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INJURY BIOMECHANICS RESEARCH
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Pleural Pressure Measurement Technique and Methodology

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ABSTRACT

The aim of this work consists of the description of the technique and the methodology used to acquire pleural pressure measurement data in order to explore the distribution of the pressure inside the chest during the tests.
To reach the aim, a specially designed device named Pleural Pressure System (PPS) was developed in order to measure the pressure inside the pleural cavity during the tests and consequently to get data on the external parenchyma pressure of the lung.
The effects of the acceleration on the device including a standard sensor are compared to the data obtained in the same condition with an isolated standard sensor in order to validate the measurement data acquired during the tests.
The methodology used to install the modified sensor is described.
The results obtained during dynamic tests are presented.
In conclusion, this validated device shows a difference between the external parenchyma pressure of the lung and the tracheal pressure during the tests. These data could allow a better understanding of certain injury mechanisms and could be used for a future evolution of a numerical model.

INTRODUCTION

This work is an exploratory approach to understand the distribution of the pressure inside the human thorax during crash-tests, better understand some injury mechanisms and provide experimental data for the development of numerical models.
In order to achieve this objective, it was decided to investigate pleural pressure measurement, considering that this pressure is an equivalent of the pulmonary external parenchyma pressure.
The specificity of this site regarding pressure measurement was examined and the following specifications, which excluded standard sensors to be used directly, were defined:

- The need for a shape fitted to the pleural cavity allowing automatic positioning during the instrumentation and a good coupling with the parietal pleura and visceral pleura when the lungs are inflated before closing the incision.
- The need for a device maintaining the sensor distant from the parietal pleura and the visceral pleura preventing any obstruction from occurring when a cylindrical pressure sensor is used.
- The use of a device whose shape cannot be involved in local pleura injuries.
- The need for a wire outlet fitted to this kind of instrumentation.

METHOD

Anatomy

Each lung is invested, upon its external surface, by an exceedingly delicate serous membrane, the pleura, which encloses the organ as far as its roots, and is then reflected upon the inner surface of the thorax. The portion of the serous membrane investing the surface of the lung and dipping into the fissures between its lobes, is called the pleura pulmonalis (visceral layer of the pleura), while that which lines the inner surface of the chest is called the pleura costalis (parietal layer of the pleura). The space between two layers is called the cavity of the pleura, but it must be borne in mind that in the healthy condition the two layers are in contact, and there is no real cavity until the lung becomes collapsed and a separation of it from the wall of the chest takes place. Each pleura is therefore a shut sac, one occupying the right, the other the left half of the thorax, and they are perfectly separate from each other. The two pleura do not meet in the middle line of the chest, excepting anteriorly opposite the second and third piece of the sternum, a space being left between them, which contains all the viscera of the thorax excepting the lungs: this is the mediastinum. (GRAY'S ANATOMY, anatomy descriptive and surgical)

Principle

The principle of the device consists of the installation, inside the virtual cavity named the pleural cavity, of a small rigid ring named "shaped torus" (drawn in gray). The two sides of the shaped torus are closed using glued latex membranes. Thus, an inner cavity filled with liquid is enclosed.

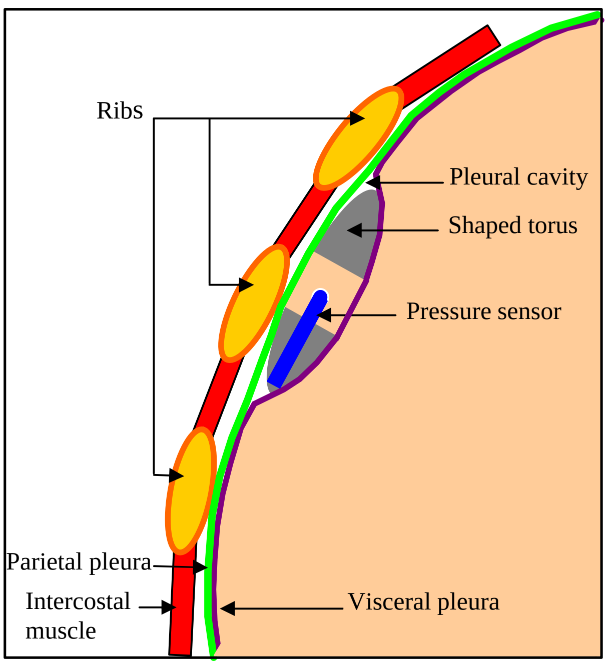

Figure 1: Transverse section of the thorax

The sensitive extremity of the sensor is positioned in the middle of the inner cavity, the rest of the sensor being held by the periphery of the torus. The cavity between the two membranes is filled with silicone oil.

Two main hypotheses on the behavior of the device can be taken into account:

-First of all, the rigid part of the device, the torus (drawn in gray on the figure 1), is considered to be an extension of the external wall of the thorax and the inner cavity considered to be an extension of the pulmonary parenchyma, the data acquired being a measurement of the peripheral pulmonary pressure.

This hypothesis allows to consider that the use of the pressure sensor is included in the normal condition of use and consequently, no validation of the behavior of the pressure sensor itself is necessary.

-Secondly, the device is considered to be a new sensor that it is necessary to evaluate particularly regarding any disturbance due to the acceleration. On the one hand this hypothesis is more complex due to the need to carry out several validation tests but, on the other hand, it allows the validation of the results obtained with the biomechanical tests. That is the reason why this hypothesis is to be taken into account in the future.

In any case, in order to obtain a good working of the device, it is necessary to carry out a good coupling of the membranes with the pleura.

Constitution of the device

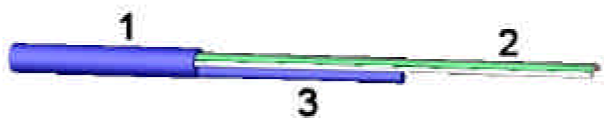

Figure 2: Pressure sensor with the wires and the vent

A relative pressure sensor 50 PSI ref : Endevco, 8514-50
①The sensor
②The wires
③The vent

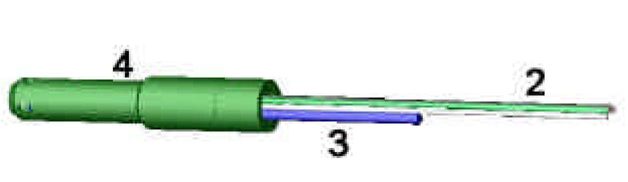

Figure 3: Stainless steel threaded sleeve

The sensor is inserted into a threaded sleeve④ (drawn in green) made of stainless steel.
The outlet of the wires② and the vent③ (drawn in blue) are located at the rear extremity of the sleeve.

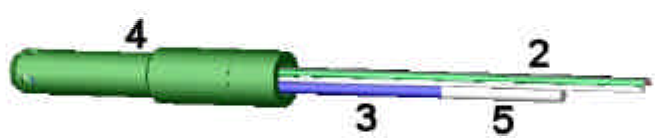

Figure 4: Plastic micro-tube extending the vent

The vent is extended using a plastic micro-tube⑤

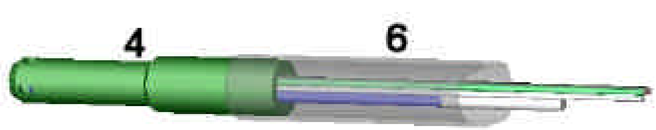

Figure 5: Transparent plastic tube glued onto the sleeve

The micro-tube of the vent and the wires are fitted inside a transparent plastic tube⑥ glued onto the rear extremity of the sleeve.

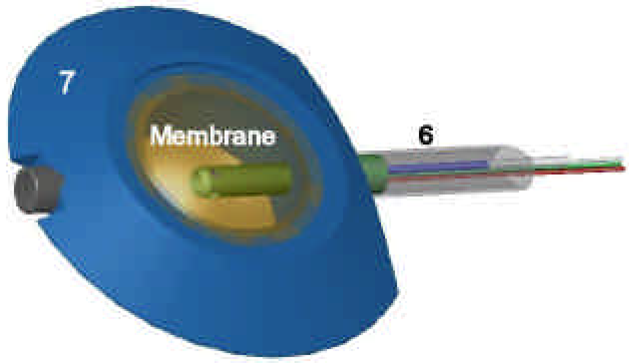

Figure 6: The whole device

The sleeve④ is screwed into the shaped torus⑦ (drawn in blue). The cavity of the torus is closed using two membranes glued onto the sides and filled with silicone oil.
A positive pressure inside the device allows a convex membrane shape to be maintained and consequently a good contact with the pleura.

Evolution, fabrication, Durability:

Evolution. Initially, the whole device was hand made and the torus was made of polyester mastic. Subsequently, the torus was machined and made of titanium. This made it more difficult to glue the membranes and the density was too high. Now, the torus is made of macrolon (a kind of plastic that it is possible to machine). The density is low (close to water) and the gluing on the sides is easy and resistant.

Fabrication. The equipment required for the fabrication of the device:

- The shaped torus machined from a kind of plastic named Macrolon
- The machined sleeve made of stainless steel
- Latex surgical gloves providing the latex membranes
- A specially designed applicator (Figure 7) in order to apply a pressure on the peripheral of the membranes when gluing
- Cyano-acrylate glue and catalyst
- Syringe and needle
- Silicone oil

- First step:

The membranes are glued onto the faces of the torus:

  - A sheet of latex is cut
  - Glue is spread on the gluing surface
  - The sheet of latex is positioned on the torus (Figure 7)
  - The sheet of latex is pressed onto the gluing surface using a specially designed applicator.
  - The catalyst is sprayed onto the torus while a pressure is maintained on the applicator for one minute.
  - The same method is applied to glue the membrane on the other side.
  - To end, the membrane is cut carefully all around the gluing surface using a sharp knife.

- Second step:
  - Silicone mastic is spread onto the thread of the sleeve (including the sensor) before screwing it into the torus.

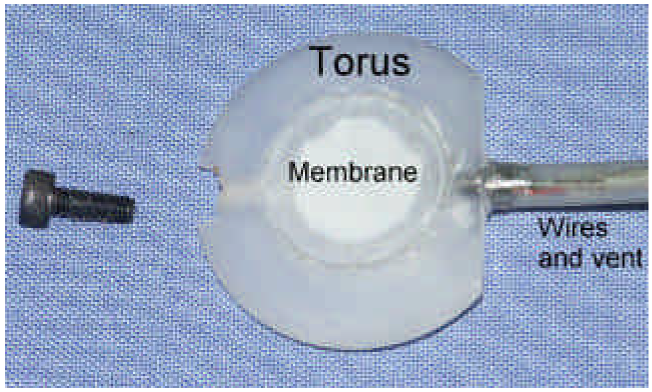

Figure 8: Device ready for filling, the closing screw on the left

- Third step

  Twenty-four hours later, the torus is positioned vertically (hole up for filling Fig 9) using a special device in order to allow sucking the membranes into two tubes each with a negative pressure. Thus, The torus is held steady and the volume of the cavity between the two membranes is increased. This device prevents damage to the membranes during the filling operation.

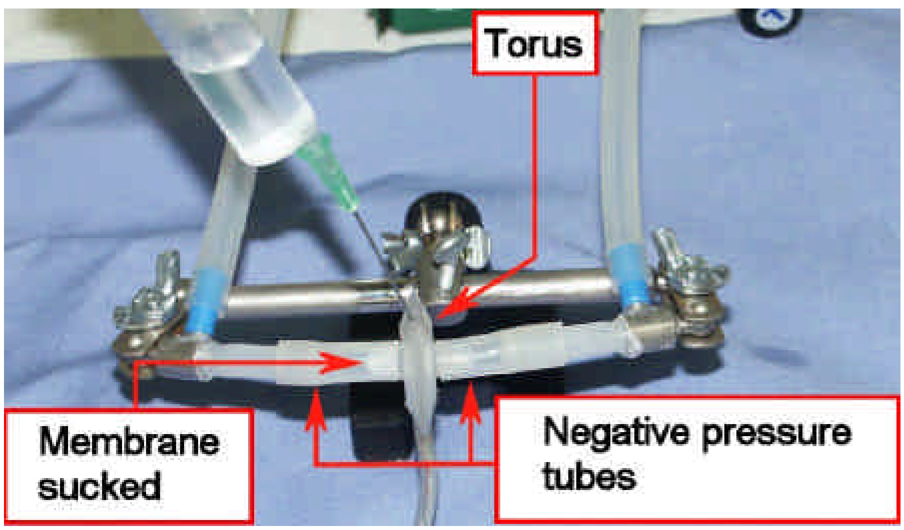

Figure 9: Device in position for filling, hole up

The torus is filled with silicone oil using a syringe, while taking care that no bubbles are included in the liquid. Then the hole for the filling is closed using a screw.
The negative pressure is removed and the torus released from the fixture.

Calibration. Then the connector of the sensor is plugged to a data acquisition system and the volume of liquid inside the torus is adjusted to be at a pressure of 3 kPa.

Durability. The durability has been estimated. It seems that there is no risk of failure with the device if it is used during the month following its fabrication. Later, oxidation of the latex begins due to contact with the atmosphere. To improve its conservation, the device can be kept plunged into silicone oil.

NB: It is necessary to prevent the membrane from coming into contact with vegetable oil or mineral oil because of a risk of damage due to an incompatibility with the latex.

Validation

Solidity. The device has been mounted on a sled allowing acceleration up to 80G during the braking phase. The device was fixed on the sled using the periphery of the torus. The membranes were free from contact, this configuration being the most unfavorable.

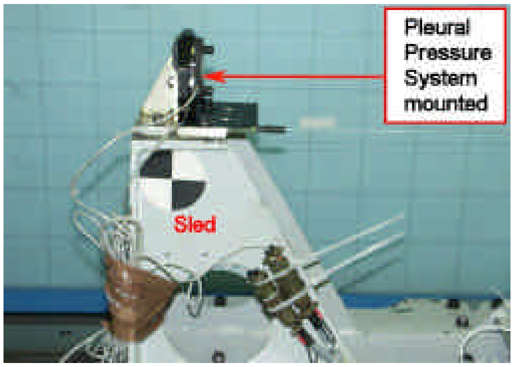

Figure 10: Membrane parallel to the y,z plane

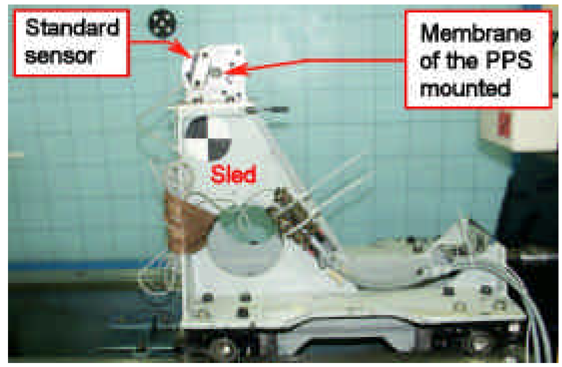

Figure 11: Membrane parallel to the x,z plane

Two categories of test were carried out:

-The orientation of the plane of the membrane parallel to the y,z plane

-The orientation of the plane of the membrane parallel to the x,z plane

Ten tests, membranes parallel to the y,z plane and ten tests, membranes parallel to the x,z plane were carried out, the acceleration measured ranging from 70G to 80G.

No damage occured to the device during the tests.

Sensitivity to acceleration. To evaluate the sensitivity to acceleration, the same configurations were used. Nevertheless, the membranes were blocked using polyester mastic in order to reproduce the coupling with the pleura of the cadaver, but, doing this, preventing what would be the effects of the peripheral tissues on the device because of the rigidity of the mastic.

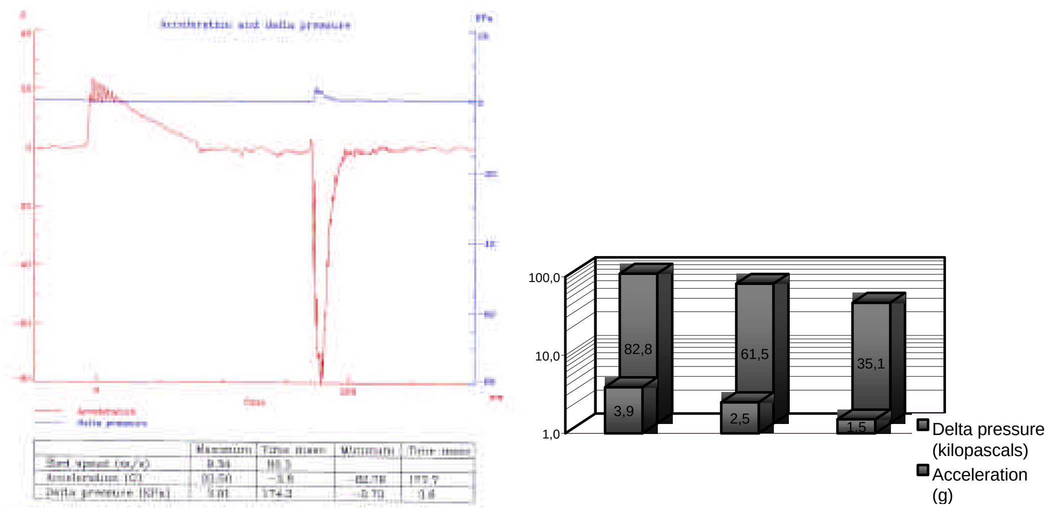

Figure 12: Sled acceleration and delta pressure (example of curves and histogram)

One pressure sensor identical to the one mounted into the torus was installed close to the pleura pressure device and in the same position in order to acquire reference data.

Three levels of acceleration were applied to the sled (82.8G, 61.5G, 35.1G) leading to measurements of pressure due to the effects of the acceleration applied to the device. Since the reference pressure sensor measured small values, the difference between the two measurements was calculated. The value obtained is named Delta pressure (Figure 12, example of curves). This corresponds to the disturbance induced by the pleural pressure measurement system on the standard sensor.

The data is filtered using a CFC180 filter.
The histogram (Figure 12) shows a linear relation ship between the acceleration and the delta pressure measured.
The error obtained is close to 0.05 kPa per G for the three tests. This is satisfactory regarding the range of acceleration usually encountered.

Instrumentation

Introduction. This is the most difficult phase as it determines whether or not pertinent measurement data can be obtained. In fact, two situations are critical. The first situation consists of the occurrence of a perforation of the visceral pleura while incising the parietal pleura. This perforation, making impossible the re-inflation of the lung and consequently the coupling of the device with the pleura, can be tested while re-inflating the lung after the positioning of the PPS. The second situation consists of the occurrence of an air leakage from the external medium into the pleural cavity. This leakage makes impossible the re-inflation of the lung in the hemi-thorax because of air in the pleural cavity. It is checked once the thorax wall incision, including the skin, is sutured. In case of a communication from the external medium to the pleural cavity, the solution consists of the installation of a small tube allowing the pleural cavity to be drained soon when the cadaver is re-inflated before the test.

Methodology. The skin is incised over a fifteen centimetres length in front of the axillary line and facing the fifth intercostal space.

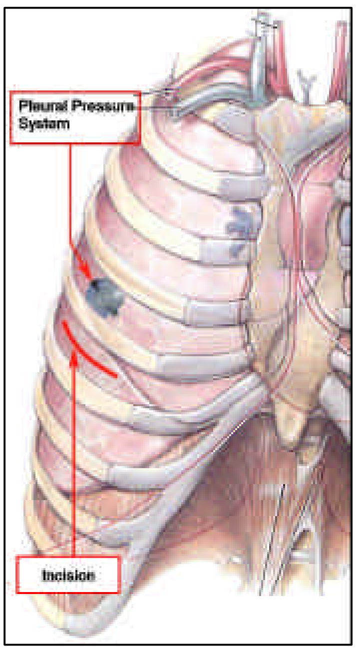

Figure 13:Theoritical position of the device

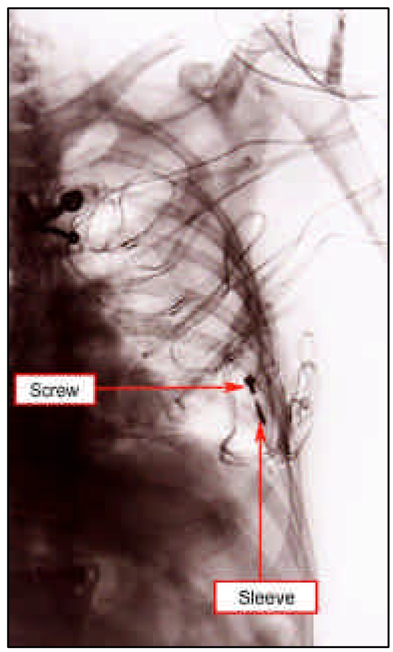

Figure 14: Radiograph after instrumentation

The incision is carried out carefully and concerns the intercostal muscles until the parietal pleura is visible.

Figure 15: Thoracic wall and parietal pleura incised (lung deflated)

The parietal pleura is then incised taking care not to damage the visceral pleura.
The lung will deflate as soon as there is an opening between the pleural area and the external medium (Figure 15). The incision is enlarged, and a search for a point of grip in periphery of the incision is carried out using the finger.
Then the sensor is inserted into the pleural area and is positioned approximately four centimetres above the incision. The lung is inflated in order to re-couple the two layers of the pleura, the pleural pressure measurement system being positioned by itself automatically because of its size and shape.
The intercostal muscular layer is sutured.
The superficial muscular layer is sutured and, before the last suture is tightened, an absorbent gelling powder is injected between the intercostal muscles and the superficial muscular layer.
The tube including the wires and the micro-tube of the vent is sutured to the superficial muscular layer while a positive pressure applied into the lung maintains the two layers of the pleura.
Before the suturing of the skin begins, an anti-slip ring is tightened around the tube.
This ring prevents the tube from slipping through the skin and consequently changing the position of the pleural pressure system.
The skin is sutured, a few loops of the tube including wires being rolled under the skin. The tube is sutured to the skin, taking care that the anti-slip ring is under the skin.
Before the last suture is tightened, an absorbent gelling powder is injected.
A radiographic image is used to check the position of the pleural pressure system. Only the sleeve and the screw are visible because the shaped torus and the silicone oil are transparent for the X-rays (Figure 14).

RESULTS

Usually, when pressure measurements are needed during cadaver tests, aortic, tracheal, pleural and gastric pressure measurement are acquired. Furthermore, the ribs are instrumented using strain gauges to acquire data in order to detect the instant of the fractures. So, much data is available to explore the behavior of the content of the thorax during the tests. The curves plotted on figure 16 and figure 17 were acquired during a laboratory frontal sled test with a restraint system consisting of a 6 kN load-limiting belt and a pyrotechnic pretensioner.

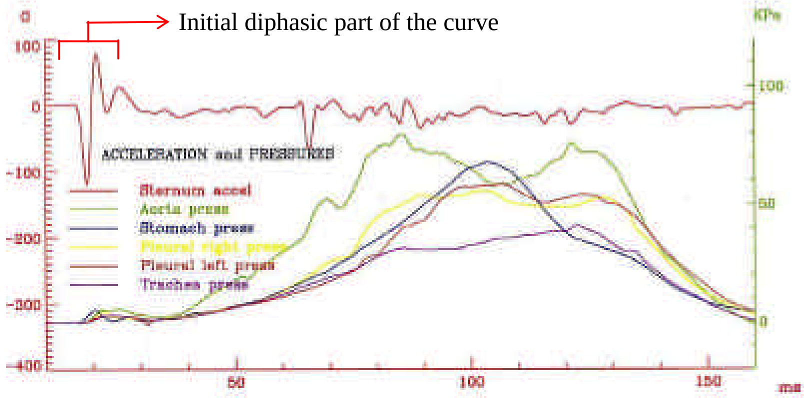

Figure 16: Pressure curves and sternum acceleration

Figure 16. On the upper part, the acceleration of the sternum is plotted in red. On the lower part, the aortic pressure is plotted in green, the pleural pressures are plotted in yellow and red, the tracheal pressure is plotted in purple and the gastric pressure is plotted in blue.

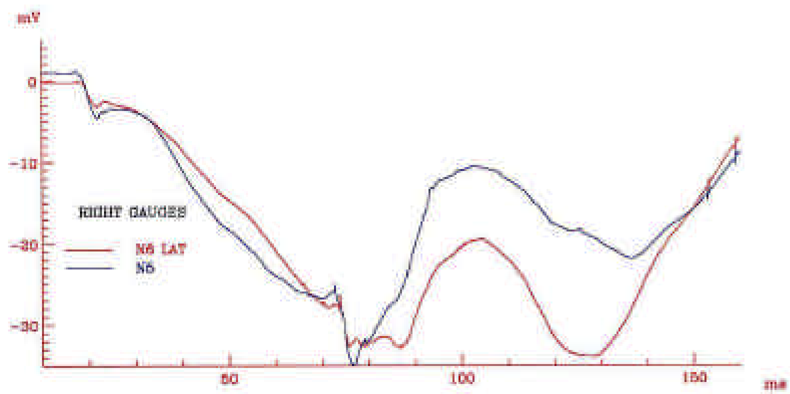

Figure 17: Right strain gages on the fifth rib and the sixth rib

Figure 17. The curve plotted in blue corresponds to a strain gauge located on the fifth right rib. The curve plotted in red corresponds to a strain gauge located on the sixth right rib

Analysis. The maximum value of the acceleration (Figure 16) is not very high because of the loading obtained with a restraint system. The initial diphasic part of the curve (first twenty milliseconds) is not representative because of the direct solicitation of the belt on the sternum accelerometer when the pretensioner fires. However, the range of the values of the acceleration obtained on the sternum are considered as being close to the values of acceleration applied to the pleural pressure system.

The figure 16 shows that the evolutions of the pleural pressures are close to the other intra-thoracic pressures even if the maximum values are higher.

The figure 17 shows an evolution of costal deflections measured using strain gauges close to the evolution of the thoracic pressures. It seems that there is a link between the data provided by the pleural pressure system and the other measurement data that are available.
Furthermore, the pleural pressure curves do not seem to be distorted by peaks values of acceleration.

CONCLUSIONS

Previously, the calculation of the error indicated a value inferior to 0.05kPa/G. The acceleration of the sternum equal to 65G allows the evaluation of the acceleration supported by the Pleural Pressure System, even if this measurement is not carried out very close. Thus, the maximal global error calculated (0.05kPa x 65G) is equal to 3.25 kPa. On the right hand side, the pleural pressure reaches 55 kPa, so, the percentage of error is equal to 5.9%. On the left hand side, the pleural pressure reaches 58 kPa, so the percentage of error is equal to 5.6%. In conclusion, considering the fact that the device mounted on the sled to evaluate the error can be improved and that consequently, the error applied in the calculation is increased, the results of the evaluation are acceptable as well as the analysis of the pleural pressure curves.

Prospects

Improvement of the evaluation of the error. It seems likely that the error is overestimated, given the technique used.

Evolution of the test configuration. This pressure measurement technique is currently in use, but the cadaver configuration will be modified. Up until now, the tracheal catheter used to inflate the cadaver lungs was closed during the test. For future tests, the catheter may be opened during the test, thanks to an automatically opening valve, if the pressure exceeds 100millibars. So, the exsufflation of the lungs could be possible when the thoracic deflection occurs. But, is the phenomenon long enough to induce an exsufflation during the test, and does the pressure in the thorax change as a consequence?

Numerical model. This exploration can provide data for a future use in a numerical model.

Injury mechanism. Some data available on the behaviour of the pressure in the thorax during the tests can help to better understand certain injury mechanisms.

REFERENCES

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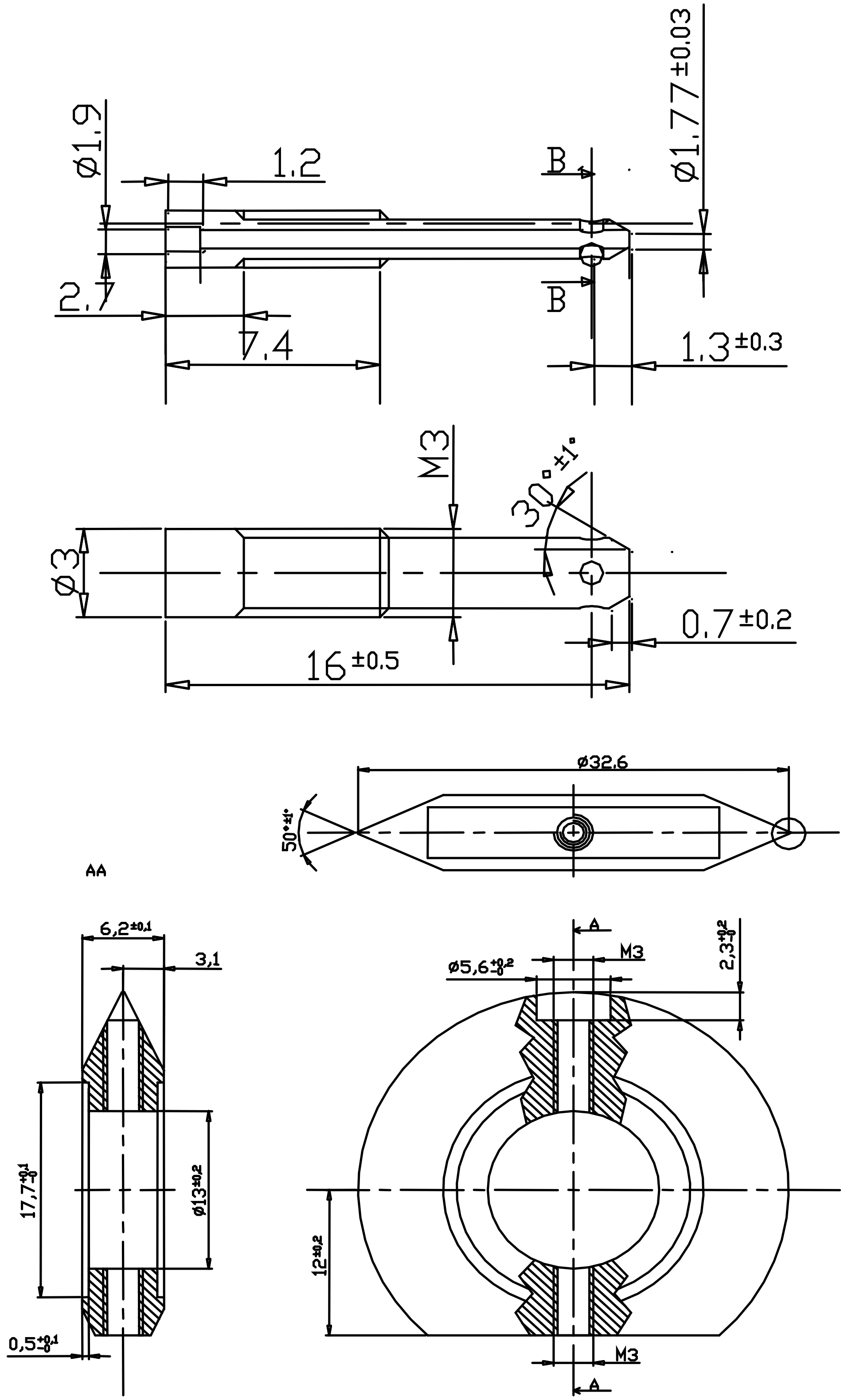
ANNE M.R. AGUR, B.Sc. (OT), M. Sc. Grant's Atlas of Anatomy, ninth edition.

ANNEXE


Ø1,9
1,2
B
Ø1,77±0.03
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M3
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Ø3
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Ø32,6
50°±1°
AA
6,2±0,1
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17,7
Ø13±0,2
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A
M3
Ø5,6
2,3
12±0,2
M3
A

DISCUSSION

PAPER : **Pleural Measurement Technique and Methodology**

PRESENTER : ***Pascal Potier, France***

QUESTION: *Guy Nusholtz, DaimlerChrysler*
Did you evaluate whether the actual surgery and injecting the pressure transducer can cause a change in response?

ANSWER: The pressure inside you, you mean?

Q: Yeah. You're going–What you're going to do is you're going to surgery and then you have to push tissue around.

A: Yeah.

Q: So, it's going disrupt the system, and you have to insert it. Will that change the local pressure measurement because now you have somewhat of a different interface between the pressure transducer than you would between the pleura and the ribs?

A: Inside the device, there a pressure equal to 3 kilopascal to have a convexity of the membranes during the making. And when it's installed into the pleural cavity, no anatomical structure is modified. But when terminating the instrumentation, the inflation of the cadaver leads to an increase of the pressure inside the lung allowing a re-coupling of the two pleura.

Q: So, I was correct. But during the dynamic response, there–that instrumentation looks like it's large enough that you could actually change what your pressure transducer is locally. And, how would you evaluate that?

A: I don't–I'm sorry, but I don't understand. Could you say it again?

Q: Okay. It's an instrumentation problem. When you introduce something of that size, you know, change the dynamic response–

A: Yeah.

Q: of the system, you know, you've got a mass and it could move a little bit...change your response.

A: Okay.

Q: How would you evaluate that?

A: The density of the device is close to the density of the water. The aim of the shape is to maintain the device as it's drawn on the first drawing, to prevent from air in the pleural cavity when the lung is re-inflated after the installation. You see, after the device has been installed into the pleura, the re-inflation of the lung associated to the shape of device allows an automatically good positioning. The density of the device close to the density of the water prevents from motion during dynamic test.

Q: Okay. So, you do everything you can to minimize. Yeah, you might have to close this so we can–Okay. Good. So, you've done everything that you can do try and minimize that problem. That's correct?

A: Sorry?

Q: I just–I sort of summarized it. You're doing everything you can to minimize that particular problem.

A: I'm sorry.

Q: Just say, "Yes."

A: Yes!

Q: Okay. This is a methodological question. You're putting this device between the parietal pleura and the visceral pleura. Is that correct?

A: Yes. Between the parietal pleura and visceral pleura.

Q: Where do you open the parietal pleura? Is it at that same location so that you incise at that same place?

A: Yes.

Q: Then, how do you close it again? You suture the pleura back?

A: Yeah. The intercostal layers, muscle layers

Q: The muscles I can see, but you

A: The pleura is to thin to allow a suture. I inject a gelling powder between the parietal pleura and the muscle layer. Then, I suture the muscle layer. Finally, I inject the gelling porter under the skin. So, at the end, something completely closed is obtained.

Q: But the parietal pleura itself may still be, may still have a cut.

A: May have–?

Q: The pleura may have a cut. You don't close the pleura?

A: No. No. What's important is that the lung, the visceral pleura is not cut. If the visceral pleura is okay, there is no problem. You can re-inflate the subject.

Q: Yes. The cadavers: Have they been frozen or are they fresh?

A: Frozen. Frozen. And, it works. It has been checked.

Q: Oh, I'm sure you can do it. I'm just wondering if I can! Okay. Thanks.

Q: *Steve Rouhana, Ford Motor Company*
Some of the result on blasts has shown that when you look at the lungs after a blast effect, you see rib markings indicating that the lungs under the bones are being loaded differently than at the intercostal spaces. This looks like you're introducing a hard spot in the intercostal space and that's gonna load the lung differently in that location. Sort of a follow-up to Guy's question.

A: You mean that it could result in injury?

Q: Yes.

A: Of the lung?

Q: Artificially, yes.

A: Of the lung?

Q: Of the lung.

A: It does not. Initially, it was a choice to do as described because of a risk of the use of a standard sensor resulting in induced injuries. It was needed to adapt a standard sensor in order to prevent from the risk of injury during the test. And, many tests were carried out with the device, and there is no, no injury on the pleura.

Q: Okay. Thanks.