SYNTHESIS OF ABDOMINAL INJURIES IN FRONTAL COLLISIONS WITH BELT-WEARING CADAVERS COMPARED WITH INJURIES SUSTAINED BY REAL-LIFE ACCIDENT VICTIMS

PROBLEMS OF SIMULATION WITH DUMMIES AND PROTECTION CRITERIA

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The wearing of the so-called three-point seat-belt has unquestionably brought about a decrease in both the frequency and the seriousness of the injuries sustained by automobile accident victims, when one compares the injuries incurred by the wearers of these belts with the injuries suffered by non-belt wearers in accidents of comparable impact violence.

However, the standard seat-belt still has room for considerable improvement. The injury-provoking mechanisms and the tolerances of the head and thorax are fairly well known, and this knowledge has enabled definition of protection criteria for frontal collisions simulated with dummies ; the situation is different as concerns the abdominal viscera and the lumbar spine. However, injuries of this type are not inconsiderable in the light of the realities concerning accidents involving seat-belt-wearers.

In what follows, after evaluating the extent of submarining-induced injuries, it is proposed to compare those of the real-life victims and those of the cadavers used in frontal impact simulations. An attempt is then made to define as accurately as possible the conditions associated with dangerous submarining, from the viewpoint of a specific protection criterion.

In order to illustrate the relative importance of the abdomen, in relation to the body segments which are commonly taken into account -the head and thorax- it suffices to consider Table I, whose data stem from the IRO - PEUGEOT RENAULT Accident Investigation.

This table concerns a sample of 938 three-point seat-belts, among whose wearers 533 drivers and 283 passengers were taken into consideration.

In order to carry out an unambiguous analysis, we eliminated a number of cases that would have been hard to interpret, including those involving excessive damage to the passenger compartments ; the selection criterion was a less than 26 centimeter rearward displacement of the dashboard ; we also eliminated the cases of victims who had been killed but whose bodies had not been autopsied, the specific causes of whose deaths did not emerge clearly.

In addition to showing the frequency of the injuries classified by A.I.S. and by body segments, this table includes an evaluation of the overall injury level of the lesions sustained by the various body parts considered. This evaluation was performed by means of the expression $\sum$ A.I.S.^{3}.

It will be noted that the importance of the injuries incurred by submarining, to be taken from the total of the abdominal lesions the lesions of the lumbar spine, can be of the same order of magnitude as that of the lesion usually taken into consideration by protection criteria.

ABDOMINAL AND DORSO-LUMBAR INJURIES SUSTAINED IN ACTUAL ACCIDENTS

The data come from the investigation noted above.

Wearers of three-point seat-belts undergoing frontal impact, selected as previously, were firstly considered. However, it was possible to take most recently available cases into account.

Table 2 lists a synthesis of the observations performed.

The abdominal lesions can be classified as follows :

a) Lesions caused by deceleration, generally found when the pelvic strap has exerted extremely energetic restraining force. The displacement of the visceral mass in a forward direction, due to inertia, triggers traction forces exerted on the mesentery which can bring about disinsertions ; we also found tearing of the liver hilus or of the gall-bladder bed.

This kind of injury is rare, and is associated with involvement in exceptionally violent frontal collisions.

For the two corresponding cases, the variations in velocity and the mean accelerations during impact are as follows :

Case # 2500 : $\Delta V = 55$ kph - $\gamma m = 14$ g
Case # 2352 : $\Delta V = 70$ kph - $\gamma m = 17$ g

These lesions are listed here just for the record, because their cause and prevention have very little to do with the problems of submarining.

b) Lesions of the viscera caused by actual submarining

In this category, we included injuries caused by overly-deep penetration of the pelvic belt into the abdomen, this part of the belt having passed above the iliac crests. This situation, which is fortunately of rare occurrence, results from the combination of unfavorable factors.

In real-life accidents, injuries to the liver or spleen can be caused by submarining. The same can be said for perforations of the small intestine or of the colon and also of a certain proportion, which is difficult to ascertain, of tearings of the mesentery.

c) Mention must also be made of lesions of the dorso-lumbar spine, althought they are infrequent. The accident investigation that was used supplied four cases, only two of which are listed in Table I, the other two cases having occurred too recently. The corresponding A.I.S. is 2 or 3 ; this involves fractures of the vertebrae, often accompanied by compression of the vertebral body.

It is reasonable to think that these four cases of injury are due to the passengers' submarining, followed by extensive flexion of their trunks around the seat-belt ; the consequences thereof were limited thanks to the blocking of their knees by the lower dashboard. This process justifies considering a large proportion of the injuries sustained by the dorsal-lumbar column as injuries caused by submarining.

Among the parameters that increase the passenger's propensity for submarining, let us note the following :

- Floor-attachment points of seat-belt located too far back.
- Slack of the pelvic belt.
- Excessive deformability of the seat cushion.
- Seat-belt buckle located too high, etc.

The complexity of the phenomenon justifies the concern with a synthesis test performed on a dummy.

Table 2 lists the countermeasures suggested by an examination of the records : theoretically, the presence of these countermeasures on the vehicles involved in the accidents would have prevented the onset of submarining. It will be noted that the adapting of the retractors and the restraining of the rear passengers should have a positive effect. It will further be noted that, even when the directions of the pelvic belt-straps are a priori correct, the buckles located in overly high positions are a major risk factor.

When the buckles are not at fault, submarining occurs only in extremely violent impacts.

DATA YIELDED FROM FRONTAL IMPACT TESTS WITH CADAVERS

Test conditions

Table 3 shows the conditions governing a selection of frontal impact simulation tests performed with seat-belted cadavers.

The subject always wears a three-point seat-belt and is generally installed in a sled borne vehicle passenger compartment, launched against an impact wall ; the deceleration pulse is dependant upon the braking device, made of collapsible tubes, installed on the front end of the sled.

Information of a more detailed sort has been published concerning the methodology of these tests (1). The tests are followed by X-rays and autopsies, among other data analyses procedures.

In the latest tests (beginning with N°1274), spinal-column samples were collected in view of a more complete autopsy process analogous to Schmidt's process (2).

Among the results available, we selected those in which abdominal injuries had occurred either or without submarining ; similarly, we selected cases of submarining without occurrence of lesions. The ratios of the type "number of cases with injuries" divided by "total number of cases" are meaningless, since the test plan called for a study of submarining and therefore required particular, non representational test conditions. The cadavers considered were those of individuals whose deaths had occurred recently (less than four days before) and who had not been embalmed, without rigor mortis. There was no abdominal injection.

The injection liquid containing formol, the occurrence of fixation of abdominal viscera is thereby obviated ; more reliable detection of injuries, during autopsy, is also insured.

The measurements made, of varying degrees of completeness depending on the test, included restraining forces and accelerations, particularly at the sacrum level, were a tridirectional accelerometer was screwed. Analysis of the films, at 1.000 fps, enabled evaluation of the importance of penetration, if any, of the seat-belt strap into the abdomen by means of sighting marks secured to the spinal column and to the iliac wings.

The seat-belts, without retractors, were adjusted to the wearers.

Injuries observed

The same classification as the one previously used for injuries sustained by real-life accident victims can be used here.

The cadavers revealed injuries of deceleration of the viscera (without submarining), represented here by two cases of mesenteric rupture (subjects # 14 and 25) and a slight fissuring of Glisson's capsule along the bladder bed (# 10).

The following injuries were found again :

- Lesions of the viscera due to submarining. The case of subject # 2 is characteristic (injury to upper surface of liver, rupturing of mesentery and perforated colon).

- Lesions of the lumbar-spine : fractures at this level occurred either in association with other lesions in the subjects of the sample group that underwent submarining, or unaccompanied by visceral lesions.

Since the observation of submarining, or of its absence, is unambiguous on cadavers, this justifies our considering the occurrence of injuries to the lumbar-spine as a frequent result of submarining, in the investigation of real life accidents.

By and large, the injuries detected in the autopsies of test subjects that had undergone submarining were similar to those in the accidentology.

If we consider the conditions governing their occurrence, we find that the causes linked to the conditions of the simulated accidents are analogous to those found to be likely in analyses of real-life accidents, a finding that is not surprising ; it is more noticeable to remark that the impact violence aera in which submarining occurs in actual accidents overlaps with the impact violence aera of accidents simulated with cadavers. Here, impact violence is expressed by a pair of values ($\Delta V, \gamma m$), in which ΔV is the variation in velocity and γm is the average acceleration during impact.

The investigation of submarining-related problems by means of impact simulation with fresh cadavers is hence a good approximation of reality.

It will be noted that the visceral injuries sustained by real-life accident victims frequently involve several different organs. One reason for this may be the fact that the real-life victims' seat-belts often have a large amount of slack : the effect of this is to make restraint by the belt more severe and may change the position of the belt on the body. In some instances the presence of an overload by an unbelted rearseat passenger can also be an injury aggravating factor.

Experiments with human subjects further enable the detecting of cases of submarining involving no sustaining of injuries, the occurrence of which cases is difficult to detect in accidentological investigations.

EVALUATION OF ABDOMINAL TOLERANCE OF SUBJECTS THAT UNDERWENT SUBMARINING

With the total abdominal injury level a known factor, we observed intrusion of the belt-strap into the abdomen, the restraint forces and the conditions attendant upon its application during intrusion, particularly at the time during which intrusion is at a maximum.

Acceleration measured for the pelvis was not taken into consideration ; few results are available, and we found no indications of a relationship between its maximum (peak, or during 3 ms) and the severity level of the injuries observed. However, the submarining often gives a signature on the acceleration pulse.

The intrusion of the pelvic strap beyond the iliac spines, in a direction that is largely perpendicular to the lower part of the torso, was evaluated as accurately as possible.

Depending on the test and on the side observed, it ranged from 20 to 75 mm in the cases in which submarining occurred.

In the injury-free cases, maximum belt intrusion was 37 mm on one side. The lowest intrusions found, associated with the occurrence of injuries, were 40 mm beyond the antero-superior iliac spines. This value was observed three times in the subjects, and the heaviest of the subjects involved weighed 71 kilograms a weight that is still lower than that of the dummy representing the 50 th male percentile.

The restraining forces that are going to be considered are the 2 traction forces of the pelvis part of the three-point seat-belt subsequently to the onset of submarining.

In the cases in which no injuries occurred, this forces remained under 280 daN (lower outer anchoring) and 250 daN on the inside of the vehicle.

In contrast, in the cases in which injuries did occur, we found a minimum of 380 daN for the vehicle's outer side and 420 daN for its inner side.

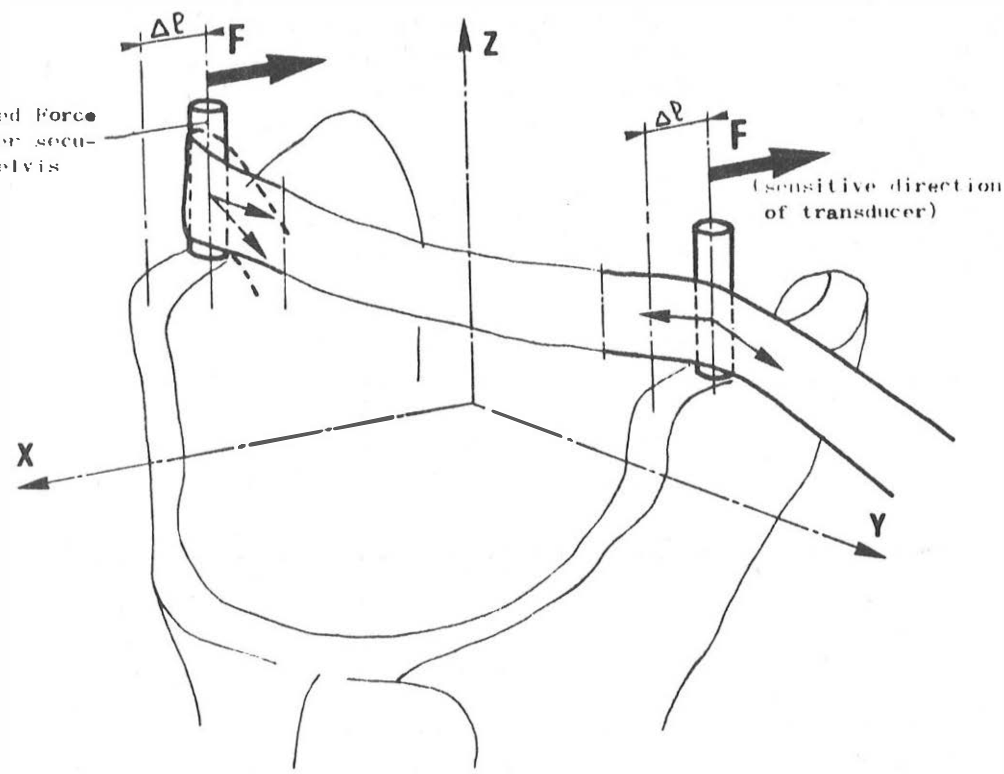
If we compare, on the one hand, the group of subjects that sustained abdominal injuries and, on the other hand, the group of those that remained uninjured despite submarining, we find distinctly separate measured values of intrusion and forces for these two groups. This remark increases the validity of the tolerance thresholds that were so evaluated. In other words, on the basis of a less-than- 35 mm intrusion on one side, associated with a less-than-200 daN restraining force on one of the pelvic belt strap side, we define a pair of values representing abdominal tolerance in the presence of submarining, while retaining a certain safety margin. These values have been given without taking into account the anthropometrical differences between subjects and 50° percentile. The subject's stature is usually lesser, so the safety margin is increased.

Belt tension is a measurement that is external to the subject, or to the dummy when dummies are used. In addition, the allowable tension values may differ depending on the conditions of seat-belt location and anchoring, of vehicle environment, etc. For this reason, we plan to use these findings to define the conditions to be measured on dummies for the purpose of ensuring protection against the dangers of submarining.

TENTATIVE DEFINITION OF A PROTECTION CRITERION

Let us assume the existence and availability of a dummy that, when exposed to submarining, displays a dybamic behavior closely akin to human behavior. Let us further assume that a criterion is desired for guaranteeing against the risks of submarining, but that its verification should involve only the dummy, and should in no case bring about a modification in the definition of the restraint system. This condition is highly important in the view of testing a system whose performances are identical to those of the systems with which cars are equipped, notably in the case of pyrotechnical retraction.

When the above situation has been assumed, it is no longer possible to undertake belt-forces measurements. We decided to use a pair of force transducers secured to the dummy's pelvis, each captor being located above the iliac crests.



These transducers read the forces exerted by the strap in direction F, in figure. They are located at a horizontal distance Δ 1 from point zero of the intrusion defined by the level of the antero-superior iliac spines.

The findings of the preceding paragraph enable definition of Δ 1, and make it possible to assign a value to F. For this purpose, we projected along an axis, parallel to OX, the resultant of the belt's action on the previously mentionned transducers (see figure). Equal belt tensions on either side of the captor were assumed.

The results of the calculations performed for the hypothetical case of the installation of such transducers on cadavers are set forth in Table 4, in the column headed "estimate of forces defined in the figure".

These results took into account the belt's angles in space, evaluated by films or by laboratory simulation.

It appears that a force transducer bears from 60 to 180 daN in cases of submarining without occurrence of injuries. It is therefore very likely that a transducer defined as above, which is located 35 mm behind the antero-superior iliac spines and on which the result of longitudinal penetration, does not exceed 100 daN, would indicate only injury-free submarining if the simulation of human kinematics by the dummy was correct.

Leung and al. (3) have shown some inadequacies of the Part 572 dummy in this respect, since the Part 572 dummy tends to submarine more readily than the human being.

They have shown significant differences in shape of pelvis and in rigidity of abdominal flesh, which by themselves are sufficient to testify of abdominal,, which by themselves are sufficient to testify to the lack of similarity in behavior during submarining.

A certain amount of testing with stress captors placed, as before, above the iliac crests have been done. The preliminary results are encouraging. The force results given here were to be modified if the sensitive directions of the transducers relatively to pelvis are changed.

SUMMARY AND CONCLUSIONS

1. In the light of current accidentological data, submarining is a not inconsiderable problem.

2. The submarining-related injuries sustained by real-life accident victims are similar to those found on fresh cadavers under comparable conditions.

3. A large number of injuries to the dorso-lumbar spine can be ascribed to submarining.

4. Submarining does not necessarily cause injuries.

5. On fresh cadavers, a limit marking the point at which submarining becomes dangerous has been defined. Information concerning abdominal tolerance has been assembled, designed to be transposed into a protection criterion on a suitable dummy.

6. The principle of a submarining avoidance criterion is presented.

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TABLE I - REAL FRONTAL COLLISIONS WITH 3PTS BELTED OCCUPANTS
SUMMARY OF INJURY SEVERITIES

DRIVERS (N = 533)

AIS	0	1	2	3	4	5	N	$\sum AIS^3$	$\sum \frac{AIS^3}{N}$
HEAD	363	122	40	6	-	2	533	854	1.602
NECK	498	33	-	2	-	-	533	87	0.163
THORAX	402	110	14	4	1	2	533	644	1.208
UPPER LIMBS	457	66	8	2	-	-	533	184	0.345
LUMBAR SPINE	517	14	1	1	-	-	533	49	0.091
PELVIS	506	21	4	2	-	-	533	107	0.201
ABDOMEN	511	15	1	-	6	-	533	407	0.764
LOWER LIMBS	365	136	11	21	-	-	533	791	1.484

FRONT PASSENGERS (N = 283)

AIS	0	1	2	3	4	5	N	$\sum AIS^3$	$\sum \frac{AIS^3}{N}$
HEAD	224	50	8	1	-	-	283	141	0.498
NECK	247	32	3	1	-	-	283	83	0.293
THORAX	174	81	21	6	1	-	283	475	1.678
UPPER LIMBS	235	37	5	6	-	-	283	239	0.844
LUMBAR SPINE	269	12	1	1	-	-	283	47	0.166
PELVIS	270	11	-	2	-	-	283	65	0.230
ABDOMEN	267	12	-	-	4	-	283	268	0.947
LOWER LIMBS	209	63	4	7	-	-	283	284	1.003

TABLE II - INJURIES OF LOWER TORSO IN REAL FRONTAL CRASHES

Case No	Seating Position	ΔV (km/h)	γm (g)	Age	A.I.S.	Injuries	Observations/Countermeasures
Lesions probably caused by deceleration							
2500	2	55	14	25	4	Tear of mesentery, devitalization of small intestine	Possible influence of a rear passenger
2552	1	65-70	18	31	4	Tear of mesocolon	
Abdominal lesions probably caused by submarining							
759	1	55	12	52	4	Tear of the mesentery, wound of liver, perforation of small intestine	Improved locations of anchorage points
2068	2	55	-	24	4	Bruise of mesocolon, wound of small intestine	Improved locations of anchorage points + reduced slack
2269	1	40	11	52	4	Wound of right liver lobe, rupture of the spleen	Reduced slack + properly worn seat-belt
2552	2	65-70	18	24	4	Tear of mesocolon, wound of colon, rupture of the spleen	Improved anchorage locations
2725	2	60	10	23	4	Rupture of the spleen, wound of liver, perforation of small intestine	Restraint of rear passengers
3018	1	-	-	39	4	Tear of mesentery, perforation of small intestine	Reduced slack + properly worn seat belt
3235	1	65-70	17	22	4	Tear of colon, wound of liver	
3472	1	55-60	-	62	4	Bruise of L. kidney, bruise of ureter, rupture of the bladder	Reduced slack

TABLE II - INJURIES OF LOWER TORSO IN REAL FRONTAL CRASHES (continued)

Case No	Seating * Position	ΔV (km/h)	γm (g)	Age	A.I.S.	Injuries	Observations/Countermeasures
Abdominal lesions probably caused by submarining							
3499	2	40-45	11	53	4	Wounds of liver, spleen, intestine, colon	Reduced slack, restraint of rear passenger
3656	1	55-60	12	39	4	Rupture of mesentery, perforation of small intestine	Reduced slack
3631	2	50-55	-	20	4	Rupture of spleen	Reduced slack, improved location of buckle
3773	2	50-55	-	54	3	Bruise of left kidney	Reduced slack
3956	1	30-35	8	33	4	Tear of mesentery, rupture of small intestine	Better locations of anchorage points
3889	2	55	14	31	4	Tear of mesentery, rupture of small intestine	Reduced slack, better locations of anchorage points.
Lesions of the lumbar spine, probably caused by submarining							
2769	2	40	-	44	3	Fracture + compression of L2	Reduced slack
2950	2	45	12	65	3	Fracture + compression of L1	Reduced slack
3726	1	45	6	48	2	Fracture of 1 transverse apophysis	Restraint of rear passenger ?
3965	1	35-40	13	52	3	Fracture of L1	Better anchorage locations

(*) - 1 = Driver
2 = Right front passenger

TABLE III - FRONTAL COLLISIONS WITH RESTRAINED CADAVERS
TEST CONDITIONS IN CASE OF ABDOMINAL LESIONS AND/OR SUBMARINING

Subject N°	ANTHROPOMETRIC DATA			TEST CONDITIONS						OBSERVATIONS
	Age/sex	Stature (cm)	Weight (kg)	ΔV (km/h)	γ_m (g)	Seating position (1)	Type of seatbelt (2)	$\alpha°$ before testing Outer side	Interior side	
Lesions probably caused by deceleration										
10	63M	163	70	64	24,4	driver	STA	45		
14	48M	162	48	62	24,3	RFP	2 R + 2 P	50		
25	43F	166	55,5	50	12,1	RFP	STA	40		
Lesions caused by submarining										
2	52M	175	71	50	20,5	driver	2 R	37		.poor anchorage locations
12	43F	152	60	64,5	21,8	RFP	STA	50	47	.very flexible seat cushion
127-4	57M	159	41	50	15,4	RRP	1 R	51	41	.buckle location-strap direction-seat flexibility
154-4	63M	171	42,5	55	25	RRP	1 R	55	40	.strap direction-buckle location
182	57M	176	62	52	17,4	RFP	1 R	44	45	
Cases with submarining, without lesions										
1	62F	162	53	50	20,5	driver	2 R	30		.poor anchorage locations
6	60F	146	55	58	21,5	RFP	STA	35	40	
34	57M	164	68	49	10,3	RFP	STA	46	50	
124-2	61M	162	52	66	15,8	RFP	1 R + 1 P	38		
148-2	65F	161	59	52	15	RFP	1 R	50	50	
148-4	62M	172	67	52	15	RRP	1 R	69	47	.poor strap direction+buckle location

(1) - RFP : right front passenger - RRP :right rear passenger
(2) - STA : static - R : retractor - P : pyrotechnic pretensionning device

TABLE IV - FRONTAL COLLISIONS WITH RESTRAINED CADAVERS

RESULTS LINKED TO SUBMARINING IN PERTAINING CASES

CASE	IN SIDE VIEW SLOPE OF PELVIC STRAP WHEN SUBMARINING OCCURS (α °)		ABDOMINAL INTRUSION BEYOND EIAS X - DIRECTION (mm)		MAX. RESTRAINT FORCES WHEN STRAP IS ABOVE EAIS (daN)		ESTIMATE OF FORCES DEFINED IN FIGURE (daN)		ABDOMINAL AND LUMBAR SPINE INJURIES		
	Outer side	Middle of the car	Outer side	Middle of the car	Outer side	Middle of the car	Outer side	Middle of the car	AIS	Description	Observations
Lesions caused by submarining											
2	24	-	40	-	-	-	-	-	5	Tear of mesentery perforation of colon, wounds of liver, F transverse process L4	Pelvis fractures
12	35	32	-	50	-	-	-	-	4	Tear of mesentery	
127-4	29	20	55	75	380	900	160	420	3	Fracture+compression L1	
154-4	36	32	40	70	650	500	390	300	5	Wound of liver fracture L2+compression+lesion of medulla	
182	35	30	41	57	420	(420)	180	(120)	3	Fracture+compression L1	
Cases with occurence of submarining and no lesions											
1	30	-	37	-	-	-	-	-	0		
6	35	26	35	-	(220)	220	(150)	(180)	0		
34	33	35	-	30	240	(240)	130	(150)	0		
124-2	26	(20)	25	-	280	(280)	60	(130)	0		
148-2	32	30	33	27	220	250	90	100	0		
148-4	25	34	28	20	260	200	80	60	0		