figs.7a,b](#) show different views of the base of one fragment. [Figs.8a,b](#) show parts of a jacket fragment with core lead material from different views. Whether both fragments were components of the same bullet could not be determined [12].

Fragments CE569 ([Figs.7a,b](#)) and CE567 ([Figs.8a,b](#)) exhibit unique features that were used for comparison with simulation results. From fragment CE569 it is evident that

- the lead core separated from the jacket base, [Fig.7a](#)
- the jacket is folded (flapped) back on one side, several millimeters above the cannelure, [Fig.7b](#), while the opposite side is torn down to just above the cannelure, [Fig.7a](#)
- the base is flattened (elliptic cylinder) and indented on one side, [Fig.7b](#)

From fragment CE567 it is evident that

- the surface of the bearing jacket is irregularly bent open
- the jacket surface is cracked and torn open in the middle (visible lead material), [Fig.8a](#)
- the core lead material is strongly deformed (mechanically and heat based), [Fig.8b](#)

4.2 Autopsy X-rays of Kennedys' head

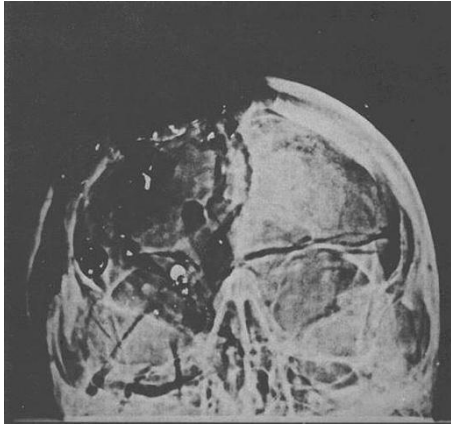


Fig.9a Front head anterior-posterior X-ray

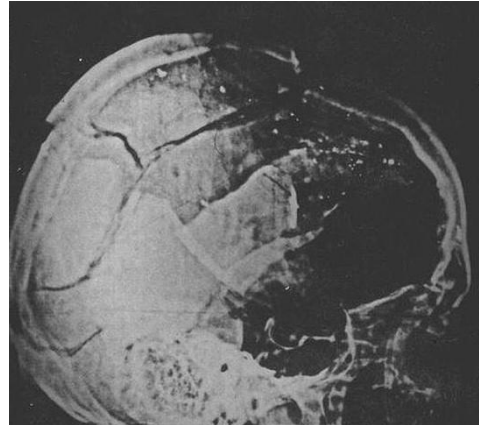


Fig.9b Lateral right side X-ray

Credit: National Archives and Records Administration

The skull X-ray photographs of JFK [5,12] have been variably interpreted, including possible alteration [81,82]. The HSCA photographic panel, however, unanimously agreed that all X-rays (and autopsy) photographs had not been altered in any manner [12]. Computer enhanced versions of the original X-ray photographs are shown in [Figs.9a,b](#), as has been shown in the HSCA report [12]. They show that the top right side of the skull is extensively damaged with extreme loss of bone ([Fig.9a](#)) and multiple fracture lines ([Fig.9b](#)), [77].

4.3 Autopsy photographic evidence

In this report the following images were partly masked, due to their graphic content. Autopsy photographs [Figs.10a,b](#) show Kennedy's head and face from both sides. In [Fig.10a](#), a large defect in the temple region of the right frontal bone resembling a sharply demarcated 'V' is apparent. No damage is visible to the left side of the head, [Fig.10b](#). The autopsy photograph [Fig.10c](#) shows a circular wound indicated with {E} (cf. also [6] and exhibit F-48 in [12]), identified as the bullet entrance site by the HSCA.



Fig.10a Autopsy photos: V-shaped trauma in the right temple region

Fig.10b Left side view

Fig.10c Top rear view: bullet entrance site [12] - indicated with {E}

Credits: US-Government/Wikimedia/Commons/Public Domain and JFK Lancer

5 Results

Based on the conditions described in section 2.1 shots were simulated from four directions: 1. from behind originating from the Texas School Book Depository, 2. from the right, the Grassy Knoll, 3. from the front/slight left - the South Knoll and 4. a storm drain in the slight right front. Simulated bullet and bone fracture characteristics resulting from these directions are compared with forensic evidence. The simulation results based on the shot direction concluded by the *Warren Commission*, i.e. from the TSBD, are presented first (analysis in full detail) followed by the results of the three other shot directions.

Numerical simulations were conducted using the LS-DYNA (Livermore Software Technology Corporation, USA) explicit hydrocode.

(Note: reported simulation times always refer to time Δt after initial bullet-head contact)

5.1 Simulated shot from the TSBD-direction

Official information of the HSCA and Clark reports differ regarding the horizontal orientation of the bullet wound to the back of JFK's head (cf. Section 2.2). An intermediate value of 21.5 mm was set as the distance from the head midline in the present investigation. In advance, due to the uncertainty of the horizontal impact location, a sensitivity analysis was conducted varying the impact site by ± 3 mm around the intermediate value in steps of 1 mm to investigate whether the bone crack propagation and bullet jacket fragmentation might change. Varying the impact site in this way resulted only in minor deviations to the shape of the fragmented skull bone and bullet geometries, indicating a robustness of the results. Simulation results (at time $t = 0.85$ ms) are depicted in [Figs.11a-c](#), correlating evidence is

shown in Figs.11d,e. In this investigation, only bullet jacket deformation was compared since lead core material deformation was unspecific in geometry.

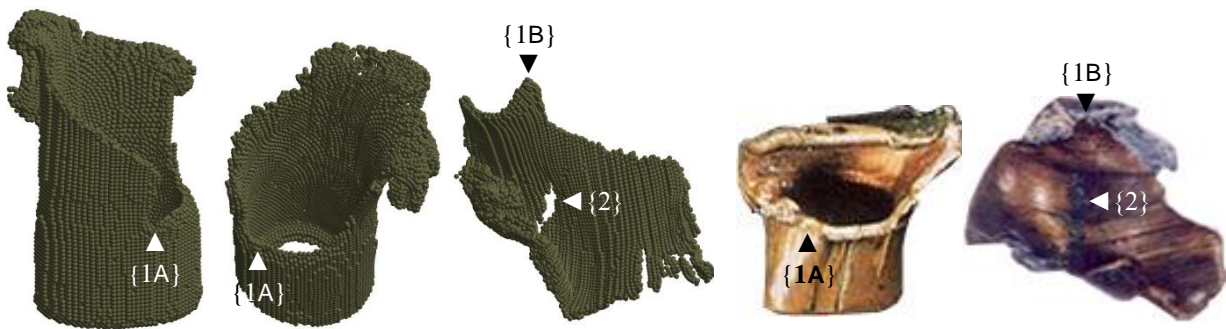


Fig.11a Jacket fragmentation

Fig.11b Top view of Fig.11a

Fig.11c Fragment torn off of the jacket surface

Fig.11d Ex. CE569

Fig.11e Ex. CE567

The simulation showed that a large portion of the jacket surface, Fig.11c, tore off the base at position {1A}, Figs.11a,b, to finally separate from it. Positions {1A} and {1B} were initially identical before separation. Further, the simulated jacket surface was cracked and torn open in the middle section at location {2}. Correlating positions in the evidence fragments are indicated. Also similar to the evidence, the jacket was flapped back on one side while the opposite side was torn down to above the cannelure, Figs.11a,b, and the base was deformed to an elliptic shape (note that proportions of Figs.11a-c and Figs.11d,e do not correspond). This agreement thus shows that both fragments were very likely components of the same bullet, an argument which has been raised in section 4.1 [12]. From the simulation process, different stages can be distinguished.

1: Initial contact with the skull bone, damaging the bullet's nose with the jacket tearing open to expose the lead core. The initially stable single cell one-end closed tube structure then assumes the shape of a fragile two-end open tube structure. Bullet entrance is indicated with {1} in Fig.12a.

2: Contact with brain tissue. Here partial asymmetric mushrooming of the jacket occurs due to asymmetrical initial bone contact (impact angle not orthogonal to bone surface) and partial disconnection of the lead core from the jacket. Disconnection was driven by faster forward movement of the lead core caused by higher contact forces (due to locking and friction) on the jacket by adjacent tissue. Due to asymmetric bullet deformation and resulting asymmetric resistance bullet rotation begins around the vertical z-axis (s. Figs.13 for coordinate system). This caused indentation of the jacket base since the lead core had already traversed forward leaving the jacket base hollow.

3: Second contact with bone as the bullet exits, indicated with {2} in Fig.12a in the right temple region, and shown in detail in Fig.12b. At exit the bullet was rotated approximately 35° about the vertical z-axis compared to its pre-impact line of flight. Here progressive damage to the jacket and core occurs (again asymmetrically, due to unilateral contact to the parietal/frontal bone structure).

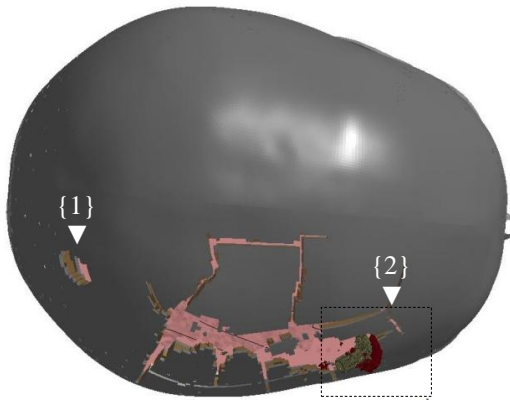


Fig.12a Bone damage at $t = 0.3$ ms; entrance wound at {1}, bullet exit site at right temple {2}

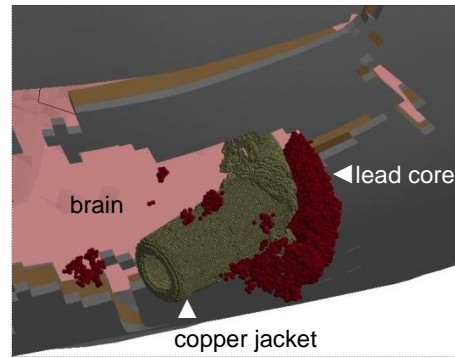


Fig.12b Detail from Fig.12a: bullet position and damage at time of exit

4: Post-impact phase ($t > 0.3$ ms). Due to centrifugal forces on the bullet material, further deformation and rupture of the jacket material occurred until the lead core base completely separated from the jacket (after exit, the bullet was free of external forces previously exerted by brain tissue and bone). Simulation showed that exiting fragments had an average resultant velocity of 350 m/s.

Forensic evidence suggests that after exit, the fatal bullet contacted the car interior [1].

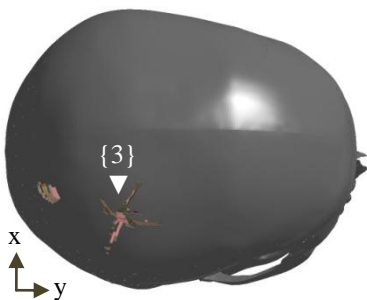


Fig.13a Bone damage initiating at time $t = 0.14$ ms

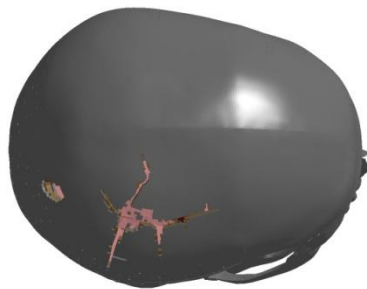


Fig.13b Time $t = 0.18$ ms

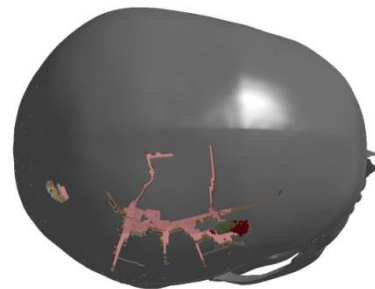


Fig.13c Time $t = 0.25$ ms

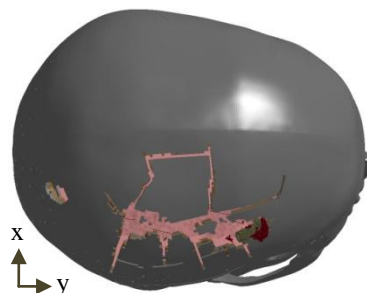


Fig.13d Time $t = 0.28$ ms

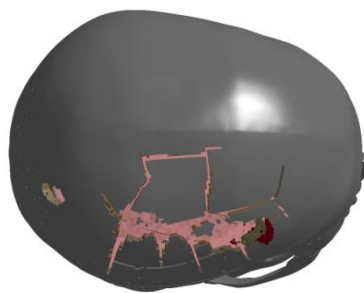


Fig.13e Time $t = 0.29$ ms

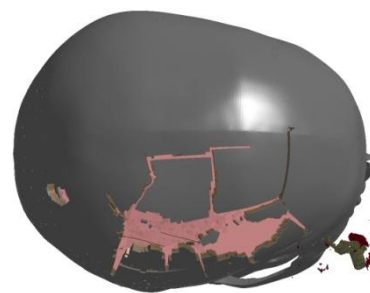


Fig.13f Time $t = 0.4$ ms

Very likely, this led to further bullet deformation, however, of unknown degree. Such additional deformation might be a source of inaccuracy between the deformation resulting from the simulations presented here, i.e. only bullet-head contact was considered, and the recovered fragments.

Besides the two large deformed jacket fragments, in the simulation the soft lead core also exhibited intense deformation and fragmentation and separated into multiple small fragments during and after brain penetration. In [Figs.13a-f](#) simulated progressive damage to the skull is shown (scalp skin, CSF and adaptive SPH brain elements are masked for better visibility). Due to the high location of bullet entrance and motion direction, the bullet travels closely beneath the inner cortical bone layer. This results in local increase of intracranial pressure which initially cracks the skull open in the right parietal rear of the head (position {3} in [Fig.13a](#)) and fracture lines, beginning around the site of the crack origin, radiate concentrically, [Fig.13a](#). As the maximum intracranial pressure location propagates along with the bullet towards the exit site, more fracture lines radiate off orthogonal to the emerging fracture path, [Figs.13b-e](#).

Plates of bone between these fracture lines are bent outwards, [Figs.14a,b](#). Similar crack propagation in bone has been reported [84]. [Figs.14a,b](#) depict the damage to the head (at times $t = 0.8$ ms and 0.85 ms, respectively) with the scalp skin and adaptive SPH brain elements shown. The V-shaped demarcation defect (localized with {1} and {2} in [Fig.14b](#)) is clearly apparent in the simulation results. The straight, sharp fracture line can be seen more clearly in

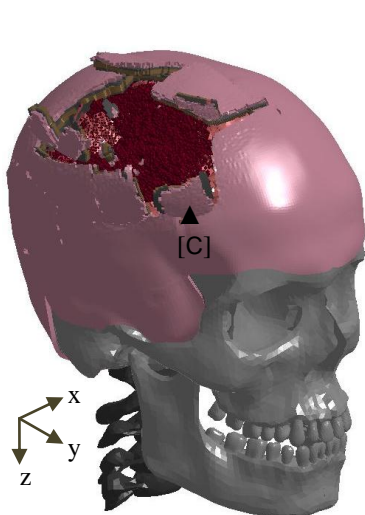


Fig.14a Model: skull and scalp skin damage at time $t = 0.8$ ms

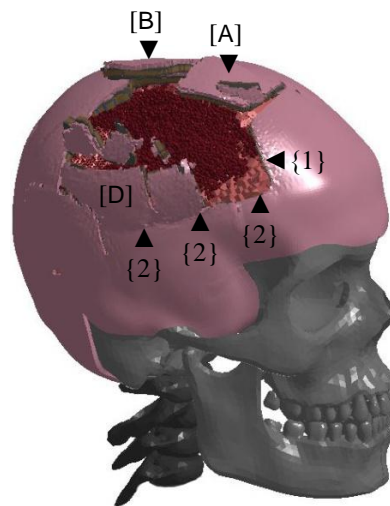


Fig.14b Model: skull and scalp skin damage at $t = 0.85$ ms (fragment [C] has separated and is not shown)



Fig.14c Autopsy photograph (identical to [Fig.10a](#))

[Fig.15a](#). The correlating positions in the evidence are indicated in [Fig.14c](#). In [Figs.14a,b](#) bone fragments [A-C] separated from the skull in the course of the simulation and moved with an

average vertical z-velocity of -16, -25 and 7 m/s, respectively, indicated by to the coordinate system shown in Fig.14a, and their lateral (x-) and forward (y-) velocity components were 7, 10, -23 m/s and 3.5, -1, 37 m/s. The masses of the bone fragments [A-C] were 23, 25, and 15g, respectively. Separation of fragments [A,B] from the skull drive them vertically away from the initial crack zone, rotating at the same time around the scalp skin connection located approximately at the sagittal suture, until total skin rupture occurs. Fragment [D] in Fig.14b behaves similarly in the right lateral direction, rotating about the scalp skin connection along fracture path {2}. Its mass is 35 g. Average vertical z-velocity of fragment [D] is -1.3 m/s, its lateral x- and forward y-velocity components are -28 m/s and 10 m/s, respectively. Fragment [B] is parietal bone. Parietal/ frontal bone fragment [A] slightly extends over the coronal suture. Analysis regarding a possible match of the fragments [A-D] with the fragments recovered from the scene of the assassination ([5], exhibit CE387) was not further pursued.

The image shown in Fig.15b is an enhanced copy of the fractures shown by X-ray (unenhanced X-ray images are presented in the HSCA report [12]) and can be compared to

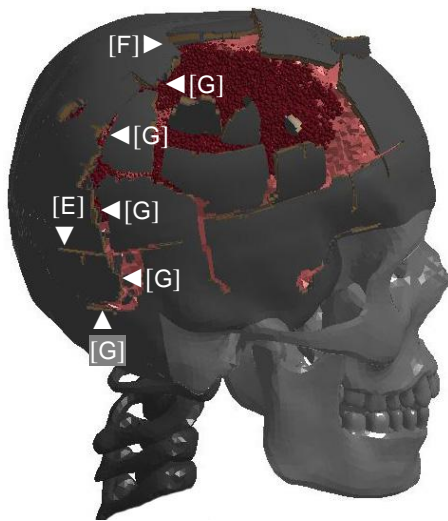


Fig.15a Underlying skull bone damage (scalp skin masked) at $t = 0.85$ ms

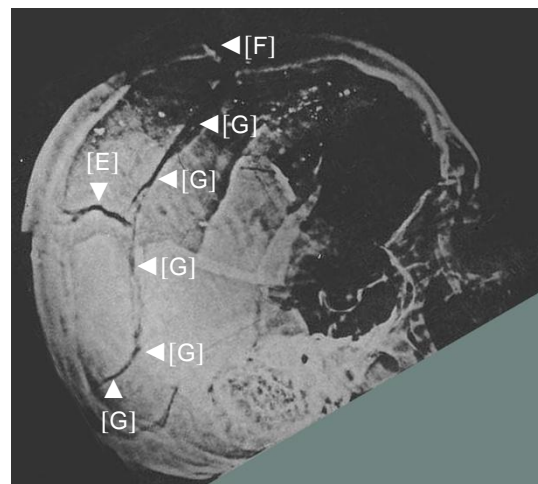


Fig.15b Lateral right side X-ray: fracture lines (analog to Fig.9b but rotated for comparison) (Credit: National Archives and Records Administration)

the simulation model Fig.15a, although exact perspectives differ. Descriptions of single fracture lines of the HSCA radiologists can be found in exhibits F-32,33 [12]. The distinct S-shape along line [G] in Fig.15b correlates with the path in Fig.15a. Similarly, [E] coincides, and [F] indicates the rearmost fracture line of fragment [B] in Fig.14b. The front head X-ray, Fig.9a, shows that skull damage extended to the sagittal suture. This is also seen in the simulation results in Fig.13f and Figs.14a,b. It becomes apparent from figures Figs.14a,b and Fig.15a that to a large extent the scalp covered underlying bone damage. Extensive underlying

bone damage coincides with the testimony of one of the autopsy pathologists stating that during the autopsy the skull was all "falling apart" [85]. The wound characteristics visible from the outside, cf. Fig.14a, could well correlate with the wound location reported by eyewitnesses [6,8] as it largely extends to the right back of the head.

5.2 Simulated shot from the GK-direction

Skull fractures and bullet fragmentation resulting from a simulated shot from the GK-direction are shown in Figs.16a-d. The bullet impact site indicated with {1} was chosen to be at the right temple region in close proximity to where the sharp bone defect is apparent in the autopsy images, cf. Figs.1,2 for geometrical orientation. The resulting exit site is indicated with {2} with the arrow indicating the bullet orientation prior to contact. Simulation shows that bone fracture lines and bullet deformation do not resemble the evidence, Figs.7-9a,b. A shot from the GK-direction would have inevitably led to a bullet exit site directly opposite the entrance site, i.e. the left temple region (evidently in contradiction to Fig.10b) and not as hypothesized by some [6,8] at the right rear of the head.



Fig.16a Scalp skin and bone damage at $t = 0.85$ ms (arrow indicates shot direction)

Fig.16b Bone damage at $t = 0.85$ ms

Fig.16c Jacket fragmentation at 0.55 ms after exit

Fig.16d Jacket fragmentation at 0.55 ms after exit (top view)

5.3 Simulated shot from the SD-direction

The skull fractures and bullet fragmentation resulting from a simulated shot from a storm drain situated almost in front of the limousine are shown in Figs.17a-d.

The bullet impact site was set at the right temple indicated with {1} in Figs.17a,b. The exit site is indicated with {2}. The arrow indicates bullet orientation prior to contact. Simulation shows that bone fracture lines and bullet deformation do not resemble the evidence. Jacket deformation shows expansion and folding back as well as indentation at the base. In the course of penetration and specifically after exit, the lead core, however, does not tear the bullet jacket to initiate separation of the jacket into another larger piece. Ejected bone fragments are also

not apparent. In addition, the V-shaped defect in the right temple is absent. The bullet exit site is indicated with {2} in the lower left area at the back of the head, Fig.17c.

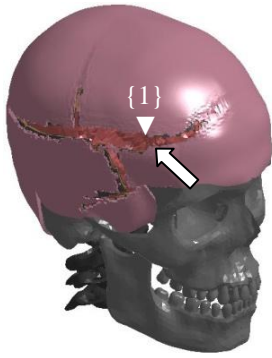


Fig.17a Scalp skin damage at $t = 0.85$ ms (arrow indicates shot direction)



Fig.17b Bone damage at $t = 0.85$ ms

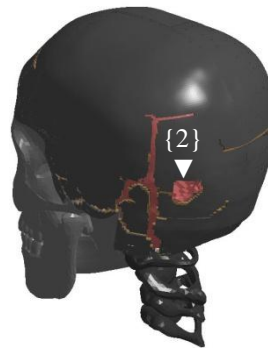


Fig.17c Bone damage at $t = 0.85$ ms (rear view)



Fig.17d Jacket fragmentation at 0.55 ms after exit

5.4 Simulated shots from the SK-direction

Three possible shooter origins, cf. Fig.1, were analyzed. Common to all sites is an assumed entrance site over the right supra-orbital ridge {1} resulting in an exit site at the right rear of the head, {2} in Fig.18a.

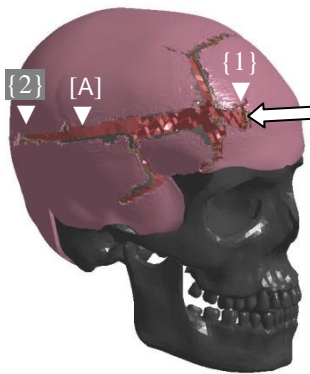


Fig.18a Shot from site (3): scalp skin damage at $t = 0.85$ ms (arrow: shot direction)

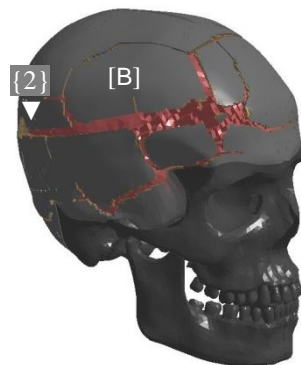


Fig.18b Bone damage at $t = 0.85$ ms



Fig.18c Jacket fragmentation at 0.55ms after exit



Fig.18d Jacket fragmentation (opposite perspective)

Bullet entrance sites further lateral left of {1} were considered geometrically unlikely due to Mrs. Kennedy's position at the time of the fatal shot shielding Kennedys' left head side, cf. Fig.3a,b. Potential shot origins (1) and (2), Fig.1, are approximately in line (from a vertical point of view) with the shot trajectory from the TSBD. Simulation showed that skull fractures and bullet fragmentation were similar for all three cases; bullet exit sites differed slightly. While for locations (1) and (2) the bullet exit site was located at the right rear of the head, for location (3) it was a further to the right. For all three cases a distinct bullet entrance opening can be detected at {1}, which is not evident in the autopsy image Fig.10a. Further, bullet jacket deformation and fragmentation, Figs.18c,d, do not resemble the evidence.

5.5 Simulated post-impact phase: head and upper body motion

Immediately after the head shot, a violent back- and leftward motion of the JFK's head and upper body is apparent, cf. *Zapruder Film* frames #316-320 [10]. This caused controversy about the shot direction since the lay community expects a body to be driven in the same direction as the pre-impact direction of a bullet that impacts it, not in the opposite direction. It could however clearly be shown by simulation employing the presented head model coupled with a dummy model that retrograde motion is of mechanical cause and based on conservation of momentum. Momentum exchange of expelled bone, parts [A-C] in Fig.14a,b, as well as brain matter drives the head into retrograde motion and not forward. This was first proposed in 1976 [86], recently confirmed by Nalli [88]. Simulation shows that 50 g of brain FE-elements fail as a result of a shot from the TSBD of which approximately 25 g had an average velocity of 25 m/s that contributed to momentum exchange. With velocity components, Fig.19a, and masses, section 5.1, the average resultant velocity of the head was deduced to be 0.53 m/s in agreement with the literature [87].

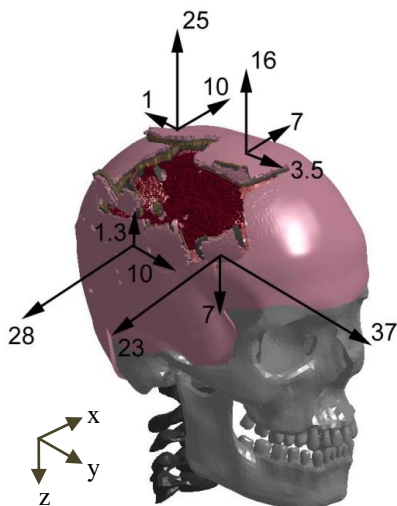


Fig.19a Velocity components [m/s] of main skull fragments at $t = 0.8$ ms

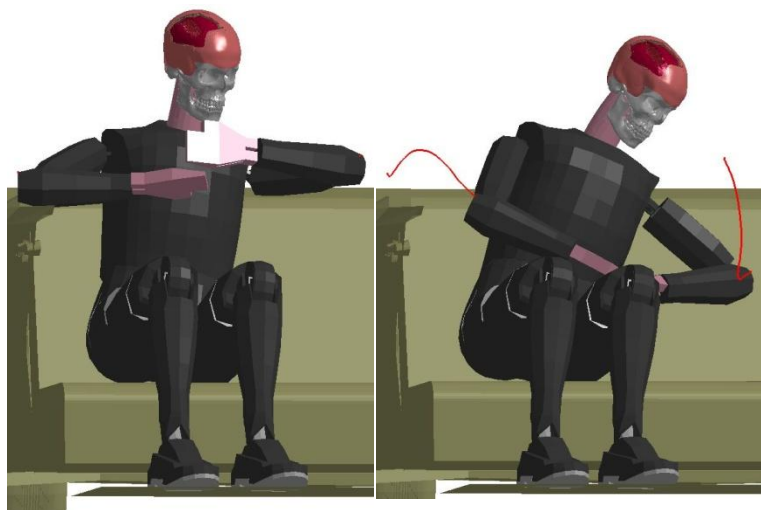


Fig.19b $t = 0.85$ ms (expelled bone/ brain was not included)

Fig.19c $t = 330.85$ ms (red lines indicate arm trajectories)

Simulation showed that transferred momentum initially leads to a head rotation around the vertical (z-) axis and, synchronously, a lateral flexion about the in-sight (y-) axis until finally being decelerated and stopped relative to the upper body by the physiologic rotation limits of the neck joints. Approaching these limits, simulation further showed that the upper body was also accelerated to rotate around the pivot at the pelvis and the lumbar vertebrae, Figs.19b,c.

6 Discussion

Due to controversy surrounding official reports in regard to the assassination of John F. Kennedy, the fatal head shot was analyzed in the present report by means of numerical

simulation and outcome of different simulated shot directions were compared to forensic evidence. Shot directions included the officially designated shot origin site from the Texas School Book Depository to the back of the president's head, as well as three additional sites promoted by conspiracy theories. It was postulated that the specific characteristics and complexity of anatomic and physical evidence existent in the form of X-ray and autopsy photographs as well as recovered bullet fragments and post-impact head motion can be reproduced by simulation from only one shot direction. Specifically, unique features were the sharply demarcated defect in the temple region of the right frontal bone, evident in autopsy photographs, as well as the specific skull bone crack formation evident in X-rays. Deformation of the bullet jacket material was also particularly characteristic. Comparing all simulation results with the evidence, it could be shown that only a bullet fired from a direction in Kennedy's rear, specifically originating from the direction of the Texas School Book Depository at a ground height approximately matching the 6th floor correlates well with the evidence. The sharply demarcated V-shaped defect in the temple region of the right frontal bone, which at first glance appears artificial and had been proposed as the result of manipulation to cover a wound resulting from a shot from the front [81], was shown to be a direct consequence of the particular loading situation. For all simulated cases it is shown that though the bullet deforms, fractures, and rotates, it generally follows a straight path in the soft brain tissue, such that the exit site is in line with the pre-impact bullet flight path. This rigorously excludes hypotheses including locations other than the TSBD as shot origin, cf. shot traces in Fig.2 as they contradict autopsy evidence, Figs.10b,c.

7 Conclusions

The presented simulations support the official commission reports regarding origin and direction of the fatal head shot to John F. Kennedy. From a mechanical standpoint, based on computational simulation, JFK's head was hit by a single bullet from the rear originating from the Texas School Book Depository. Deformation patterns regarding skull fracture and bullet jacket deformation as shown in photographs could be matched by simulation with unambiguous consistency, leaving little room for further speculation about the origin of the projectile. Simulated post-impact head motion corresponds to evidence provided by the *Zapruder Film*. Simulation results together with forensic evidence exclude the sites "*Grassy Knoll, South Knoll, and storm drain*", as potential origins of the fatal shot.

The modeling approach employed here, based on computer-aided simulation, could be applied to similar cases in the forensic field.

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