LACERATIVE PROPERTIES OF THE HUMAN SKIN DURING IMPACT (*)

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ABSTRACT

372 tests were performed for the investigation of lacerative properties of human skin during impact. The skin specimens were obtained from different body regions of 4 living persons supplied by plastic surgeon after operations, and another group of specimens were from a fresh unembalmed cadaver.

It was found that the severities of lacerative injury of skin depended on the applied load, the lacerative resistance, and on the geometrical shape of impactor. These experimental results were shown to be in agreement with the theoretical calculations. The results also showed that the lacerative resistance of human skin is dependent upon body region, human subject and age.

All of the experimental results were dependent on the lacerative orientation in relation to Langer's lines. They were in accordance to the statistical results that the lacerative facial injuries along the lines were most frequently found in traffic accident investigations.

The choice of lacerative resistance for simulating facial skin of anthropometric dummy can be determined by both experimental and statistical results.

INTRODUCTION

In their traffic accident investigations, Cromack and Ziperman (1) had found skin and facial injuries that occurred most frequently in relation to body organ and region, respectively.

The purpose of this work was to investigate the lacerative properties of human skin. The data obtained may be used for further investigation of artificial soft tissue of dummy face. At the same time, the lacerative properties of human skin should be of interest to the plastic surgeons.

The experimental results showed that the lacerative resistance perpendicular to Langer's lines was always stronger than that parallel to the lines.

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In order to determine the lacerative resistance for simulated skin, a program of statistical analysis of accident investigations was performed. This program was designed to find the frequency of lacerative facial injuries in relation to the orientation of Langer's lines. The results were found to be in accordance with experimental data and also enabled one to determine the lacerative resistance of simulated skin of dummy's face.

METHODOLOGY

Lacerative properties of human skin had been reported previously (2, 3). Considerable differences between these reports could be explained by the different means employed in tests. Therefore it seemed important to determine the geometrical shape of impactor and to compare the lacerative strength of skin.

Impactors were conceived by the ways of different sharp angles (Φ) and diameters (D). The details of nine impactors ($D_i\Phi_j$, i, j = 1, 2, 3) are presented in Table 1.

Table 1 - Details of Impactor (weight, grams).

Sharp Angle Φ_j	Diameter of Impactor, D_i D_1=15cm	D_2=20cm	D_3=25cm
Φ_1 = 30°	$D_1\Phi_1$=350.54	$D_2\Phi_1$=383.18	$D_3\Phi_1$=446.68
Φ_2 = 60°	$D_1\Phi_2$=350.71	$D_2\Phi_2$=384.89	$D_3\Phi_2$=441.41
Φ_3 = 90°	$D_1\Phi_3$=346.80	$D_2\Phi_3$=374.69	$D_3\Phi_3$=429.44

The geometrical shape of these impactors is illustrated in Figure 1.

Fig. 1 - Geometrical shape of the impactor

Free Fall Test Device - The impactor was guided by two columns and released in free fall from prescribed heights. The acceleration-time history of impact was achieved by accelerometer which was mounted on the impactor. Skin specimens were nailed on the 6 x 6 cm wooden board glued to a metallic plate that was supported in 4 corners. This free fall test device was put on a load cell. The measurements of load-time history obtained during impact could be used to compare with acceleration-time history.

Skin Specimens - One group of skin specimens were obtained from the mammary and abdominal skin of 4 living persons, another group was from similar regions plus the facial skin of a fresh unembalmed cadaver. Before the tests, all specimens were preserved for not more than 4 days in bottles with physiological serum after removing from the bodies. During tests, the specimens were exposed on the wooden board in the same dimension as in situ. Langer's lines were determined by the surgeon.

The data of skin specimens employed for tests were tabulated in the following table:

Table 2 - Data of Skin Specimens

Subject	Sex & Age	Body Region	Adipose Tissue	Thickness (mm)
living	F 22	Breast	without	2.1
living	F 34	Abdomen	without	2.2
living	F 39	Breast	without	2.2
living	F 27	Abdomen	without	2.5
dead	F 82	Face	without	2.3
dead	F 82	Face	with	8.9
dead	F 82	Breast	without	2.0
dead	F 82	Abdomen	without	2.1

The severity of laceration has been defined by the Triplex Laceration Index (4) which is a mathematical formula relating to the number, length and depth of cuts in tissues simulations. This formula was difficult to apply in the investigation of lacerative properties of the human skin, but both practical and theoretical definitions were satisfactorily established in this work.

Practical Definition - The lacerative injury scales were simply defined as the indexes corresponding to the cut depth:

0 no macroscopically visible injury in the skin,
1 1/3 cut depth of skin,
2 2/3 cut depth of skin, and
3 whole cut depth of skin.

Theoretical definition - The applied load (F) was resolved into two forces (F_1) perpendicular to the flanks of impactor. Cut in skin specimens by these forces was determined by the following equation:

$$F_1 = \frac{F}{2 \sin \frac{\Phi}{2}} \qquad (1)$$

If the sharp angle of cutter (Φ) is determined, the lacerative resistance of skin will be represented by F_1. Force supported by a unit cross-sectional area is usually given by "stress", defined for tensile and compressive resistance. Similarly, the lacerative stress may be also defined here as a lacerative resistance of skin (*). It will provide for the comparison of lacerative properties of human skin, thus:

$$\sigma = \frac{F_1}{S} \qquad (2)$$

where "S" is profile area cut by impactor as shown in Figure 2:

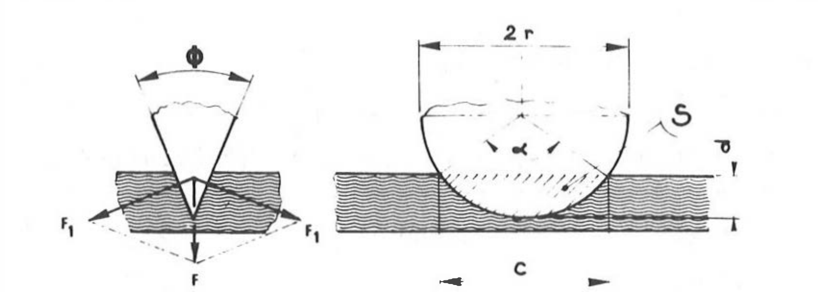

Fig. 2 - Diagram of skin specimen cut by the impactor.

This area can be calculated by:

$$S = r^2\left(\frac{\pi}{180} \cdot \frac{\alpha}{2} - \sin\frac{\alpha}{2}\right) + d.r.\sin\frac{\alpha}{2} \qquad (3)$$

where "c", length of laceration measured in tests; "r" is the radius of flank of impactor and "d" is the cut depth of skin.

Equation (3) can be rewritten in another form:

$$S = f(r,d) \qquad (4)$$

If "r" is determined, "s" is then a function of "d". The relationship S-d is non-linear, as shown:

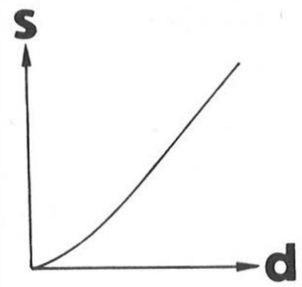

Fig. 3 - Relationship S-d

Usually, $\alpha > 30°$ and $d > 0{,}40$mm were found in the tests, the relationship S-d was not in the "toe" part. Therefore, the linear relationship will be approximately established as:

$$S = \eta r.d \qquad (5)$$

Where η is a coefficient.

(*) It is different from that the compressive stress is caused in skin by applied load "F".

The relationship between radius of impactor "R" and mean radius flank of impactor "r" is given by:

$$r \approx R.\cos\frac{\Phi}{2} \qquad (6)$$

From equations (1) and (2), lacerative stress can be determined by the following equation:

$$\sigma = \frac{F}{2\ S.\sin\frac{\Phi}{2}} \qquad (7)$$

If "S" is replaced by equations (5) and (6), the expression of lacerative stress becomes:

$$\sigma = \lambda\frac{F}{D.d.\sin\Phi} \qquad (8)$$

The lacerative severity of injury defined in tests corresponded to the cut depth of skin "d". From equation (8), this severity scale (I) can be written as:

$$I = d = \lambda\ \frac{F}{\sigma.D.\sin\Phi} \qquad (9)$$

Where "λ" is a coefficient depending on the units employed in the calculations, the scale's expressions and the lacerative resistance of skin. If the units (kgf, mm^2) and scales (1, 2, 3) employed are the same as in this study, the coefficient "λ" determined is approximately in a 55-81 range. Since the lacerative resistance is a function of impact velocity, therefore the coefficient is variable. For instance, at 2.7 km/h, the coefficient is about 70.

The expressions of lacerative severity of injury are derived by equation (9). It is quite evident that the lacerative severity of injury depends on two factors: the interior one is lacerative resistance of skin (σ) and the exterior one is applied load (F) and geometrical shape of impactor (D,Φ). These are in agreement with experimental results.

EXPERIMENTAL RESULTS AND DISCUSSION

Lacerative Resistance of Skin As a Function of Impact Velocity - The comparative tests of different impactors and severities of injury on laceration perpendicular and parallel to Langer's lines were performed.

The lacerative resistance of skin is defined as "stress" and is a function of the impact velocity as illustrated in figure 4.

It is significant that the lacerative resistance of skin (σ) increases with decreasing impact velocity (v). This relationship can be expressed by the following equation:

$$\sigma = \frac{\xi}{v} \qquad (10)$$

where "ξ" is constant.

If "σ" is replaced by "v", equation (9) can be rewritten as:

$$I = \Psi \frac{F.v}{D.\sin\Phi} \qquad (11)$$

where "ψ" is another coefficient which is equal to $\frac{\lambda}{\xi}$.

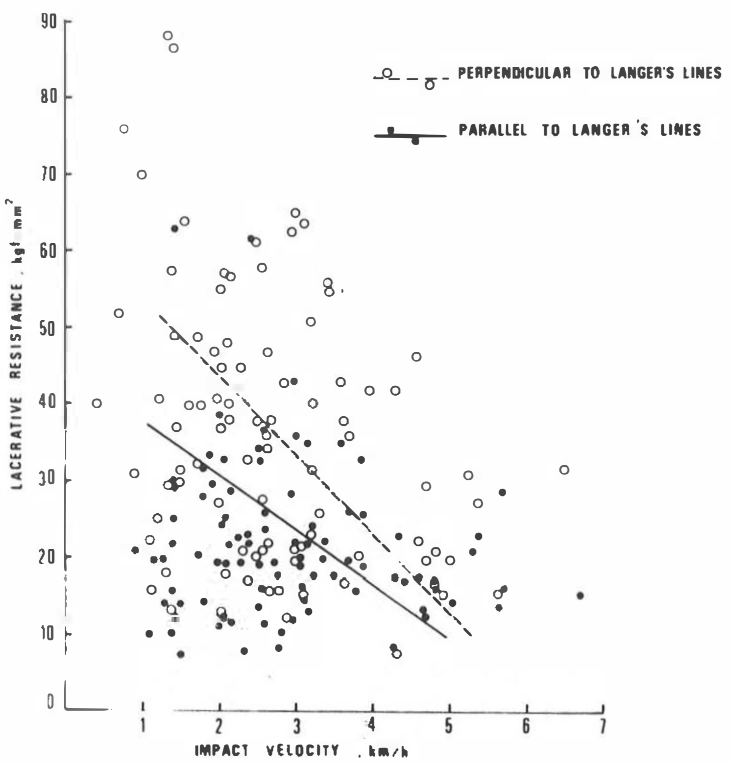

Figure 4 - Lacerative resistance of skin (σ) as a function of impact velocity (v).

In the comparative tests, the lacerative resistance across Langer's lines is always stronger than that along the lines. For instance, at the velocity of 2.7 km/h, it shows 36 and 27 kgf/mm^2 of lacerative resistance across and along Langer's lines, respectively. The lacerative tests were performed with different impactors on the specimens cut off from different regions of 5 human bodies (4 living persons and 1 cadaver). For these reasons, the experimental results vary largely from those shown in figure 4. However, it did illustrate clearly that the lacerative resistance varies inversely as impact velocity.

Lacerative Severities of Injury as Function of Applied Load and Geometrical Shape of Impactor - Results obtained with different impactors used in the tests were shown in figures 5 and 6. Lacerative severities of injury increased with increasing applied load. On the other hand, with regard to the function of the geometrical shape (Φ, D), it was shown that a larger sharp angle (Φ) or a larger diameter (D) of the impactor was needed to cut the skin with a stronger load for the same injury severity.

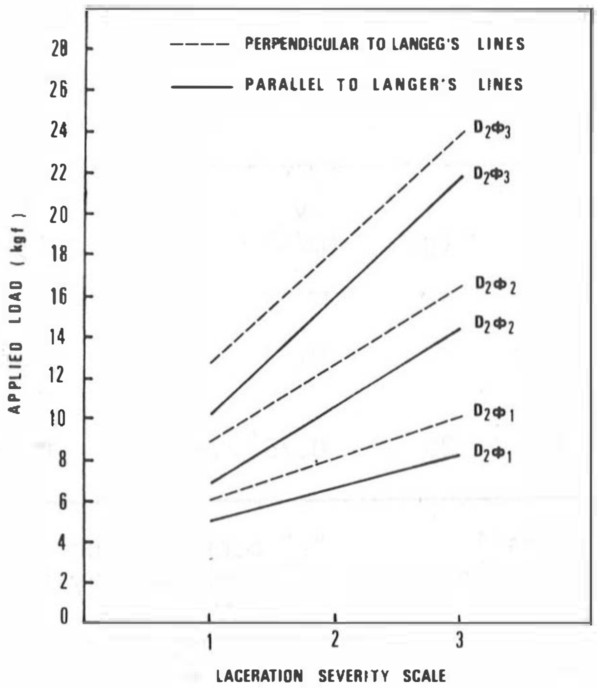

Fig. 5 - Relationship between lacerative severity scale and load applied by different impactors (different sharp angles, Φ).

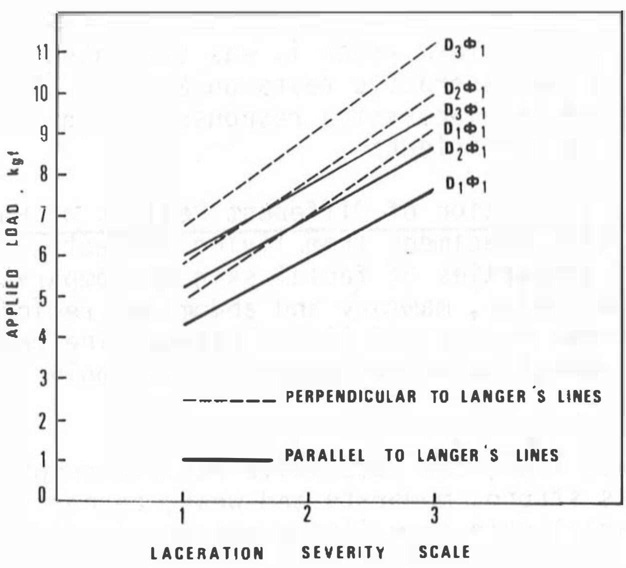

Fig. 6 - Relationship between lacerative severity scale and load applied by different impactors (different diameter, D).

Comparison Between the Energy Absorbed by Facial Skin with and without Adipose Tissue - Lacerative tests were carried out with different impactors for comparative studies between the facial skin with and without adipose tissue of the right and left maxillary regions cut from a fresh cadaver (F/82). The results of two tests are shown in Table 3:

Table 3 - Comparison Between Energy Absorbed by Facial Skin With and Without Adipose Tissue.

Test n°	Studied Region	Adipose Tissue	ζ (mm)	h (cm)	γ (g)	v (m/s)	t (ms)	E (j)
346	right maxilla	without	2.3	2	20	0.43	7.30	0.23
364	left maxilla	with	8.9	7	26	0.75	10.66	0.78

"ζ" thickness of skin "h" height of fall "γ" acceleration
"v" impact velocity "t" impact duration "E" work done by impactor

These two tests were performed with the same impactor D2Φ1 with a weight of 0.384 kg. An index "3" was indicated on a similar lacerative severity scale.

In Table 3, the difference of work done by the impactor could only be considered as energy absorbed by the adipose tissue which was 239% higher than the energy absorbed by skin without adipose tissue. Apparently, the adipose tissue played an important role in the diminution of lacerative severity of facial injury.

Since adipose tissue had no a distinct form after it was separated from the skin, it was impossible to perform the lacerative tests on adipose tissue alone. However, for the understanding of its lacerative response during impact, this comparative study seems to be sufficient.

Lacerative Resistance of Skin as a Function of Different Regions of Human Body - Due to the lack of facial skin specimens from living subjects, it was necessary to infer the lacerative properties of facial skin by comparing a cadaver's (F/82) skin specimens from facial, mammary and abdominal region with those from the mammary and abdominal region of living beings. The results show the resistance of skin of laceration along Langer's lines only which are illustrated in figure 7.

It could be seen that with subject F/82, the lacerative resistance of abdominal, mammary and facial skin was strong, moderate and weak, respectively. Although there was a lack of facial skin from living beings of middle age, it appeared that its lacerative resistance might be less than that of an old dead subject. On lacerative scale "3", the lacerative resistance was about 5 kgf/mm^2 found in the facial skin of an old dead subject.

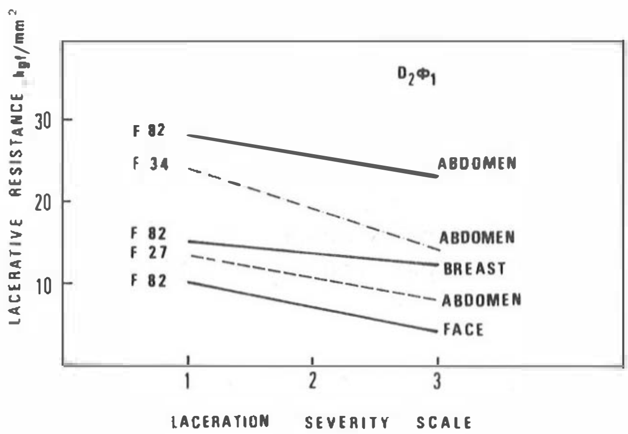

Fig. 7 - Comparison of lacerative resistance of skin between different body regions.

The correlation between lacerative resistance and age is significant: because, with the same abdominal region, the lacerative resistance increases with age. Although there had been no reports on the differences of lacerative properties between living and dead subjects, it seemed that age could be an influential factor. This is supported by several authors who had reported that the stiffness of skin increased with age (5) (6) (7).

The results also demonstrated that the lacerative resistance of skin varies inversely with injury severity, and this is in accordance with equation (9).

<u>Lacerative Severities of Injury as a Function of Impact Velocity</u> - The results are shown on the gloomy area of figure 8 where the lines represent the average results for the skin specimens of different body regions tested with different impactors. It is apparent that severity increases significantly with impact velocity and it is in good agreement with equation (11).

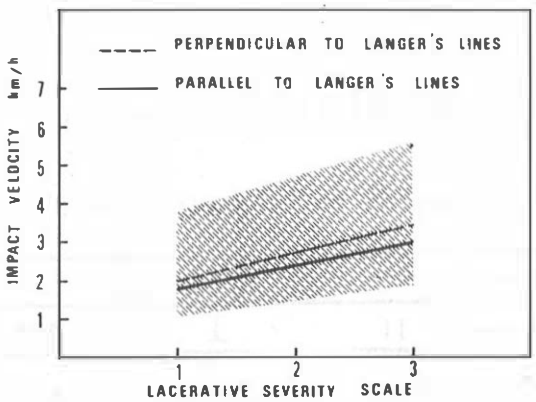

Fig. 8 - Relationship between impact velocity and lacerative severity.

<u>Comparison of Severity Between Laceration Along and Across Langer's Lines</u> - Results in figures 5 & 6 clearly demonstrated that the injury severity of laceration along Langer's lines was more serious than that across the lines for the same load applied. A problem is then developed as how to simulate Langer's lines in the artificial tissue, and how to determine lacerative resistance for simulated skin? The answers can be found in the accident investigation given in following statistical results.

STATISTICAL RESULTS AND DISCUSSION

Frequency of Lacerative Facial Injury in Relation to Langer's Lines - This program was performed in the traffic accident investigations. The documents were supplied by St. Louis Hospital and Peugeot-Renault Association.

The statistical results were arranged in three groups in relation to the lacerative orientation, they are: parallel, perpendicular and 45° to Langer's lines of face as shown in figure 9.

Fig. 9 - Langer's lines of face (8).

The principles employed in statistical investigations are given as below:

1/ All lacerative injuries were located on face defined by distance between the mid-point of the nasal root depression and menton (9) (10).

2/ If the injuries were situated between two groups, they were arranged into the nearer group.

3/ If the injuries were crossing over the different fields of Langer's lines, they were arranged into the respective groups.

4/ If the injuries had the curve form, the tangent of curve's middle point was defined to be the direction of the injuries.

On the basis of these principles, the statistical results were achieved and summarized in Table 4:

Table 4 - Frequency of Facial Injuries in Relation to Langer's Lines.

Sources of Documents	Accident N°	Injury N°	Group (%)		
			∥	⊥	45°
1 St. Louis Hospital	59	121	57.02	26.44	16.52
2 Peugeot-Renault	31	55	58.18	29.09	12.72
1 + 2	90	176	57.38	27.27	15.34

In spite the fact that documents were supplied by different sources, the results were close enough and acceptable. These results are not only statistical, but also correlate to the experimental results: the lacerative resistance perpendicular to Langer's lines are always stronger than the parallel to the lines. If an impact does not have enough strength to cut across Langer's lines, the visible injury will not appear on facial skin, but by the same impact, it may cut along the lines. This is the reason why lacerative injury along Langer's lines is most frequent.

The experimental results are in good agreement with the statistical results. Both results allow one to investigate the simulated skin in that its lacerative resistance will correspond to the cutting along Langer's lines of human skin.

With the aid of micro-architectural studies, these results will be well comprehended:

Investigation of Microarchitecture of skin - When the skin was penetrated by a sharp conical instrument, it did not show a round hole but a slit as if it was cut by a flat blade. The direction of these slits was defined as cleavage lines of skin or Langer's lines (8).

In microscopic section cut parallel to these lines, most of the collagenous bundles were cut longitudinally, while in sections cut across the lines, the bundles were cut in cross section (8). These observations can be shown directly by an excellent picture (6).

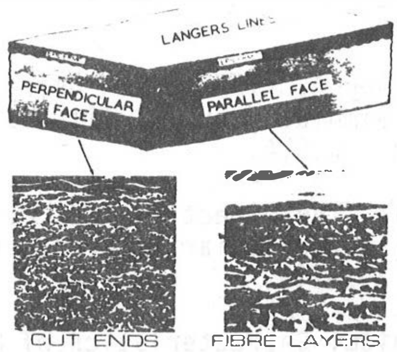

Fig. 10 - Micro-architectural appearance along and across Langer's lines. (6).

CONCLUSIONS

1/ Lacerative severity of human skin increases with i) increasing applied load and ii) decreasing lacerative resistance.

2/ Lacerative severity of skin is a function of the geometrical shape of impactor. It increases with diminishing diameter and sharp angle of impactor.

3/ Lacerative resistance of skin depends on the impact velocity. It increases with decreasing impact velocity, and on the other hand, it varies according to subject, body region and age. Some of results can be described as:

- For all skin specimens, at velocity of 2.7 km/h,
  lacerative resistance along Langer's lines: 27 kgf/mm2
  lacerative resistance across Langer's lines: 36 kgf/mm^2 (Fig. 4).
- For the facial skin specimens of an old dead subject, on severity scale "3", lacerative resistance along Langer's lines: 5kgf/mm^2 (Fig. 8)

4/ Resistance of skin is a function of orientation of laceration in relation to Langer's lines: the resistance to cut across Lines is always stronger than that to cut along Lines.

5/ Frequency of lacerative injury along Langer's lines is considerably more than that across lines in facial injuries found in the traffic accident investigations.

6/ Lacerative resistance of simulated skin of dummy's face will be investigated on the basis of both experimental and statistical results which is in accordance with the resistance of human facial skin cut along Langer's lines.

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APPENDIX

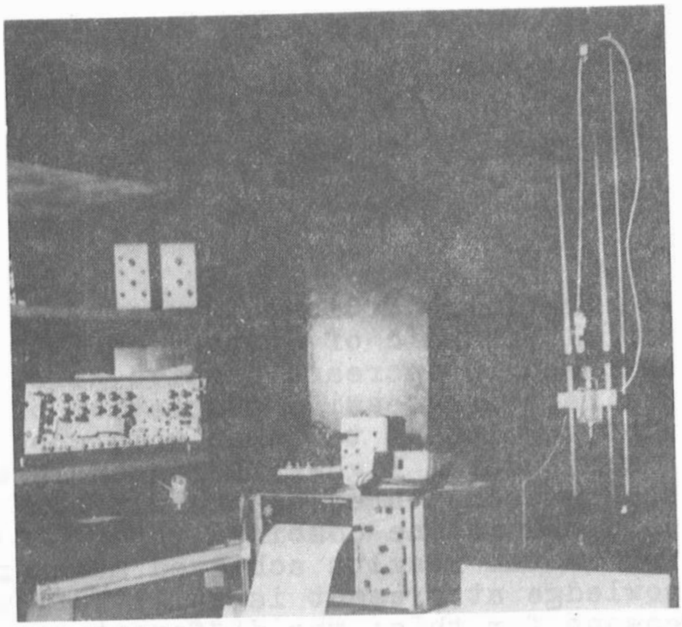

Fig. 11

Free-Fall Test Device and Measuring Instruments.

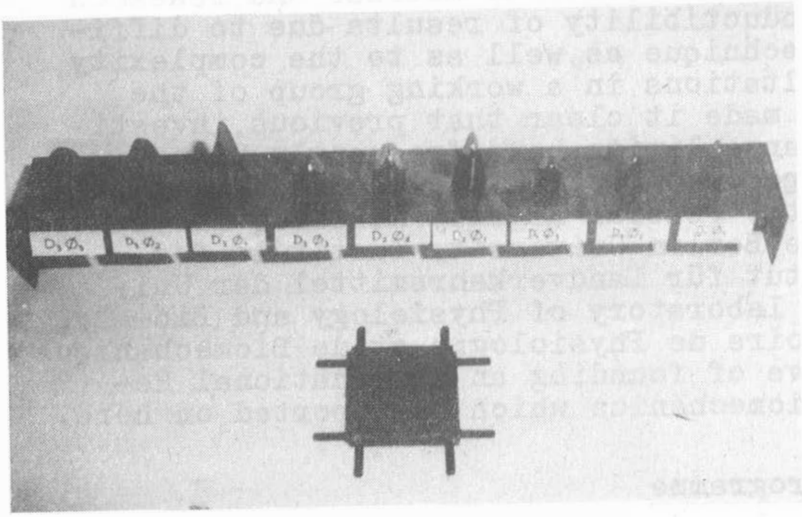

Fig. 12

Impactors and Metallic Plate Glued with Wooden Board for Nailing The Skin Specimens.

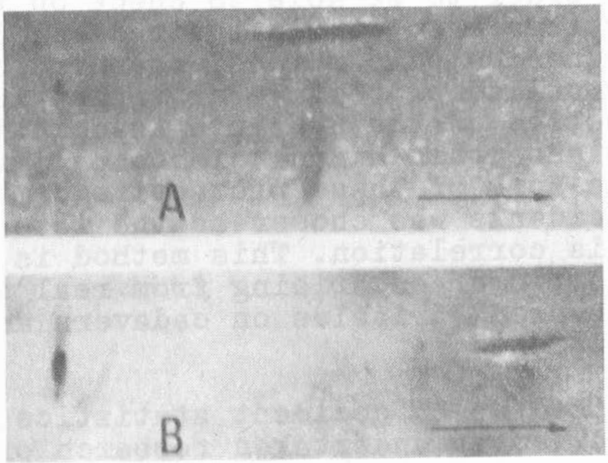

Fig. 13 Skin Specimens (x 3)

Comparative Tests of Different Severities of Injury on Laceration Parallel and Perpendicular to Langer's Lines.

A. Tested with Impactor $D_3\phi_1$,
  ∥ , — Injury Scale: "2",
  ⊥ , — Injury Scale: "1",

B. Tested with Impactor $D_2\phi_1$,
  ∥ , — Injury Scale: "> 3",
  ⊥ , — Injury Scale: "3".

⟶ Orientation of Langer's Lines.