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Chest compression of a pregnant woman by a seatbelt might affect fetal outcome, even in minor to moderate frontal vehicle collisions

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ABSTRACT

Introduction: Pregnant women often suffer from negative fetal outcomes, despite wearing a seatbelt correctly. When restrained vehicle passengers are involved in a frontal collision without suffering from any injuries, the forces they experience are particularly concentrated in the chest because of the seatbelt. We analyzed the biomechanics of chest injuries sustained by restrained pregnant drivers and possible effects of these injuries on the fetus.
Material and methods: The Maternal Anthropometric Measurement Apparatus dummy, version 2B, representing a pregnant woman at 30 weeks of gestation, was used. Sled tests were performed for recreating frontal impact situations with vector velocity changes at impact speeds of 13, 26, and 40 km/h. Overall kinematics of the dummy were examined using high-speed video imaging. Quantitative dummy responses, such as time course of acceleration of the sled and chest, pressure of the belt, and deflection of the chest (right and left) during impact were also measured.
Results: Although collision velocities were different, the distances of forward movement of the dummy were similar (121–129 mm) owing to the safety devices. However, maximum deflection of the chest (35.4 mm to the left and 15.7 mm to the right) was obtained at a 26-km/h collision. Additionally, maximum deflection of 28.7 mm to the left and 10.9 mm to the right of the chest were obtained at 40 km/h.
Conclusions: Because the uterus enlarges and the fundus reaches the lower part of the rib cage during late pregnancy, we consider that the reason for negative fetal outcomes is partly owing to chest compression and subsequent applied forces on the uterus, even in minor to moderate frontal collisions. This knowledge may be useful for forensic scientists who determine the causes and mechanisms of a fetal death or the offenders' responsibilities for both maternal and fetal outcomes when the mother is involved in a frontal vehicle collision.

1. Introduction

Trauma during pregnancy is a leading cause of maternal and fetal morbidity and mortality. Motor vehicle collisions (MVCs) are a significant cause of trauma during pregnancy. Annually, in the United States, approximately 130,000 women are involved in MVCs during the second half of their pregnancy [1]. Of the survivors, 300–3800 sustain fetal loss. According to a national population-based study in Sweden, the incidence of maternal and fetal deaths related to MVCs were 1.4 and 3.7 per 100,000 pregnancies, respectively [2]. Therefore, underlying mechanisms of maternal injuries should be investigated for reducing and/or preventing maternal, as well as fetal, MVC-related injuries worldwide.

Wearing three-point seatbelts reduces the mortality and extent or severity of injuries of the vehicle occupants. According to previous reports, wearing a seatbelt during pregnancy has better fetal outcomes after MVCs than not wearing a seatbelt [3,4]. Therefore, wearing seatbelts by drivers and vehicle passengers is legally required in many countries. Additionally, the American College of Obstetricians and Gynecologists recommends wearing seatbelts correctly for reducing the risk of injury to the mother and fetus [5]. We have previously performed a series of front and rear

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impact sled tests using an anthropometric model of a pregnant woman and studied the mechanism of injuries in pregnant drivers [6–8]. We found that wearing a seatbelt reduced abdominal pressure or prevented contact with the steering wheel during frontal and rear collisions. Therefore, we biomechanically confirmed the positive effects of wearing a seatbelt.

However, if belted, pregnant women who are involved in MVCs sustain more morbidities than those not involved in a vehicle collision [9]. When belted vehicle passengers are involved in a frontal collision without sustaining any injuries, any forces they experience are particularly directed at the chest through the seatbelt. For women in late pregnancy who have enlarged uteri reaching the lower part of the chest, forces to the chest may have an impact on the uterus containing the fetus. Therefore, underlying mechanisms of chest injuries in pregnant women need to be understood for forensic scientists to determine causes and mechanisms of a fetal deaths, even if the mother's injuries are considered as minor. However, to the best of our knowledge, there have been no reports concerning the mechanism of chest injuries of restrained pregnant women who are involved in vehicle collisions.

Therefore, in this study, we aimed to examine the biomechanics of chest injuries of restrained pregnant drivers during minor to moderate frontal vehicle collisions.

2. Material and methods

2.1. Dummy

We used the most recent version of the Maternal Anthropometric Measurement Apparatus dummy, version 2B (MAMA-2B), which was developed by First Technology Safety Systems and the University of Michigan Transportation Research Institute in 2001 [10]. This dummy was developed based on the Hybrid-III, which renders it suitable for vehicle impact tests and for analyzing kinematics of pregnant women during a MVC. The dummy has a modified pelvis and ribcage to enable installation of a silicone rubber bladder representing the uterus at 30 weeks of gestation [11]. The size of the dummy was based on an American female dummy in the fifth percentile, which represents a small female with a height of 153 cm. This size is in accordance with that of a standard Japanese pregnant woman at 30 weeks of gestation [12].

2.2. Seating position of the dummy

We determined the seating position on the basis of Japanese pregnant women at 30 weeks of gestation with similar anthropometric dimensions as the dummy [12]. The seating position and posture of the dummy were then determined as follows: seat slide position of 70 mm from the full forward position and reclined at 8.0° (torso angle of 21°).

2.3. Test setup

We used the Instron Servo Sled Apparatus. The seat, seatbelt, steering wheel, and steering column that were installed in the test setup were the same as those in the vehicle in which the seating positions of the volunteers were measured. At each test, the dummy was seated in the driver's seat wearing a three-point seatbelt. To represent situations of a frontal impact while driving a passenger vehicle, trapezoid waveforms that were measured during a flat barrier test with vector velocity changes at the time of impact (delta-V) of 13, 26, and 40 km/h were applied to the sled (corresponding to tests 1–3, respectively). Fig. 1 shows the deceleration pulse applied to the test setup.

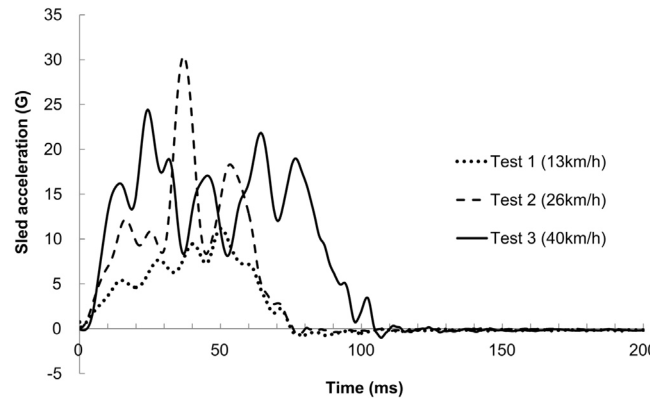

Fig. 1. Deceleration pulse applied to the test setup.

A pretensioner retracted the safety belt almost instantly in a crash to prevent excess slack. This secures the occupant to the vehicle while in early deceleration during the crash. Furthermore, to avoid chest injuries, the belt forces were limited by a force limiter reducing the peak load experienced by the occupant. Vehicles are usually equipped with both systems and were used in these experiments. During test 1, the airbag was not deployed and the pretensioner or force limiter of the seatbelt was not activated. During test 2, the airbag was deployed and the pretensioner was activated without activation of the force limiter. During test 3, the airbag was deployed, and both the pretensioner and force limiter were activated. These conditions were the same as those in real-world frontal collisions. To measure deflections of the chest to the right and left of the chest, a system called Infrared Telescoping Rod for Assessment of Chest Compression (IR-TRACC) was used. This system was mounted inside of the right and left second rib of the dummy. Overall kinematics of the dummy were examined using high-speed video imaging. Quantitative dummy responses, such as time course of acceleration of the sled and chest, pressure of the belt, and deflection of the chest to the right and left during an impact, were also measured.

3. Results

3.1. Kinematics of the dummy

During test 1, the dummy's chest moved the furthest forward by 125 mm from the initial position at 87 ms from initiation of the impact. The chest did not make any contact with the steering wheel (Fig. 2A). During tests 2 and 3, the dummy moved the furthest forward by 129 mm from the initial position at 69 ms and by 121 mm from the initial position at 72 ms, respectively (Fig. 2B). During tests 2 and 3, the upper chest and the face of the dummy came in contact with the airbag, subsequently causing the dummy to move downward.

3.2. Belt force

The time course of belt force that was measured at the shoulder belt is shown in Fig. 3. Maximum values were observed at the time when the dummy moved to the forward-most position at 81, 62, and 49 ms in tests 1, 2, and 3, respectively. With an increase in collision velocity from 13 to 26 km/h, the maximum shoulder belt forces increased from 2.6 to 5.0 kN, respectively. At a collision velocity of 40 km/h, as the force limiter was activated, the maximum shoulder belt force was 4.6 kN, similar to that at 26 km/h.

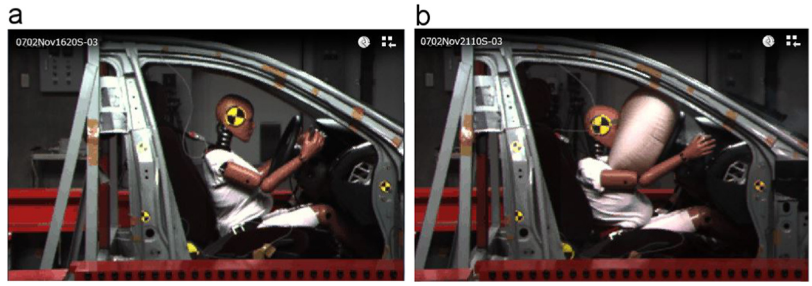

Fig. 2. (A) The instant at which the dummy's chair moved forward the furthest during test 1. (B) The instant at which the dummy's chair moved forward the furthest during test 3.

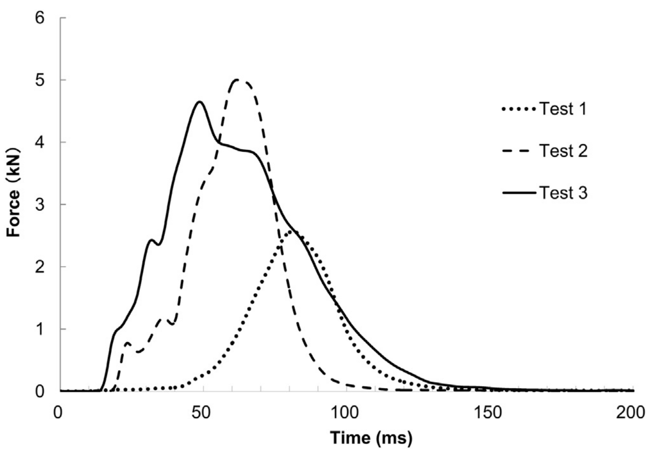

Fig. 3. Time courses of shoulder belt forces during each test.

3.3. Deflection of the chest

Time histories of deflection of the chest are shown in Fig. 4. The course of the shoulder belt depends on whether the vehicle is driven on the right or on the left side. In all tests, the values of deflection of the chest to the left were much higher than those to the right owing to the belt path of the driver's seat (from the right shoulder to the left pelvis). During test 1, the maximum values of deflection, 14.2 mm to the left and 3.9 mm to the right, were obtained at 105 ms from initiation of the impact. The maximum deflection, 35.4 mm to the left and 15.7 mm to the right, was obtained at 86 ms in test 2. During test 3, the maximum values of deflection were 28.7 mm to the left and 10.9 mm to the right, which were similar at 72 and 90 ms after initiation of the impact.

4. Discussion

In the present study, regarding the scenes of collision, although collision velocities were different, the distances of forward movement of the dummy were similar (121–129 mm) owing to the safety devices, pretensioner, and force limiter of the seatbelt and airbag. During tests 2 and 3, as the pretensioner was activated in accordance with elevation of delta-V, the maximum forward displacement was observed earlier than that during test 1. In our series, because the dummy did not come in direct contact with the steering wheel, we assumed that pregnant women would not suffer severe chest injuries (i.e., multiple rib fractures and lung laceration) when involved in frontal collision with a delta-V of ≤40 km/h. Overall, airbags contributed to the safety of the driver by mitigating forward movement, as shown above. In addition, airbags had additional potential benefits related to filling some of the space between the driver and steering wheel. The airbag provided a primary restraint for the head and face, as shown in Fig. 2, minimizing contact with the steering wheel. Furthermore, the airbag distributed the force on the chest and shared loading with the belt system, meaning that belt loading was also reduced with the addition of an airbag. Therefore, the deflection of the chest may be more severe if an airbag is not deployed in tests 2 and 3.

When a pregnant female vehicle passenger is involved in a low-velocity frontal collision, she is considered to be safe if she has no external abnormalities [13]. Indeed, minor injuries that require only emergency department evaluation and subsequent discharge or those that are not referred to physicians are much more common. However, according to epidemiological research studies in the USA, women who are involved in a vehicle collision are more likely to suffer from problems during pregnancy [9,14]. Furthermore, the risks are higher following the second or subsequent crashes [9]. A retrospective cohort study showed that even if pregnant women had worn seat belts, preterm births occurred in 122 of 100,000 pregnancy days [9]. In this retrospective study, 5.2 stillbirths, 7.0 placental abruptions, and 22.3 premature rupture of the membranes were also observed. A population-based study showed that minor injuries for which hospital admission was not required among women in the first or second trimester were independently associated with fetal demise, prematurity, and low birth weight at delivery [15]. Another study reported that 19.2% women with only minor bruising, contusions, or lacerations

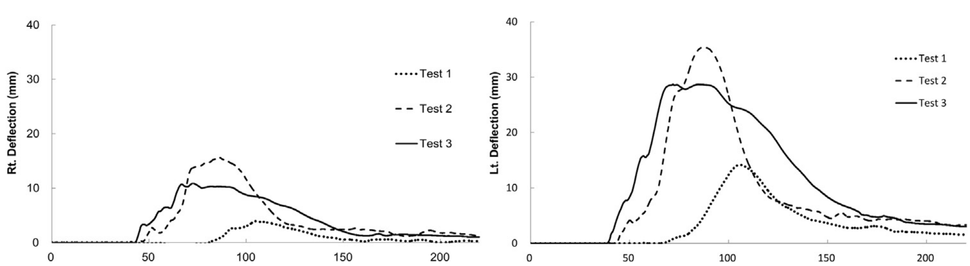

Fig. 4. Time courses of deflections to the left and right of the chest during each test.

suffered from placental abruption, premature delivery, or low birth weight [16]. These results are in accordance with previous reports that state that pregnancy loss can occur after relatively minor collisions without maternal anatomical injury [17,18]. Additionally, a study that reviewed insurance reports of pregnant women involved in traffic accidents showed similar conclusions and mentioned that predicting fetal loss on the basis of severity of anatomical injury is difficult [19]. Therefore, minor injuries may not be as minor for pregnant women as considered previously.

During vehicle collisions, not all external forces that are applied on a pregnant woman will result in demonstrable anatomical injuries with an abbreviated injury scale score of $\geq$1. Indeed, according to a study on pregnant MVC casualties in levels 1 and 2 emergency medical services, although 40.8% of women reported experiencing forces to the chest or abdomen, only 15.6% showed overt injuries to the chest or abdomen [20]. Because the lap belt is placed on the lower part of the abdomen, it sometimes causes abdominal injuries when positioned inappropriately. The lap belt crosses between the right and left anterior superior iliac spine to restrict the bone when used correctly. Under the present study conditions, we considered that the lap belt was not harmful for the abdomen. Therefore, in this study, we focused on the mechanism of minor chest injuries that were sustained by restrained pregnant women using a seatbelt.

In our study, when a dummy representing a pregnant female driver experienced frontal collisions at delta-Vs of 26 and 40 km/h, chest compression of 35.4 and 28.7 mm was sustained, respectively. As gestation progresses, the uterus enlarges and the fundus reaches the lower part of the rib cage. Therefore, chest compression from frontal collisions during later stages of pregnancy could result in external forces to the uterus including the fetus. Klinich et al. showed the risk curve of adverse fetal outcomes by the delta-V of the involved vehicle [4]. If the occupant was properly restrained, the rate of an adverse fetal outcome was approximately 30% at a delta-V of 40 km/h. We considered that the reason for the negative outcome was partly because of chest compression and subsequent applied forces to the uterus. Deflection of the chest leads to acute changes in intrathoracic or intra-abdominal pressure in women during late pregnancy and results in a direct blunt force to the uterus.

Before development of the system of the dummy model with IR-TRACC, which was used in this study, deflection of the chest was only measured by deflection of the sternum. Deflection of the sternum is an injury criterion that is used in current regulatory and consumer tests worldwide to assess the risk of thoracic injury. In vehicle safety regulations, the threshold at which a small, young, middle-aged woman suffers from severe chest injuries with an abbreviated injury scale of $\geq$3 was set as a deflection of the sternum of 48 mm [21]. However, according to recent cadaver and animal experiments, the thorax deformation pattern appears to be sensitive to the geometry of the seat belt; displacement of the thorax is different between the right and the left [22,23]. The MAMA-2B has IR-TRACC, which enables separate measurement of deflection of the chest to the right and left. Therefore, we could obtain the actual response of the chest for localized seat belt loading [24]. In crash tests, crash test dummies are used to estimate a human's risk of injury. Consequently, the dummy must possess a sufficient mechanical impact response similar and sensitive enough to cause them to interact with the vehicle's interior in a human-like manner. In this study, although deflected values of the chest were <48 mm below the threshold of the safety standard, any force might apply to the uterus of a late-term pregnant woman because of chest compression.

Fetal deaths related to MVCs arise with considerable frequency. Placental abruption is the most likely cause of adverse fetal outcome in MVCs. Placental abruption frequently arises alone or in conjunction with other common crash-induced injuries to the pregnant abdomen, such as direct fetal or uterine injuries [18]. Uteroplacental interface failure, which is the postulated major mechanism of placental abruption, can be caused by external forces at the time of a crash. Characteristics of the uterine muscle (elastic) and placental tissue (inelastic) differ in the pregnant uterus. Therefore, when an external force is applied, the impact on both tissue surfaces act as a separating force. The surface of the uteroplacental border can be damaged because of lower tensile strength than the uterus or placental tissue [25]. Furthermore, the amniotic fluid is incompressible. Therefore, the force applied on the uterus causes the uterine muscle to extend beyond the impact site because of the amniotic fluid. This then causes separation, even though there is no relationship between the impact site and the position of placental attachment [26]. Moreover, increased intrauterine pressure promotes placental abruption and facilitates formation and growth of retroplacental hematomas [25].

During pregnancy, the diaphragm is positioned higher than usual, and the uterus grows and occupies the greatest space in the peritoneal cavity. We observed a considerable amount of thoracic cavity displacement in our test dummy at the time of frontal impact in the present study. This finding suggests that increased intrathoracic pressure in pregnant women at the time of a collision might also cause an external force through the diaphragm. This then leads to a “difference” in the uteroplacental surface, which can cause increased intrauterine pressure. We consider this to demonstrate the cause of premature placental abruption in cases without direct trauma to the maternal abdomen.

5. Conclusion

We found that the MAMA-2B dummy, which mimicked a restrained pregnant woman, sustained maximum chest deflection of 35.4 mm when involved in frontal collision with a delta-V of $\leq$40 km/h. This finding suggests that chest compression via the seatbelt might lead to a fetal negative outcome, even in minor to moderate frontal collisions. This knowledge may be useful for forensic scientists who determine the causes and mechanisms of a fetal death or the offenders' responsibilities for both maternal and fetal outcomes when the mother is involved in a frontal vehicle collision. Furthermore, development of the seatbelt system for reducing the forces to the chest is desired to safeguard the fetus.

Authors' contributions

Akiko Ishiko designed the study, analyzed the data and drafted the manuscript.

Masahito Hitosugi designed the study, obtained funding, performed the crash test, and drafted the manuscript.

Marin Takaso performed the crash test and acquired the data.

Koji Mizuno analyzed the data and edited a draft of the manuscript.

Shunichiro Tsuji and Tetsuo Ono analyzed the data and created the figures.

Fuminori Kimura interpreted the data and edited a draft of the manuscript.

Takashi Murakami reviewed the work critically for important intellectual content.

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Conflict of interest

The authors report no conflict of interest.

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