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A Transtracheal Catheter for Recording the Static Tracheal Pressure in the Exercising Horse

By *K. Roethlisberger-Holm, L. Roepstorff* and *N. Obel*

Department of Medicine and Surgery, Swedish University of Agricultural Sciences, Uppsala, Sweden

Roethlisberger-Holm K., L. Roepstorff and N. Obel: A transtracheal catheter for recording the static tracheal pressure in the exercising horse. Acta vet. scand. 1995, 36, 461-473. – After giving an account of the principles of pressure measurement in flowing air and a review of the literature on tracheal catheters, the authors describe the construction, the introduction and the function of their own transtracheal catheter. This is a teflon catheter with several side-ports which is introduced into the cervical trachea by a guide technique. After introduction, the catheter is stiffened by the insertion of 2 steel wires. The catheter was studied in model experiments concerning:

a) the ability to measure the static pressure in flowing air, and

b) the dynamic accuracy of a recording system built up around the catheter.

The results indicated that the intratracheal pressure sensed in exercising horses well reflected the static pressure, and that the dynamic accuracy of the recording system was good to about 60 Hz. The present technique of recording the intratracheal pressure was used on 122 occasions in 69 exercising horses with only one complication referable to the catheter occurring. The transtracheal route of catheterisation may be superior, as catheters introduced by this route do not appear to influence the function of the pharynx and larynx. In contrast, nasotracheal catheters that traverse the larynx, might interfere with the respiratory function.

upper airway obstruction, frequency response.

Introduction

General considerations

Increased resistance in the upper airways is considered to be an important cause of limited performance in the race-horse (*Cook* 1981, *Morris & Seeherman* 1988). As upper airway resistance (impedance) is defined as the ratio of peak static (lateral) intratracheal pressure to peak air flow rate for a given breath (*Derksen et al.* 1986), the availability of a clinically applicable device for exact recording of the static intratracheal pressure seems to be of paramount importance for the investigator of equine respiratory diseases, as well as for the equine practitioner with demands for objectivity in his clinical work.

The different types of pressure that may be measured in gas flowing through a tube (such as the trachea) are illustrated by the diagram in Fig. 1. The diagram warrants the following comments (1-3).

1. The total (impact) pressure is sensed by a probe that causes local stagnation of the air flow and that has an open tip (a) directed against the flow (*Benedict* 1969, *Blake* 1983).

2. The static (lateral) pressure is the pressure that can be measured via an opening that is at rest with regard to the flowing medium and that does not disturb the flow (*Benedict* 1969). The static pressure may be sensed either through a lateral opening in the tube (b) or by a probe with a closed tip that is directed along the flow and

is fitted with side ports (c) (*Blake* 1983). To counteract errors in pressure measurement due to flow irregularities caused by the presence of the probe in the flowing medium, there should be several small ports placed around the circumference of the probe, and these should be located some distance, at least 7 probe diameters, from the tip (*Benedict* 1969, *Blake* 1983, *Nielan et al.* 1992). At high velocity the tracheal air flow is highly turbulent, a fact which accentuates the need for methods that will counteract errors of measurement (*Nielan et al.* 1992).

3. The dynamic pressure is the pressure equivalent to the kinetic energy of the flowing medium (*Benedict* 1969). It may be determined by calculating the difference between total pressure and static pressure (*Blake* 1983).

When the direction of the air flow is reversed, as in the trachea at a switch from expiration to inspiration (and vice versa), the "ejector effect" of the flowing air may cause the pressure sensed by a probe, as a) in Fig. 1, to be lower than the static pressure when the flow is directed *away from* the port of the probe.

Static and dynamic accuracy of a recording system

"Static accuracy is the reliability of the instrument to record stationary or extremely slowly varying events". "Dynamic accuracy of a recording system is the fidelity with which the response of the system will simulate the dynamic events being measured" (*Fry* 1960). There is no pressure recording system which at all frequencies will give a true copy of the driving pressure fluctuations. The term "frequency response" may be defined as the change in amplitude and phase lag in the recordings that occurs when the frequency of the driving pressure fluctuations is altered. The "dynamic" accuracy of a pressure recording system is considered to be good if the indicated amplitudes are within the range of + 5% of the amplitudes of the "driving" pressure (*Fry* 1960). A recording system is often characterized by giving the highest frequency of the

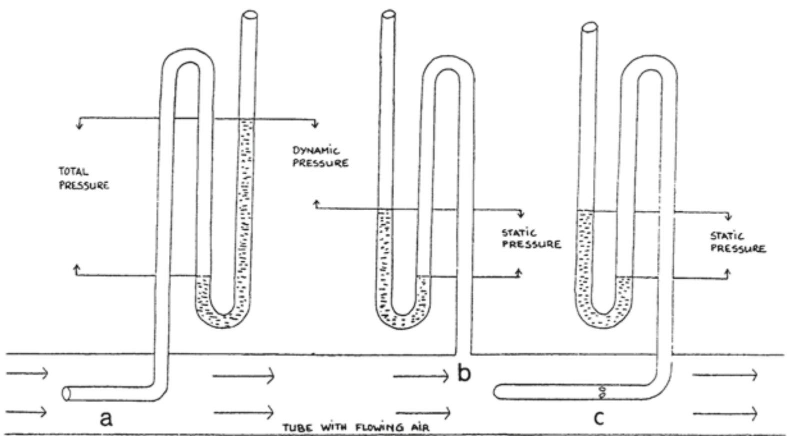

Figure 1. The different types of pressure that may be measured in air flowing through a tube. a: Probe with an open tip for measurement of the total pressure. b: Lateral opening in the tube for measurement of the static pressure. c: Probe with a closed tip and side ports for measurement of the static pressure in another way. Modified after *Benedict* (1969) and *Blake* (1983).

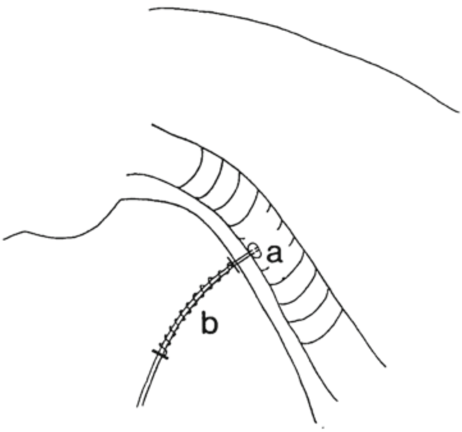

Figure 2. The catheter of Mangseth. a: Latex balloon for retention of the catheter. b: Spring arrangement outside the horse´s skin for keeping the balloon pulled tight against the tracheal wall. Modified after *Williams et al.* (1990).

driving fluctuations that is compatible with accurate recording, e.g. "the frequency response is good to 35 Hz" (Mangseth 1984).

The results of a pressure recording are greatly influenced by the characteristics of the transducer as well as by the dimensions and the compliance of the catheter and any connecting tubes (*Shapiro & Krovetz* 1970). Hence, if a model experiment is to give a meaningful result as regards dynamic accuracy, it is necessary to construct a recording system that is consistent with the type used in vivo.

Principles of tracheal pressure recording

The intratracheal pressure fluctuations in an exercising horse are usually recorded via a tracheal catheter of varying construction. The catheter is connected to a pressure transducer, which is placed either on the horse (*Mangseth* 1984) or, if the examination is performed on a treadmill, possibly in its immediate vicinity (*Nielan et al.* 1992). The pressure transducer converts the pressure variations to voltage signals, which are fed to a voltage-to-frequency converter. This device converts the varying voltage signals to frequency variations suitable for recording on a tape recorder (*Mangseth* 1984). The tape recorder may then be taken to the laboratory and the taped information played back through a frequency-to-voltage converter. The voltage variations, reflecting the tracheal pressure, may be displayed on a chart recorder (*Mangseth* 1984) or studied further with a computer.

Different catheter systems for recording intratracheal pressure in the horse

A catheter for recording the tracheal pressure in the exercising horse has been described by *Mangseth* (1984). This was a transtracheal catheter, i.e. a catheter for introduction through a tracheal puncture. (The conception "transtracheal catheter" was introduced by *Williams et al.* (1990) to distinguish this type of catheter from their own non-invasive nasotracheal catheter). The catheter of Mangseth (Fig. 2) was a modified (shortened) Swan-Ganz cardiac catheter which, after percutaneous insertion, was retained in the tracheal lumen by inflation of a latex balloon at the tip. A spring arrangement outside the skin kept the balloon pulled tight against the wall of the trachea (Fig. 2). Further, a stainless steel jacket, placed over the catheter to cover its initial length, not shown in the drawing, prevented the catheter from being deformed during its passage through the skin and the underlying muscle into the trachea. Mangseth considered the protecting jacket particularly important, as significant shear forces are generated between the trachea and the overlying muscle when the horse is stretched out at the gallop. He gives no details concerning the construction of his catheter. However, *Williams et al.* (1990) (cf. below), who performed comparative studies of the equine tracheal pressure with 2 different catheter systems, including that

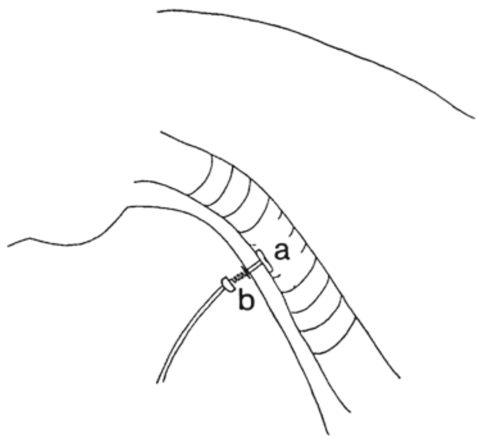

Figure 3. The catheter of Derksen. a: Plastic washer, fixed by flaring the tip of the catheter after its exit through a nostril and introducing it into a hole in the washer. b: Spring assembly for securing the catheter in place. Modified after *Derksen et al.* (1986) and *Nielan et al.* (1992).

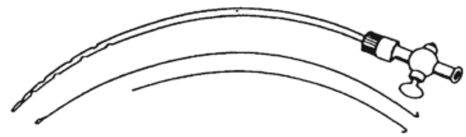

Figure 4. The present tracheal catheter and the 2 steel wires to be introduced for increasing its rigidity. Modified after *Funkquist et al.* (1988).

of Mangseth, used a 7 F double-lumen Swan-Ganz catheter.The size 7 F means a main-tube inner diameter of 2.33 mm. According to the manufacturer the Swan-Ganz catheters are made of polyvinyl chloride. The transtracheal catheter of Mangseth was attached to a pressure transducer mounted on a latex rubber support, taped onto the horse's neck. The frequency response of the recording system was good to 35 Hz (*Mangseth* 1984). *Derksen et al.* (1986) studied the lateral tracheal pressure with a transtracheal catheter of polyethylene, ID 3.17 mm, OD 3.99 mm and length 100 cm. The catheter was introduced through a metal cannula inserted percutaneously into the rostral third of the cervical trachea. The catheter was advanced rostrally and exited through a nostril. A plastic washer, 1.5 cm in diameter, was placed over the anterior end of the catheter. After flaring of the tip, the catheter was withdrawn until the washer was seated firmly against the tracheal wall (Fig. 3). The catheter was secured in place, using the spring assembly described above (*Mangseth* 1984). The pressure of the airway was recorded with a differential pressure transducer. The airflow through a pneumotachygraph, fixed on a face mask, was recorded simultaneously, and the upper airway pressure was defined as the difference between the pressure in the tracheal catheter and the mask pressure. The frequency response of the recording system was not given. The transtracheal catheter of *Funkquist et al.* (1988), described in detail below, was a teflon catheter (ID 2.00 mm, OD 2.50 mm, length 18 cm) to be introduced with a guide technique after puncture of the anterior tracheal wall. The catheter (Fig. 4) had 8 side openings, 1 mm in diameter, evenly distributed around the circumference on an approximately 5 cm long area near the tip. After insertion into the trachea, it was stiffened by the introduction of 2 stainless steel wires. The pressure was recorded with a device, the principle of which is described above (*Mangseth* 1984), based on a Sensym transducer (type LX0600IG). The frequency response of the recording system was not given.
Williams et al. (1990) compared intratracheal pressure recordings obtained in experimental horses with use of 2 different catheter systems (Fig. 5): a side-port polyethylene nasotracheal catheter, ID 5 mm, length 97 cm, and a transtracheal catheter, essentially similar to that described by *Mangseth* (1984) and mentioned above. Radiographically, the tips of the two catheters were situated at about the same level

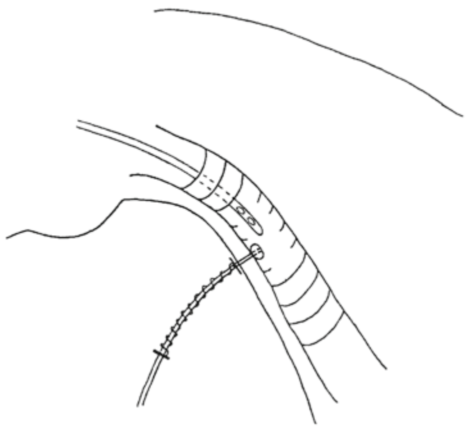

Figure 5. The 2 catheter systems used in the comparative studies by *Williams et al* (1990): a nasotracheal side-port catheter and the catheter of Mangseth (see legend to Fig. 2). Modified after *Williams et al.* (1990).

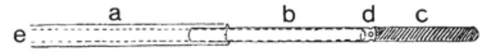

Figure 6. Tip and adjacent parts of the catheter used by *Nielan et al.* a: Outer teflon tubing. b: Inner teflon tubing. c: Rigid extension of polycarbonate. d: Ports. e: To transducer. Modified after *Nielan et al.* (1992).

in the rostral third of the trachea. The frequency response of the recording system was not given. The authors found no significant difference between the pressure recordings obtained with the 2 catheter systems.

Nielan et al. (1992) described a nasotracheal side-port catheter constructed with consideration of the aerodynamic principles briefly discussed above. The catheter consisted of an inner and an outer teflon tubing. The inner tubing had an ID of 1.3 mm, OD 1.9 mm and length 200 cm, and the "anterior" part passed through the outer teflon tubing, which had an ID of 2.4 mm, OD 4.0 mm and length 100 cm.The "anterior" part of the inner tubing (Fig. 6) had a rigid extension consisting of a polycarbonate tubing, the end of which was closed with a plug of latex caulk to prevent air and liquids from entering. The polycarbonate tubing was designed so that the inner teflon tubing fit snugly inside and the outer teflon tubing snugly fit outside. Four ports, each 1 mm in diameter, were situated radially and symmetrically, 1.9 cm (8 diameters) from the tip. The tracheal pressure oscillations were sensed and transmitted to the lumen of the inner teflon tubing via the rigid extension on the anterior end. The purpose of the outer tubing was to provide the catheter system with the rigidity necessary for tracheal insertion and to prevent damage to the inner tubing when the horse swallowed or coughed. A polyvinyl chloride tubing, ID 2.5 mm, OD 3.5 mm, was placed around the "posterior" 100 cm of the inner teflon tubing to prevent kinking. The frequency response of the recording system, built up around the catheter described, was good to 33 Hz according to a study of the response of the system to an instantaneous pressure change, calculated according to *Fry* (1960).

The following observations have been made regarding the occurrence of complications and other factors that may influence the suitability for clinical use of the catheters described above: *Mangseth* (1984), who used his transtracheal catheter in 7 experimental horses, reported that the puncture sites healed cleanly without incident. Air dissection between the trachea and overlying tissue was not observed. *Derksen et al.* (1986) used their transtracheal catheter for repeated recording in 5 experimental horses and do not mention complications in connection with its use. However, *Nielan et al.* (1992), who compared a transtracheal catheter with their own nasotracheal catheter, state that in their experience the use of the transtracheal catheter in exercising horses is associated with an unacceptable incidence of complications such as cellulitis, granulomas and chondromas. *Funkquist et al.* (1988), who used their catheter for repeated recording in 5 exercising experimental horses, do not mention the occurrence of complications in connection with their recordings. The same catheter was used, however, by *Roethlisberger-Holm* (1993 and 1994) in a somewhat modified way. Because one horse at an early recording occasion experienced a transient subcutaneous infection, the routine of flushing the catheter with a solution of penicillin during withdrawal was introduced (2-3 ml of a solution of 1 g benzylpenicillin in 20 ml of sterile water). Using this modified technique, Roethlisberger-Holm repeatedly recorded the intratracheal pressure on 48 occasions in 23 exercising experimental horses and on 46 occasions in 37 exercising privately owned horses without observing any complications. As mentioned above, *Williams et al.* (1990) made repeated recordings in 10 horses with naturally occurring upper airway obstruction with their own nasotracheal catheter and with the transtracheal catheter of *Mangseth* (1984). They state that both catheter systems were tolerated well by the horses. As the placement of the transtracheal catheter was more invasive and time-consuming, however, the use of the nasotracheal catheter was considered to be a more clinically acceptable method. *Nielan et al.* (1992), with their nasotracheal catheter, made repeated recordings of the intratracheal pressure in 15 experimental and more than 30 privately owned horses. The only detrimental effect of the use of the catheter that was observed on subsequent endoscopy was a mild hyperaemia of the tracheal mucosa lasting for 24-48 h. During recording it was observed, however, that the catheter could be partially obstructed by fluid (condensate, mucus or blood), necessitating flushing with compressed air after disconnection from the transducer. The authors therefore recommend that only measurements performed immediately after flushing should be considered accurate, as obstruction of the catheter may slow the pressure transmission along the tubing.

Since, as emphasized above, most of the conditions adversely affecting the course of the tracheal pressure in the exercising horse are related to disturbances of upper airway function, it seems important to find a technique for tracheal pressure measurement that leaves the pharynx and larynx unaffected. For this reason we have studied the characteristics and the fitness for clinical use of the transtracheal catheter of Funkquist et al (1988), briefly described above. The aim of our studies may be divided into the following 3 sections:

I. Construction of the catheter and technique of its insertion.
II. Measurement of the pressure of flowing air in model experiments with the studied catheter.
III. Dynamic accuracy of a recording system built up around the catheter.

Materials and methods

I. Construction of the catheter, and technique of its insertion

The principles of the construction and the practical use of the catheter have been described by *Funkquist et al.* (1988). Some details of that description, with additions to certain points, may be of interest in the present context.

As mentioned above, the catheter was made of teflon tubing, ID 2.00 mm, OD 2.50 mm and length (adapter excluded) 18 cm. To facilitate its insertion with a guide technique, its wall was thinned at the tip by stretching the tubing during heating. The catheter had 8 side openings, 1 mm in diameter, evenly distributed around the circumference on an approximately 5 cm long area near the tip (Fig. 4). Under local anaesthesia the catheter was inserted at the borderline between the rostral and the middle third of the

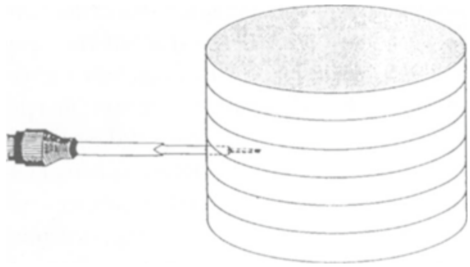

Figure 7. Principle of drilling a hole in the tracheal wall for "compression-free" passage of the present tracheal catheter. Modified after *Funkquist et al.* (1988).

cervical trachea. The procedure was started with a tracheal puncture, performed through a skin incision, a few millimetres long, on the lower midline of the neck. The tracheal puncture was performed with a coarse injection needle, ID 1.60 mm, OD 2.00 mm and length 8 cm. To avoid deformation of the catheter by compression by the tissues of the tracheal wall, the original puncture hole was widened a few tenths of a millimetre as follows (Fig. 7): a 1.45 mm blunt stainless steel pin (length 24 cm) was introduced into the trachea through the injection needle. The latter was then replaced by a blunt stainless steel tube, ID 1.55 mm, OD 2.00 mm, length 15 cm, using the pin as a guide. Thereafter the pin was removed. The widening of the puncture hole was accomplished with a purpose-made tubular bore (ID 2.10 mm, OD 2.80 mm, length 4 cm). The bore, which was made of a stainless steel tube (yard goods) by double oblique grinding, was manoeuvred with a chuck of suitable dimensions (Fig. 7). Using the blunt stainless steel tube as a guide, the tubular bore was introduced into the trachea by slow rotating movements with least possible pressure. After the bore had passed the anterior tracheal wall, it was removed and a flexible spring guide wire (PE 205) of the Seldinger type (*Seldinger* 1953) was introduced into the

Figure 8. The present catheter was introduced into the trachea by threading it over a flexible guide. The dimensions of the catheter are greatly exaggerated in this drawing. Compare radiograph in Fig. 9.

trachea via the blunt tubular guide. The tube was removed and the catheter was introduced into the trachea by threading it over the flexible guide (Fig. 8).

In addition to the above technique for boring a hole in the tracheal wall sufficiently large for "compression-free" passage of the catheter, deformation was counteracted by stiffening the catheter. This was achieved by introducing, via the applied adapter, two 0.5 mm metal wires made of hard-drawn stainless steel (yard goods, Fig. 4). One of these wires was of such a length that after introduction its tip was located immediately »anterior« to the most »anterior« side opening of the catheter, while the tip of the other (shorter) wire was located immediately »posterior« to the most »posterior« side opening. The 2 wires had a hook at the "posterior"

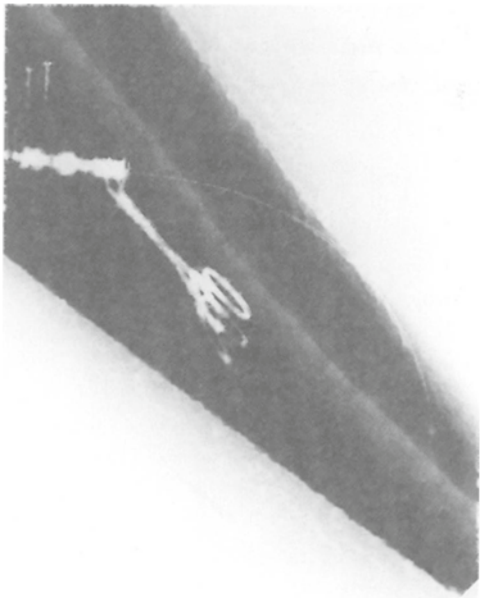

Figure 9. Radiograph of the present catheter, visualized by the stiffening wires introduced, in situ in the trachea after exercise on a treadmill at speeds up to 7 m/sec.

end which prevented them from falling into the catheter (Fig. 4). Further, the tip of the longer wire had a 180° bend (Fig. 4), preventing it from being caught by the side holes of the catheter during its introduction. The difference in length of the stiffening wires was based on an observation in preliminary experiments that the presence of 2 wires in the part of the catheter that was fitted with lateral ports resulted in entrance of disturbing fluid into the catheter.

As both the teflon tubing and the stiffening wires were constructed of factory-made material, supplied in rolls, the resulting catheter was slightly curved. Thus, after »premature« introduction of the steel wires, the catheter, placed on the bench top, had the shape of an arc of a circle with a diameter of 15-20 cm. After proper insertion, the tip of the catheter pointed in the aboral direction and the convex aspect rested against the posterior tracheal wall (Fig. 9).

The adapter of the catheter was provided with a butterfly of adhesive tape, which was fixed to the skin with towel clamps.The catheter was connected to the transducer mentioned in the introduction. The transducer was fixed with Velcro band and towel clamps to a collar of adhesive tape placed around the horse's neck above the tracheal puncture.

The time taken for introducing the catheter, including insertion of the stiffening wires, was about 3 min. When the time required for attach-

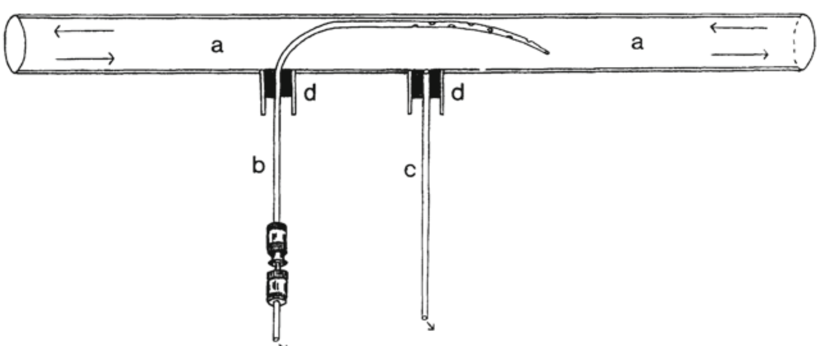

Figure 10. Schematic drawing of the device for measuring the static pressure and the pressure sensed by the present catheter, in model experiments with flowing air. a: Plexiglass tube with air flowing at a velocity of 35 m/sec. b: Catheter to be tested. c: Teflon tubing for measuring the static pressure. d: Lateral plexiglass tube.

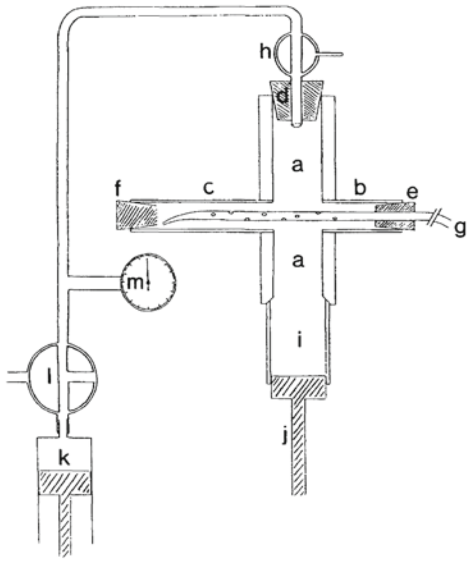

Figure 11. Schematic drawing of the device for determining the dynamic accuracy of a recording system, including the present catheter, by subjecting the catheter to a step-wise pressure change. a, b and c: Plexiglass tubes. d, e and f: Rubber plugs. g: Catheter to be tested. h: Stopcock. i: Piece of the cylindrical part of a syringe. j: Plunger. k: Syringe for production of a vacuum in the system. l: Three-way cock. m: Manometer.

ing and connecting the transducer is added, the total time taken for application of the recording device may be estimated to be < 5 min (the onset time of the local anaesthetic not included).

II. Measurement of the pressure of flowing air in model experiments with the studied catheter

The experiments were performed with the device illustrated in Fig. 10, the main component of which was a plexiglass tube, ID 19 mm. Introduced into the tube through lateral openings, situated near the middle and about 5 cm apart, were two smaller, lateral, plexiglass tubes, with an ID of 10 mm and 1.5 cm long (Fig. 10). The inner ends of the lateral tubes were glued flush with the wall of the large tube. One of the lateral tubes was for introduction of the catheter to be tested and the other was for introduction of a teflon tubing (ID 2.00 mm) for measuring the static (lateral) pressure. The latter tubing had a squarely cut tip situated flush with the wall of the large plexiglass tube. Airtight introduction of the catheter and the teflon tubing was achieved via holes drilled in exactly fitting rubber plugs which completely filled the inner part of the lateral plexiglass tubes. The catheter and the teflon tubing, which sensed the static pressure, were each connected to their own water manometer. Flow of air through the large plexiglass tube was brought about by a compressor supplying about 600 l/min. Connected between the compressor and the tube was a conventional mechanical flowmeter. The connection of the plexiglass tube could be reversed.

The experiments consisted in measurement, at an air flow of maximally 600 l/min through the 19 mm plexiglass tube, of the static pressure and the pressure sensed by the catheter. Through the possibility of reversing the connection of the tube, measurements could be performed both when the flow was directed *away from* the tip of the catheter (as in inspiration) and when it was directed *towards* the tip (as in expiration). Ten experiments of each type were carried out.

III Dynamic accuracy of a recording system built up around the catheter

The characteristics of this pressure recording system were determined by subjecting the connected catheter to a sudden change in pressure (Fry 1960). The device (Fig. 11) that we used for these studies consisted of one large plexiglass tube with an inner diameter of 19 mm (a) and 2 smaller ones with an inner diameter of 10 mm (b and c). The tubes were glued together and closed at the upper end and at the 2 lateral ends, respectively, by rubber plugs (d, e and f).

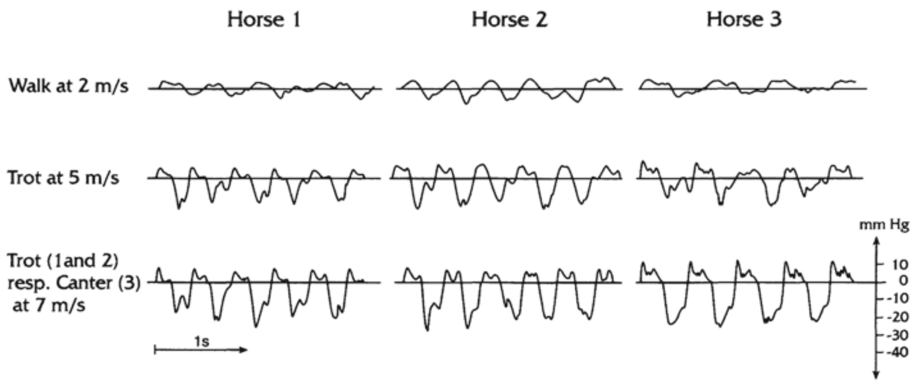

Figure 12. Tracheal pressure curves from 3 different, normal horses exercising at different speeds and gaits on a treadmill.

The rubber plug (e) of the smaller plexiglass tube to the right had a hole for airtight passage of the catheter to be tested (g). Introduced into the catheter, but not shown in the figure, were the 2 stiffening steel wires, illustrated in Fig. 4. The upper rubber plug (d) had a hole for airtight passage of a metal tube connected to a stopcock (h) just above the plug. Glued to the lower end of the large plexiglass tube was a piece of the »cylinder« of a disposable 20 ml syringe (i), which could be closed temporarily by the introduction of a few millimetres of its plunger (j). Connected to the stopcock (h) via a rubber tubing was a syringe (k) for producing a vacuum in the plexiglass tubes. The syringe was connected via a three-way cock (l) for removal of any superfluous air. The pressure of air within the system was measured by a manometer (m), constructed for measuring negative pressure.

After connecting the catheter to the recording system and introducing a few millimetres of the plunger (j) into the "cylinder" (i), the pressure in the system was lowered to -40 mm Hg by aspiration with the syringe (k). Then, after closing the cock (h) at the upper end of the large plexiglass tube, the plunger (j) was rapidly removed. In 3 experiments the recordings of the after-vibrations following the sudden change in pressure were analysed regarding frequency and amplitude (*Fry* 1960).

Results and discussion

The results of the practical use of the present catheter have been reported by *Holm et al.* (1991) and *Roethlisberger-Holm* (1993 and 1995). The catheter has been used for recording of the tracheal pressure in a total of 69 exercising horses at 122 occasions with a transient, subcutaneous infection in 1 horse as the only complication occurring. From these recordings, 74 were made in 30 normal, experimental horses (*Funkquist et al.* 1988, *Holm et al.* 1991 and *Roethlisberger-Holm* 1993). The 30 normal horses were exercised at speeds up to 8 m/sec. during an incremental exercise test on a treadmill or in the field. Examples of pressure tracings from 3 different, normal horses are shown in fig. 12. The shape of the pressure recordings is uniform for different normal horses at the same speed, when the horses are trotting at 4 m/sec or faster.

The uniformity of the pressure recordings indicates that any entrance of fluid into the catheter, as observed in the case of the nasotracheal cath-

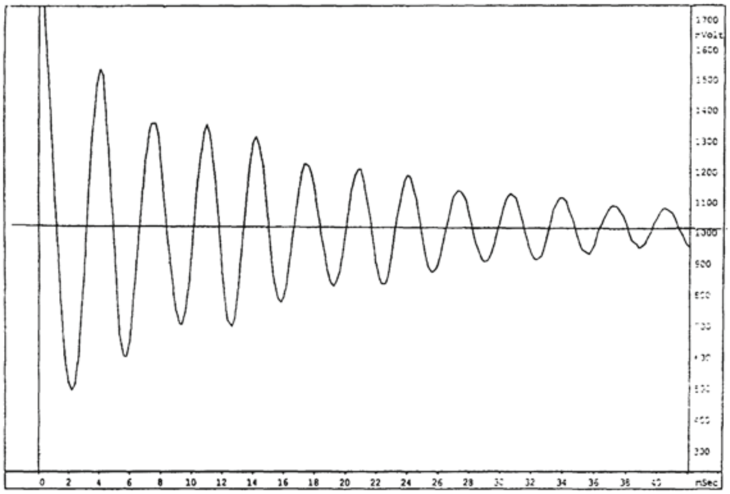

Figure 13. After-vibrations of the present recording system following a sudden pressure change.

eter of *Nielan et al.* (1992), does not obstruct the present catheter to such a degree as to jeopardize the pressure transmission. As regards the possibility of reducing the dimensions of the present catheter, it should be noted that, contrary to the above observations, *Nielan et al.* (1992) found such a degree of obstruction of their 1.3 mm catheter by fluid penetration that they recommended that only measurements performed after flushing of the catheter with compressed air should be considered accurate. Thus there seems to be no reason to reduce the dimensions of the present catheter. See further "General discussion".

Both the pressure sensed by the catheter and the static pressure, simultaneously measured with the teflon tubing, increased with increasing flow. The pressure sensed by the catheter at maximal flow (mean of ten experiments), expressed with the simultaneously measured static pressure as reference, was -0.1 cm H_2O when the flow was directed away from the tip and +0.2 cm H_2O when it was directed towards the tip.

The maximum velocity of air flowing through the tube was calculated to be about 35 m/sec, which considerably exceeds the maximal velocity (21.8 m/sec) that has been calculated for the air in the trachea of a horse galloping at 14 m/sec (*Nielan et al.* 1992). Thus, within the range of the air velocity occurring in the trachea of an exercising horse, the dynamic components of the pressure measured seem to be reduced to negligible values by the construction of the present catheter.

The after-vibrations of the recording system caused by the sudden pressure change are shown in Fig. 13. On analysis of the graphs a low damping ratio was found. The accuracy of the recording system under the prevailing experimental conditions appeared to be good up to about 60 Hz, when calculated according to *Fry* (1960).

The low damping of the recording system may imply a source of error in certain situations. Advantages and disadvantages of the characteristics observed will be discussed in detail below.

General discussion

For reasons mentioned above, it seems most important to find a technique of recording the intratracheal pressure that leaves the structures of the upper airways unaffected. The present catheter, with its transtracheal route, seems to meet great demands in this respect. When estimating the fitness for clinical use of a catheter for recording the intratracheal pressure in an exercising horse, the following factors should also be taken into consideration:

1. The time required for introduction of the catheter.
2. The exactness of the pressure information obtained.
3. The risk of complications.

These 3 points are discussed further below:

1. The time taken for introducing and connecting the catheter was about 5 min (excluding the onset time of the local anaesthetic).

2. According to model experiments with the catheter in air at a steady flow, the pressure sensed by the catheter may be considered to well reflect the static pressure. As regards the dynamic accuracy of the recording device, it should be noted that the low damping of the system means that the amplitude of the pressure events occurring at a very high frequency may be overestimated. On the other hand, the accuracy of the recording was good up to about 60 Hz, i.e. considerably above the frequency at which most of the pressure events of equine respiration are considered to occur (*Nielan et al.* 1992, *Mangseth* 1984). The accuracy of the present recording system up to 60 Hz opens the possibility of observing and analysing pressure fluctuations with an unexpectedly high frequency, as those observed by *Roethlisberger-Holm* (1995), which might have remained undiscovered if a recording system with greater damping had been used.

3. According to *Nielan et al.* (1992), who compared a transtracheal catheter with a non-invasive nasotracheal catheter, the use of transtracheal catheters is attended with a high frequency of infectious complications at the site of the tracheal puncture. It is possible that the high frequency of complications at the puncture site, associated with the transtracheal catheter of *Nielan et al.* is partly due to their problems to keep it properly positioned during exercise. The present catheter has, with a final penicillin flushing, been used without complications for tracheal pressure recording on 48 occasions in 23 exercising experimental horses and on 46 occasions in 37 exercising privately owned horses in which the examination was performed because of clinical signs.

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Sammanfattning

En transtracheal kateter för registrering av det statiska trycket i luftstrupen på häst under arbete

Författarna redogör för principerna vid tryckmätning i strömmande luft och gör en genomgång av litteraturen över trachealkatetrar. Konstruktion, införande och funktion av deras egen transtracheala kateter beskrivs. Detta är en teflonkateter med ett flertal sidoöppningar. Den förs in i luftstrupen med hjälp av en guideteknik. Efter införandet förstyvas katetern med två metalltrådar. Katetern har studerats i modellförsök med avseende på:

a. förmåga att mäta det statiska trycket i strömmande luft, och

b. den dynamiska exaktheten i ett registreringssystem uppbyggt kring katetern.

Resultaten tyder på att det intratracheala trycket registrerat hos arbetande hästar väl avspeglar det statiska trycket, och att den dynamiska exaktheten hos registreringssystemet var god upp till c:a 60 Hz. Den beskrivna tekniken för intratracheal tryckmätning användes vid 122 tillfällen på 69 hästar under arbete, med en komplikation som kan hänföras till katetern i endast ett fall. Den transtracheala metoden för katerisering synes överlägsen, eftersom en kateter införd med denna metod, i motsats till nasotracheala katetrar, ej tycks påverka funktionen i pharynx och larynx.

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Reprints may be obtained from: K. Roethlisberger-Holm, Dept. of Medicine and Surgery, Swedish University of Agricultural Sciences, Box 7037, S-750 07 Uppsala, Sweden.