A Parametric Study of Age-Related Factors Affecting Intracranial Responses under Impact Loading Using a Human Head/Brain FE Model

Toshiyuki Yanaoka, Yasuhiro Dokko

Abstract The high frequency of fatal head injuries in elderly people in traffic accidents is one of the important issues in Japan. One of the causes may be vulnerability of the aged brain. While a human head/brain FE model is a useful tool to investigate head injury mechanism, there has not been such a model considering the structural and qualitative changes of the brain caused by aging. The objective of this study was to clarify the influence of intracranial changes on intracranial responses relating to brain injuries, which could be the basic knowledge to develop a head/brain model capable of representing injury mechanisms of the aged brain. The influence of eight factors representing structural and material features on intracranial response was parametrically studied using a human head/brain FE model. Furthermore, influence of the impact direction was studied swapping the axis in the model along which the acceleration pulses were applied. The following results were found: 1) PAC (Pia-Arachnoid Complex) layer volume and stiffness of bridging vein (BV) had a strong influence on elongation of BV, 2) stiffness of the brain strongly influenced dilatational damage measure (DDM) and 3) stiffness of the brain and PAC layer volume had a strong influence on cumulative strain damage measure (CSDM).

Keywords age-related changes, brain Injuries, human FE model, parametric study

I. INTRODUCTION

The Japanese accident statistics from ITARDA (Institute of Traffic Accident Research and Data Analysis) [1] show the elderly who was older than 65 years old accounted for 36.8% of all traffic accident fatalities in 2001, which increased to 49.0% in 2011. In fatal traffic accidents, the head accounted for 47.6% of all most severely injured body regions in 2011, which was the highest of all the body regions. Therefore, in order to reduce the number of fatalities in traffic accidents, countermeasures to reduce head injury in the elderly are important issues in Japan when a growing aging society in the near future is taken into consideration.

To improve the fatality situation, an injury criterion considering the elderly is desired for the development of appropriate protective technologies. While a human head/brain FE model is a useful tool to investigate head trauma, especially brain injuries, and while there have been many studies that have investigated brain injury using human head/brain FE models, most of them did not take the structural and qualitative changes of the aging brain into account. In order to investigate the mechanism of brain injury of the elderly, a human head/brain FE model considering the characteristics of the aged brain is needed.

For development of a head/brain model capable of representing injury mechanisms of the aged brain, it is necessary to clarify the characteristics of the aged brain and then incorporate these factors into the model. Kleiven et al. [2] demonstrated the effect of brain atrophy on the brain's relative motion to the skull. Their result showed that a significant increase in relative motion was found between the skull and brain which correlated with the reduction of the brain size relative to the whole intracranial volume. However, knowledge of the influence of other characteristics of the elderly brain are lacking.

The objective of this study, therefore, was to clarify the influence of various intracranial changes, such as brain atrophy and the changes of stiffness of brain matter, blood vessels and other intracranial components, on various intracranial responses relating to brain injuries, which could provide the basic knowledge to develop a

Toshiyuki Yanaoka is assistant chief engineer at Honda R&D Co., Ltd. Automobile R&D center in Japan (tel: +81-28-677-3311, e-mail: Toshiyuki_Yanaoka@n.t.rd.honda.co.jp). Yasuhiro Dokko is chief engineer at Honda R&D Co., Ltd. Automobile R&D center in Japan.

head/brain FE model capable of representing injury mechanisms of the aged brain.

II. METHODS

Human Head/Brain FE model

In this study, the mid-sized male (AM50%ile) human head/brain FE model developed by Global Human Body Models Consortium LLC. (GHBMC)[3] was used (Figure 1). This model consisted of around 260,000 elements representing scalp, skull, cerebrospinal fluid (CSF), meninges, bridging veins (BVs), cerebrum and cerebellum by their appropriate types of elements and material models as shown in Table 1. The model was validated against the head impact tests of Hardy et al.[4][5] for maximum and minimum value of brain relative displacement to the skull (Figure 2) and against those of Nahum et al. [6] and Trosseille et al.[7] for intracranial pressure (Figure 3). From these results, it was confirmed that this model had enough accuracy to conduct a parametric study about the influence of the characteristics of the aged brain on intracranial responses.

In order to investigate the influence of increase of the pia-arachnoid complex (PAC) layer volume by brain atrophy, shrunk-brain models were prepared by scaling a brain simply referring to the center of gravity of brain. Figure 4 shows the baseline model and a sample of shrunk-brain model.

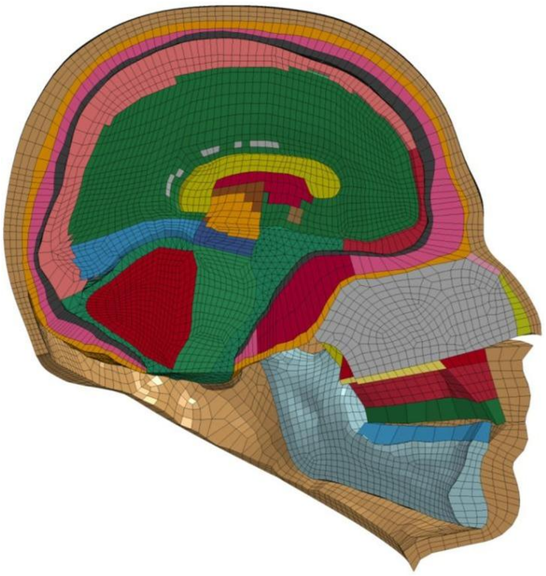

Fig. 2. GHBMC human head/brain FE model

TABLE 1
SUMMARY OF FE MODEL

Part	Element Type	Material Type
Cerebrum (White, Gray)	Solid (Hexa)	Kelvin-Maxwell Viscoelastic
Cerebellum	Solid (Hexa)	Kelvin-Maxwell Viscoelastic
Ventricle	Solid (Hexa)	Kelvin-Maxwell Viscoelastic
Cerebrospinal Fluid	Solid (Hexa & Tetra)	Kelvin-Maxwell Viscoelastic
Meninges (Dura, Arachnoid, Pia, Falx, Tentorium)	Shell	Elastic
Bridging Vein	Beam	Piecewise Linear Plasticity
Skull	Solid(Hexa)	Piecewise Linear Plasticity
Scalp	Solid(Hexa)	Viscoelastic

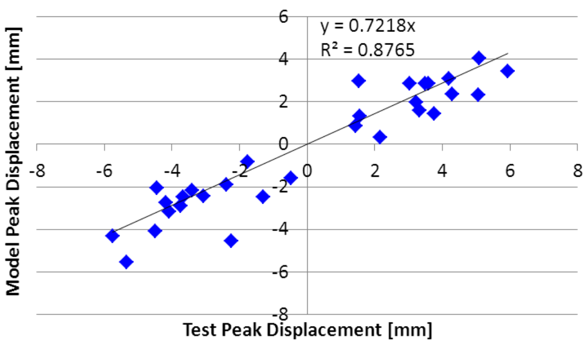

Fig. 2. Correlation of the maximum brain displacement between the model and the test

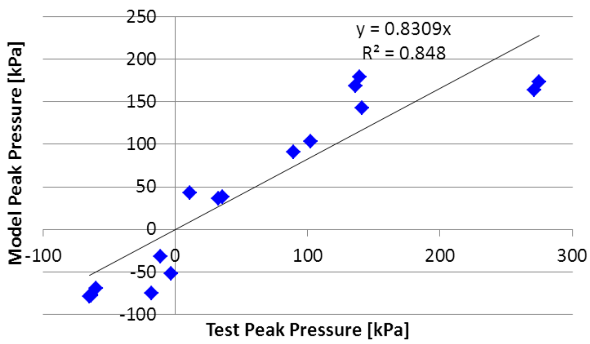

Fig. 3. Correlation of the maximum intracranial pressure between the model and the test

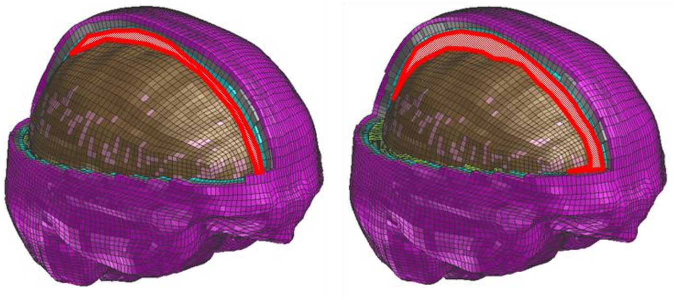

Fig. 4. Baseline model (left) and shrunk-brain model (right)

Input Conditions for Parametric Study

In order to investigate the influence of various parameters on intracranial responses, occipital head impact acceleration data from Hardy et al. [5] shown in Figure 5 and Figure 6 were adopted for input pulses for this study. In addition, to study the influence of the impact direction, temporal head impact condition was represented by swapping the axis in the model along which the acceleration pulses were applied. Table 2 shows the combination of the input pulses and the impact directions for each case.

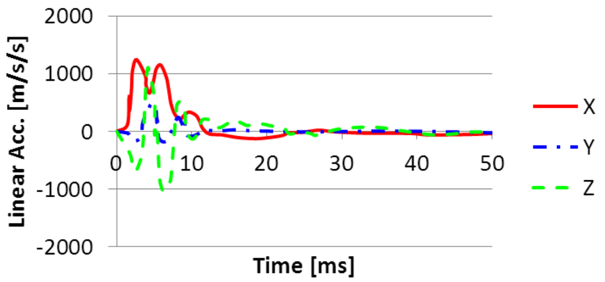

Fig. 5. Input pulses (translational)

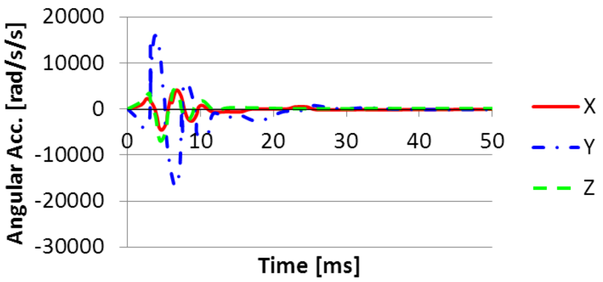

Fig.6. Input pulses (rotational)

TABLE 2
COMBINATION OF INPUT PULSES AND DIRECTIONS

Model axis	Case 1 (Occipital Impact)	Case 2 (Temporal Impact)
X	Test X	Test Y
Y	Test Y	Test X
Z	Test Z	Test Z

Since the objective of this study was to clarify the influence on intracranial responses, the skull and scalp parts of the model were treated as rigid bodies. Rigid body motion of the head impact test was represented by applying the 6DOF (Degree of Freedom) acceleration to the center of gravity of the rigid body of the skull and scalp parts. In this study, LS-DYNA mpp971sR4.2.1 (Livermore Software Technology Corporation) was used as an FEM solver.

Parameters and Levels for Parametric Study

In order to investigate the influence of age-related factors, eight structural and material parameters likely to influence intracranial responses were selected. In addition, to clarify the influence of these eight parameters, the levels of each parameter were set in 2 or 3 levels based on the following previous research results: 1) result of Yamada [8] and Jin et al. [9] for stiffness of falx cerebri and tentorium, 2) result of Kleiven et al. [2] and Taki et al. [10] for level of brain atrophy (change of PAC layer volume), 3) result of Sack et al. [11] for stiffness of white matter (WM), gray matter (GM) and CSF and 4) result of Asiminei et al. [12] for stiffness of BV. Table 3 summarizes the eight parameters and their normalized values, which have different actual values for 1.0 in their parameters, for each level.

TABLE 3
SELECTED PARAMETERS AND THEIR LEVELS FOR ANALYSIS (NORMALIZED)

ID	Parameters	Value	Level		
			1	2	3
A	Stiffness of Falx cerebri	Young's Modulus	1.0	2.0	
B	Stiffness of Tentorium	Young's Modulus	1.0	1.5	2.0
C	Brain Atrophy	PAC layer volume	1.0	1.3	1.6
D	Stiffness of WM	Shear Modulus	0.5	1.0	1.5
E	Stiffness of GM	Shear Modulus	0.5	1.0	1.5
F	Stiffness of CSF	Shear Modulus	0.5	1.0	1.5
G	Stiffness of Ventricle	Shear Modulus	0.5	1.0	1.5
H	Stiffness of BV	Young's Modulus	0.2	1.0	1.8

Design of Simulation

For either case 1 (occipital impact) or case 2 (temporal impact), 18 different combinations of the eight structural and material parameters were determined using L18 orthogonal array to see statistical significance of each parameter on intracranial responses with a minimal number of simulations. Table 4 shows the combination of the levels of each parameter for case 1 and case 2.

TABLE 4
L18 ORTHOGONAL TABLE OF PARAMETERS

No.	A	B	C	D	E	F	G	H	No.	A	B	C	D	E	F	G	H
1	1	1	1	1	1	1	1	1	10	2	1	1	3	3	2	2	1
2	1	1	2	2	2	2	2	2	11	2	1	2	1	1	3	3	2
3	1	1	3	3	3	3	3	3	12	2	1	3	2	2	1	1	3
4	1	2	1	1	2	2	3	3	13	2	2	1	2	3	1	3	2
5	1	2	2	2	3	3	1	1	14	2	2	2	3	1	2	1	3
6	1	2	3	3	1	1	2	2	15	2	2	3	1	2	3	2	1
7	1	3	1	2	1	3	2	3	16	2	3	1	3	2	3	1	2
8	1	3	2	3	2	1	3	1	17	2	3	2	1	3	1	2	3
9	1	3	3	1	3	2	1	2	18	2	3	3	2	1	2	3	1

Intracranial responses

Kameyama et al. [13] investigated the incidence of such brain injuries as diffuse injury, contusion, acute subdural hematoma (ASDH) and epidural hematoma (EDH) by age group. Figure 7 summarizes the results, showing that the incidence rates of ASDH and contusion increase with age and that of diffuse injury is high in each age group. From these results, the following three injury metrics were selected for the index of intracranial response to be investigated.

- Elongation of BVs: this metric is thought to be a predictor for rupture of BV which is one of the main causes of ASDH.
- Dilatational Damage Measure (DDM) [14]: this metric is the volume ratio of the brain experiencing a specified negative pressure level (-100kPa) and is thought to be a predictor for brain contusion.
- Cumulative Strain Damage Measure (CSDM) [14]: this metric is the volume ratio of the brain experiencing a specified maximum principle strain level (0.2) and thought to be a predictor for diffuse axonal injury (DAI).

For the occipital impact (case 1), in order to investigate a mechanism of intracranial responses, a peak value of the brain-skull relative motion at the front end of the brain, internal energy of CSF and internal energy of the brain were checked.

Furthermore, in order to investigate the influence of impact direction on intracranial responses, total internal energy and peak ratio of the sum of internal energy of the falx cerebri and tentorium to total internal energy, which was assumed to be related to the restriction of the falx cerebri and tentorium, were checked in each impact direction.

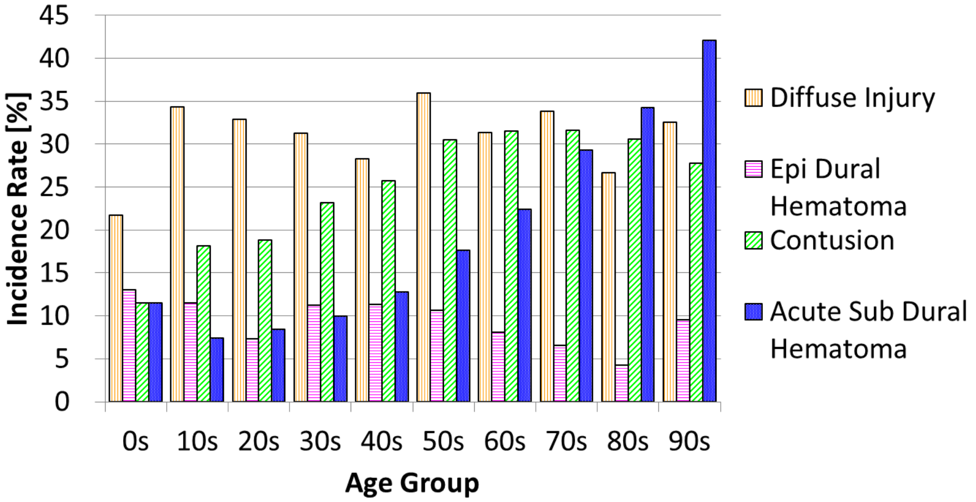

Fig. 7. Incidence rate of typical traumatic brain injuries by age group

III. RESULTS

Influence of each parameter on injury metrics (case 1: occipital impact)

Table 5 shows the simulation results of 18 combinations of parameters. In order to clarify the influence of each parameter on each injury metric, a factorial effect graph was plotted using the average value of each level for each parameter and the statistical significance of each parameter was confirmed by the analysis of variance. Figure 8 to Figure 10 show the factorial effects of each parameter on each injury metric where a dashed line shows the average of all combinations, * means p<0.05 and ** means p<0.01. Additionally, Figure 11 shows the percent contribution of each parameter, which was calculated by dividing variance resulting from each parameter by total variance.

TABLE 5
RESULT OF L18 FOR CASE 1 (OCCIPITAL IMPACT)

No.	Elongation of BV [mm]	DDM [%]	CSDM [%]	No.	Elongation of BV [mm]	DDM [%]	CSDM [%]
1	2.21	15.9	47.2	10	2.21	24.9	14.7
2	2.24	21.6	25.9	11	2.26	15.9	44.8
3	2.33	24.0	9.0	12	2.35	21.9	20.7
4	2.15	19.9	38.5	13	2.18	23.8	20.5
5	2.27	22.9	17.7	14	2.24	19.0	27.0
6	2.37	19.6	22.4	15	2.40	20.0	30.2
7	2.16	18.5	37.8	16	2.19	23.4	21.9
8	2.29	22.4	19.5	17	2.23	20.5	26.1
9	2.36	21.2	20.8	18	2.40	18.4	29.9

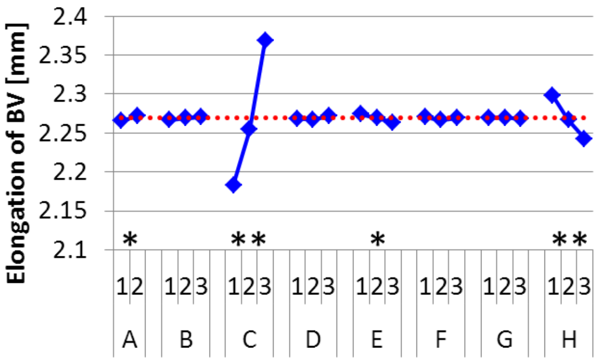

Fig. 8. Factorial effects of parameters on Elongation of BV for Case 1 (Occipital Impact)

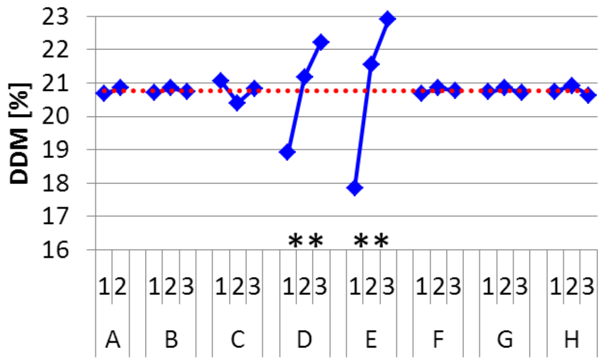

Fig. 9. Factorial effects of parameters on DDM for Case 1 (occipital Impact)

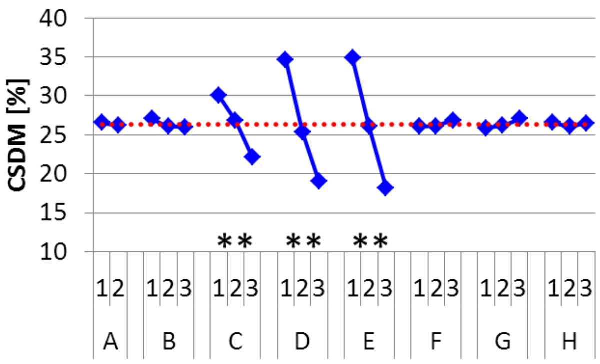

Fig. 10. Factorial effects of parameters on CSDM for Case 1 (Occipital Impact)

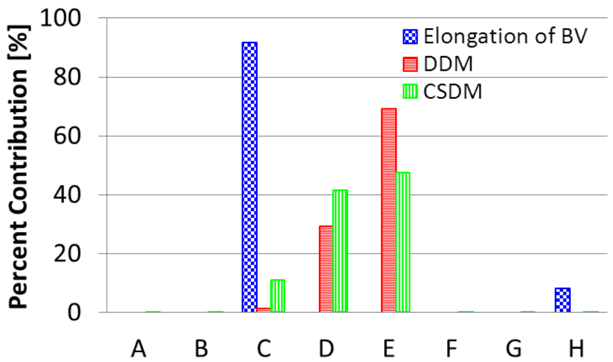

Fig. 11. Percent contribution of parameters for Case 1 (Occipital Impact)

For elongation of BV, as shown in Figure 8, PAC layer volume and stiffness of BV had significant influence ($p<0.01$), while stiffness of falx cerebri and gray matter had secondary influence ($p<0.05$). Focusing on PAC layer volume and stiffness of BV that had strong influence on elongation of BV, there was positive correlation between elongation of BV and PAC layer volume while there was negative correlation between that and stiffness of BV.

For DDM, as shown in Figure 9, stiffness of brain (white and gray matter) had significant influence ($p<0.01$). There was positive correlation between DDM and stiffness of brain.

For CSDM, as shown in Figure10, stiffness of brain and PAC layer volume had significant influence ($p<0.01$). There was negative correlation between CSDM and stiffness of brain and PAC layer volume.

The results from the contribution ratio of each parameter shown in Figure 11 are as follows: 1) PAC layer volume and stiffness of BV had high percent contribution (91% and 8%) on elongation of BV, 2) stiffness of gray and white matters had high percent contribution (69% and 29%) on DDM and 3) stiffness of gray and white matters and PAC layer volume had high percent contribution (47%, 41% and 11%) on CSDM. The trend of percent contribution of elongation of BV was different from that of DDM or CSDM.

Influence of each parameter on injury metrics (case 2: temporal impact)

Table 6 shows the simulation results of 18 combinations of parameters. Figure 12 to Figure 14 show the factorial effect graphs of each parameter on each injury metric where a dashed line shows the average of all combinations, * means $p<0.05$ and ** means $p<0.01$. Additionally, Figure 15 shows the percent contribution of each parameter.

TABLE 6
RESULT OF L18 FOR CASE 2 (TEMPORAL IMPACT)

No.	Elongation of BV [mm]	DDM [%]	CSDM [%]	No.	Elongation of BV [mm]	DDM [%]	CSDM [%]
1	1.03	11.0	24.0	10	1.03	17.7	7.2
2	1.08	14.2	11.5	11	1.07	10.0	20.2
3	1.16	15.5	3.4	12	1.16	13.6	7.6
4	0.99	13.8	18.7	13	1.01	16.6	9.5
5	1.11	15.4	7.8	14	1.05	12.6	11.9
6	1.18	12.3	9.3	15	1.21	12.3	11.4
7	1.00	12.8	18.9	16	1.01	16.7	10.2
8	1.12	15.5	8.6	17	1.05	13.9	10.9
9	1.18	13.4	8.0	18	1.21	11.3	11.7

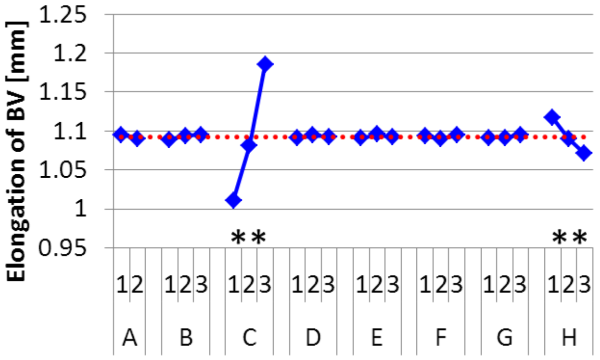

Fig. 12. Factorial effects of parameters on Elongation of BV for Case 2 (Temporal Impact)

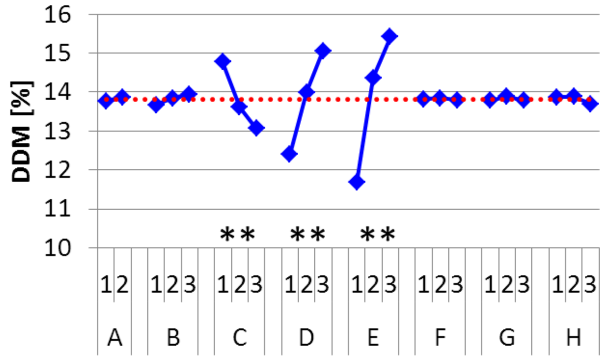

Fig. 13. Factorial effects of parameters on DDM for Case 2 (Temporal Impact)

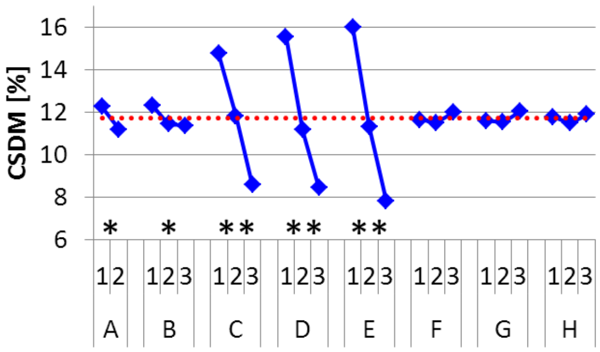

Fig. 14. Factorial effects of parameters on CSDM for Case 2 (Temporal Impact)

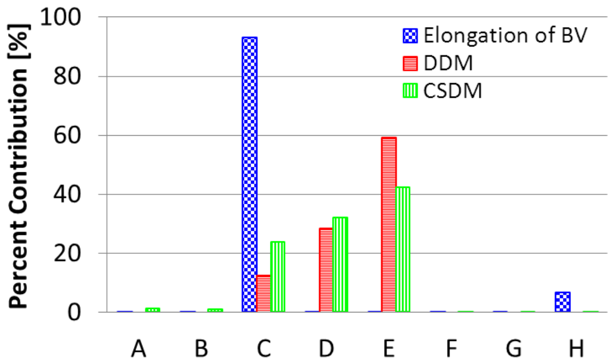

Fig. 15. Percent contribution of parameters for Case 2 (Temporal Impact)

For elongation of BV, as shown in Figure 12, PAC layer volume and stiffness of BV had significant influence ($p<0.01$). There was positive correlation between elongation of BV and PAC layer volume while there was negative correlation between that and stiffness of BV.

For DDM, as shown in Figure 13, stiffness of brain (white and gray matter) and PAC layer volume had significant influence ($p<0.01$). There was positive correlation between DDM and stiffness of brain while there was negative correlation between that and PAC layer volume.

For CSDM, as shown in Figure 14, stiffness of brain and PAC layer volume had significant influence ($p<0.01$), while stiffness of falx cerebri and tentorium had secondary influence ($p<0.05$). There was negative correlation between CSDM and stiffness of brain and PAC layer volume.

The results from the contribution ratio of each parameter shown in Figure 15, are as follows: 1) PAC layer volume and stiffness of BV had high percent contribution (92% and 6%) on elongation of BV, 2) stiffness of gray and white matter and PAC layer volume had high percent contribution ratio (59%, 28% and 12%) on DDM and 3) stiffness of gray and white matter and PAC layer volume had high percent contribution (42%, 32% and 24%) on CSDM. The trend of percent contribution of elongation of BV was different from that of DDM and CSDM.

Influence of each parameter on brain relative motion and internal energy

Table 7 shows the simulation results of 18 combinations of parameters in occipital impact. Figure 16 to Figure 18 show the factorial effect graphs of each parameter for each intracranial response where a dashed line shows the average of all combinations, * means p<0.05 and ** means p<0.01. Additionally, Figure 20 shows the percent contribution of each parameter.

TABLE 7
RESULT OF L18 FOR INTRACRANIAL RESPONSES FROM CASE 1 (OCCIPITAL IMPACT)

No.	Brain Relative Disp. [mm]	Internal Energy of Brain [J]	Internal Energy of CSF [J]	No.	Brain Relative Disp. [mm]	Internal Energy of Brain [J]	Internal Energy of CSF [J]
1	0.978	0.070	0.165	10	0.970	0.086	0.164
2	1.174	0.073	0.177	11	1.184	0.061	0.179
3	1.283	0.059	0.283	12	1.292	0.059	0.285
4	0.958	0.079	0.166	13	0.963	0.085	0.165
5	1.172	0.073	0.178	14	1.184	0.070	0.180
6	1.302	0.057	0.286	15	1.305	0.056	0.285
7	0.962	0.078	0.168	16	0.966	0.086	0.167
8	1.179	0.074	0.180	17	1.175	0.070	0.180
9	1.296	0.057	0.286	18	1.314	0.055	0.288

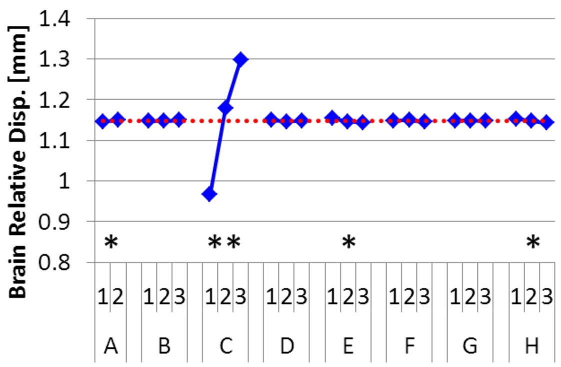

Fig. 16. Factorial effects of parameters on brain relative displacement for Case 1 (Occipital Impact)

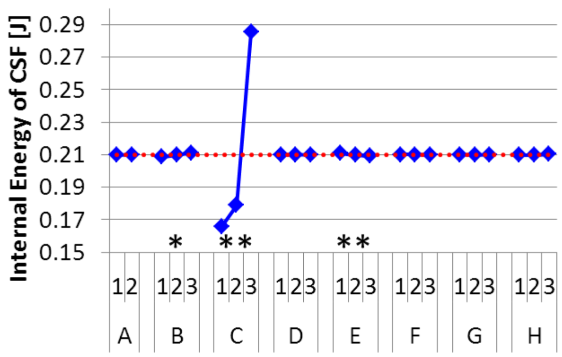

Fig. 17. Factorial effects of parameters on internal energy of CSF for Case 1 (Occipital Impact)

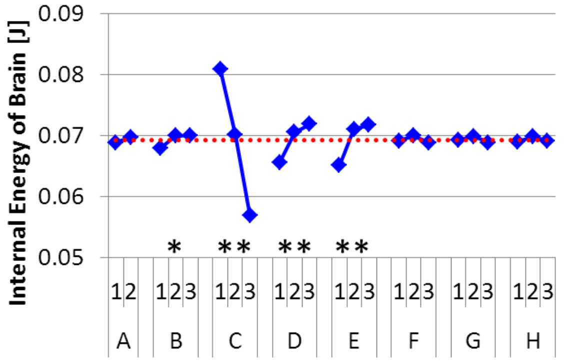

Fig. 18. Factorial effects of parameters on internal energy of brain for Case 1 (Occipital Impact)

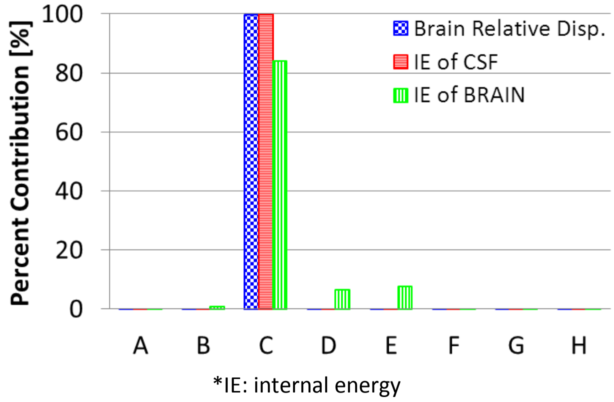

Fig. 19. Percent contribution of parameters on brain relative displacement and internal energies of CSF and Brain for Case 1 (Occipital Impact)

For brain relative displacement, as shown in Figure 16, PAC layer volume had significant influence ($p<0.01$), while stiffness of falx cerebri, gray matter and stiffness of BV had secondary influence ($p<0.05$). There was positive correlation between brain relative displacement and PAC layer volume.

For internal energy of CSF, as shown in Figure 17, PAC layer volume and stiffness of gray matter had significant influence ($p<0.01$), while stiffness of tentorium had secondary influence ($p<0.05$). There was positive correlation between internal energy of CSF and PAC layer volume while there was negative correlation between that and stiffness of gray matter.

For internal energy of brain, as shown in Figure 18, PAC layer volume and stiffness of brain had significant influence ($p<0.01$), while stiffness of tentorium had secondary influence ($p<0.05$). There was positive correlation between internal energy of brain and stiffness of brain while there was negative correlation between that and PAC layer volume.

From the percent contribution of each parameter shown in Figure 19, the influence of PAC layer volume accounted for most of the change of these intracranial responses.

Influence of impact direction

Table 8 shows the peak total internal energy (IE_{tot}) and peak ratio of the sum of internal energy of falx cerebri and tentorium (IE_{ft}) to IE_{tot} in each impact condition from the L18 simulation results. In order to compare the results of occipital impact and temporal impact, the average value and standard deviation of each intracranial response were calculated from 18 combinations of parameters. Figure 20 shows the comparison of the average value of each intracranial response with each impact direction. In Figure 20, error bars show the standard deviation of all combinations.

TABLE 8
RESULT OF L18 FOR PEAK TOTAL INTERNAL ENERGY AND PEAK RATIO OF SUM OF INTERNAL ENERGY OF FALX CEREBRI AND TENTORIUM TO PEAK TOTAL INTERNAL ENERGY IN EACH IMPACT DIRECTION

No.	IE_{tot} [J]		Ratio of IE_{ft} to IE_{tot} [%]		No.	IE_{tot} [J]		Ratio of IE_{ft} to IE_{tot} [%]	
	Occipital	Temporal	Occipital	Temporal		Occipital	Temporal	Occipital	Temporal
1	0.784	0.453	5.23	8.05	10	0.787	0.455	5.12	7.74
2	0.805	0.457	5.39	7.90	11	0.804	0.455	5.35	8.57
3	0.794	0.472	6.42	8.42	12	0.794	0.471	6.37	8.65
4	0.799	0.459	5.50	8.29	13	0.795	0.459	5.46	8.23
5	0.804	0.460	5.74	8.72	14	0.816	0.462	5.64	9.00
6	0.791	0.476	6.91	9.41	15	0.784	0.474	6.86	9.61
7	0.803	0.462	5.71	8.83	16	0.799	0.462	5.68	8.81
8	0.807	0.463	5.96	9.31	17	0.818	0.464	5.82	9.50
9	0.794	0.478	7.13	9.95	18	0.789	0.477	7.10	10.18

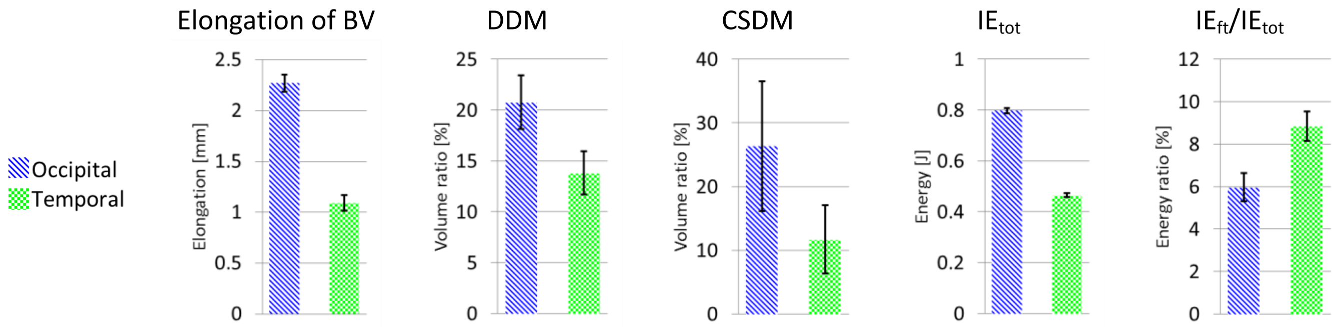

Fig. 20. Comparison of average value with each impact condition

From Figure 20, elongation of BV, DDM, CSDM and IE_{tot} in occipital impact was greater than those in temporal impact while the ratio of IE_{ft} to IE_{tot} in occipital impact was smaller than that in temporal impact.

IV. DISCUSSION

In both occipital and temporal impacts, it was found that elongation of BV increased with PAC layer volume and that PAC layer volume had a strong influence on brain-skull relative displacement. On the other hand, there was negative correlation between elongation of BV and stiffness of BV, while stiffness of BV had little influence on brain-skull relative displacement. From these results, it is suggested that elongation of BV is influenced by both the change of brain-skull relative displacement caused by the change of PAC layer volume and by local deformation around the roots of BVs on the brain surface caused by the relative difference of stiffness between brain matter and BV. Further investigation is needed to confirm if such a phenomenon may actually occur, since rupture of BV was not considered in this study.

In both occipital and temporal impacts, DDM increased with stiffness of gray and white matter. On the other hand, percent contribution of stiffness of brain matter for internal energy of CSF and brain was quite little in spite of its significant influence on internal energy of CSF and brain. In the condition of equal internal energy with the material whose stress increases with strain monotonically, stress increases while strain decreases when the stiffness of the material is increased. This is considered as the reason why DDM which is the index of the stress level increased with stiffness of brain matter although the change of the internal energy of brain was little.

In both occipital and temporal impacts, CSDM decreased when PAC layer volume and stiffness of brain matter increased. Internal energy of CSF increased and that of brain decreased when PAC layer volume increased. From these results, it is considered that strain energy of the brain decreases because of more impact energy absorption by the PAC layer when PAC layer volume increases. Furthermore, it is considered that CSDM which is the index of the strain level decreases when stiffness of brain matter increases, since the influence of the change of stiffness of brain matter on the internal energy of brain is little and there is negative correlation between the change of stiffness of brain matter and the strain of the brain as previously mentioned.

In comparing both impact conditions, all injury metrics (elongation of BV, DDM and CSDM) in occipital impact were greater than those in temporal impact. Furthermore, IE_{tot} in occipital impact was greater than that in temporal impact, while the ratio of IE_{ft} to IE_{tot} in occipital impact was smaller than that in temporal impact. From these results, it is considered that the decrease of injury metrics in temporal impact is caused by the decrease of total internal energy by more restricted brain motion by the falx cerebri and tentorium.

In this study, although the influence of various aging factors on intracranial responses was clarified, injury risk considering the tolerance of tissue was not investigated. For example, concerning the relationship between stiffness and elongation of BV, Delye et al. [15] and Monson et al. [16] conducted tension test of BV from which it is suggested that stiffness of BV increases while rupture strain of BV decreases with aging (Table 9). In this study, it was shown that elongation of BV decreased when stiffness of BV increased, which meant that the incidence risk of ASDH decreased. This contradicted the relationship between the incidence rate of ASDH calculated from the result of Kameyama et al. [13] and age. But, it is presumed that the incidence risk of ASDH is changed when not only the stiffness of BV but also rupture strain of BV is considered.

TABLE 9
MECHANICAL PROPERTIES OF BV (MEAN VALUE)

	Age	Ultimate Stress [MPa]	Ultimate Strain [%]	Young's Modulus [MPa]
Delye[15]	59	1.32	50	6.43
Monson[16]	78	4.99	25	30.69

Although the influence of aging factors on intracranial responses were investigated to get the basic knowledge for development of the elderly head/brain FE model in this study, further investigation on input condition, i.e. impact direction, magnitude, duration time and so on, is needed .

V. CONCLUSIONS

The influence of aging factors on intracranial responses under head impact was clarified by using a human head/brain FE model which represented the detailed intracranial structure. Furthermore, influence of the impact direction on intracranial responses related to the characteristic brain injury of the elderly was studied swapping the axis in the model along which the acceleration pulses were applied. From these simulation results, the following were found:

- PAC layer volume and stiffness of BV had strong influence on elongation of BV.
- Stiffness of brain matter strongly influenced DDM.
- Stiffness of brain matter and PAC layer volume had a strong influence on CSDM.
- All of the injury metrics studied in this study in occipital impact were greater than those in temporal impact.

From these results, the possible factors of aging affecting brain injuries were found, which could be the basic knowledge for the future development of age specific head/brain models to study elderly brain injury mechanism.

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