Basic principles

of

urodynamic measurements

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Some introductory stuff

The *Good Urodynamic Practices* document (*Neurourology Urodynamics 2002: 21;261-274*) published by the ICS should be seen as the standard for performing urodynamics and interpreting urodynamic traces. It's n ot an easy read - here's a sentence from that document:

> *"The desired and actual accuracy of uroflowmetry should be assessed in relation to the potential information that could be obtained from the urinary stream compared to the information actually abstra cted for clinical and research purposes."*

The document you're reading now is a potted summary of the way we do things, along with a few of the reasons. It leaves out the clinical application of these methods, which is the business of the clinicians. It's not as comprehensive as the *Good Practices* document, but we hope you might find it a bit more accessible.

What is urodynamics about?

Most of urodynamics is about measuring two physiological parameters:
- Urine flow rate (normally given the symbol Q);
- Bladder pressure (pressures in general are normally given the symbol p)

Why are they important?

Why are flow rate and voided volume important?

An abnormal flow of urine is a key symptom in many urological conditions. For men, a reduced, hesitant or intermittent urine flow is a key symptom of prostatic obstruction. For women, poor flow can also be present and it may not only be an important symptom but also may reflect inefficient bladder emptying that might affect the surgical approach to correct female incontinence. It is therefore clear that an objective measurement of urine flow rate and volume would be desirable.

Why is the measurement of pressure important?

An abnormal urine flow is a key symptom of a urological complaint, but does not indicate the cause . In very general terms, the flow rate is affected two factors:
- The driving pressure from the bladder;
- The opposition to flow presented by the outlet.

Flow takes place when the driving pressure exceeds the opposition to flow. Under most circumstances (ie. when the patient is not trying to void), the main opposition to flow is presented by the sphincters, which should keep the patient continent.

Therefore, symptoms of urine leakage might be due to:
- An overactive bladder that contracts spontaneously.

Or equally, due to:
- A weak sphincter producing inadequate opposition to flow.

Of course, when the patient is actively trying to void, you would like the minimum opposition to flow.

Symptoms of hesitancy or a poor flow rate might be due to:
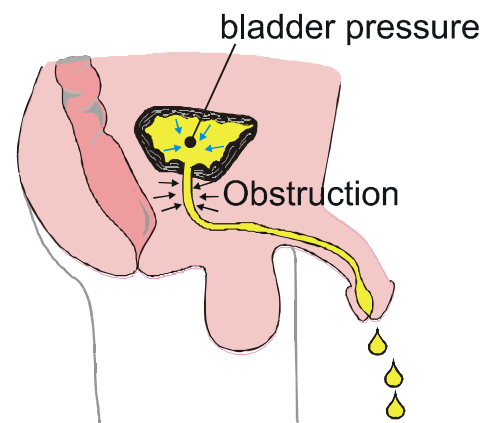- A weak bladder contraction.

Or equally, due to:
- An enlarged prostate (*right*) producing a large obstruction to flow.

Clearly, a flow rate alone is not enough to diagnose these conditions. You need to measure bladder pressure as well - both while the patient is filling up (to spot over-activity), and when they are voiding (to measure bladder contraction).

A basic urodynamics system

The picture below shows the constituents of a basic urodynamics system used to diagnose the conditions described.
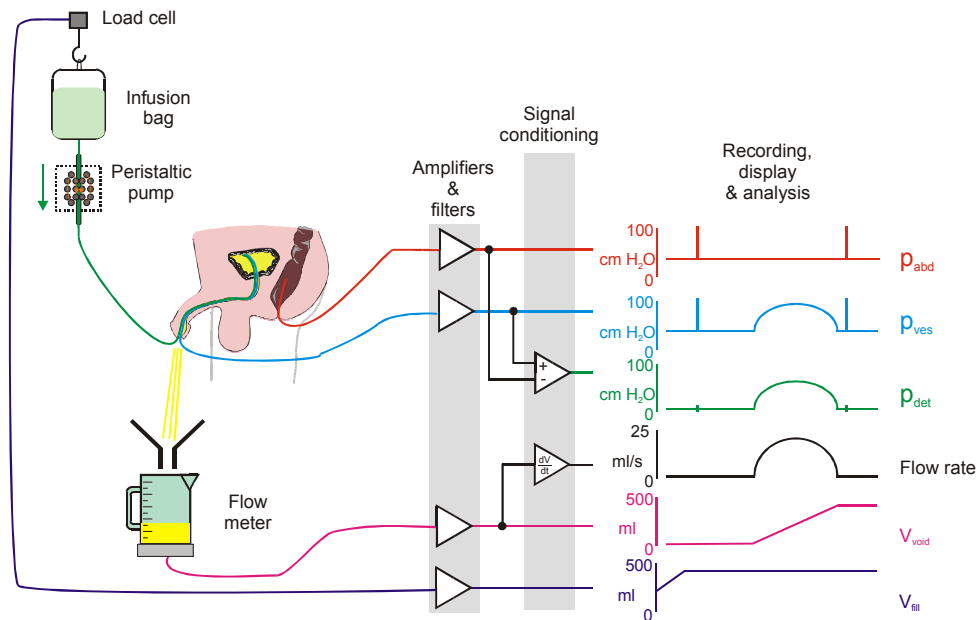
Measurement of flow rate and voided volume

In every urodynamics system there will be a flow meter to provide measurements of flow rate (Q) *and* voided volume (V_{void}). V_{void} is usually measured in millilitres (ml), while Q is measured in millilitres per second (ml/s). Flow rate and voided volume are clearly related. It's not important to understand these relationships fully, except to say that:

Flow rate is the rate of change of volume
$$Q = \frac{dV}{dt}$$
If V_{void} can be measured, Q can be calculated.

Volume is flow rate integrated over time
$$V = \int Q\, dt$$
If Q can be measured, V_{void} can be calculated.

There are a few different types of flow meter (*see later*), but they all measure *either* flow *or* volume, and then calculate the other parameter. Most measure volume directly, then deduce the flow by determining the rate of change of volume - a process called *differentiation*. The notable exception is the spinning disk flow meter, which measures flow then obtains volume by *integration*.

Measurement of pressure

Pressure in the bladder is measured using a *pressure transducer,* which converts a pressure to an electrical signal. Since the bladder is not readily accessible to the outside world, the transducer is allied to a catheter. The most-used systems are the *fluid-filled catheter with external transducer* and the *catheter-tip transducer* - both are described later.

The pressure in the bladder (vesical pressure, p_{ves}) has contributions from the bladder detrusor muscle (p_{det}) and from abdominal pressure (p_{abd}). To determine the pressure due to the bladder muscle alone (p_{det}), it is necessary to subtract the abdominal contribution. Abdominal pressure p_{abd} is normally measured in the rectum (*as shown*), but can also be measured in the vagina, or via a stoma. Normally, one anticipates most detrusor activity during the voiding phase, but it is important to measure pressures during filling to identify the contractions of an over-active bladder (*for example*).

Filling

So that the study can be completed in a reasonable time, the patient is usually filled via a second catheter into the bladder. The infused volume (v_{fill}) is normally determined by weighing the infusion bag using a load cell.

A basic urodynamics system (continued…)

Amplifiers, filters and signal conditioning

The signals from pressure transducers are extremely small, and so must be amplified before being recorded. In addition, there will probably be some filtering that cleans the signals by removing high frequency noise. Finally, some simple signal conditioning is used to make the data more easily interpretable by the user. Shown are:

- Electronic subtraction, to determine p_{det} by subtracting abdominal pressure from vesical pressure.
- Electronic differentiation, to determine flow rate from voided volume.

Recording, display and analysis

You will, of course, want to record the cystometric data for later display and analysis. A chart recorder might be used in earlier systems and in some basic flow meters, but a urodynamics system today will almost always use a computer here.

And finally…

The figure (*below*) shows a basic urodynamics system:

- A load-cell flow meter (*see later*) with stand, funnel and jug is to the left of the picture.
- The tall stand to the right is fitted with a load cell to measure infusion volume (*top*), infusion pump (*level with top of printer*) and two external pressure transducers (*below pump, level with top of trolley*).
- The amplifers, filters and signal conditioning electronics are in the box on the trolley (*middle shelf, right*).
- The computer is used for recording, display and analysis of the urodynamic signals.

Performing urodynamics - a cribsheet

This document contains quite a lot of detailed information about urodynamics. To make things easier, here's a list of the steps you'll follow when performing a urodynamic investigation.

Check calibration of the flow meter

The flow meter shouldn't need calibrating often, and in any case there might be no way for the user to adjust the calibration itself. However, it is good practice to check the calibration before every session.

- For more information about the different types of flow meter, see page 6.
- To learn about calibrating flow meters, see page 7.
- For some information about basic artefacts in flow measurement, see page 8.

Calibrate the pressure transducers

Pressure transducers are prone to drift - you need to calibrate your pressure transducers for every session, particularly when you are working with disposable transducer domes.

- For information about the basic physics of pressure measurement, see pages 9 to 10.
- For general information on pressure transducers, see pages 11 to 15.
- For more information on calibrating pressure transducers, see page 16.

Catheterise the patient

This is the nurse's or clinician's problem, and we won't say much here. You'll normally be passing three catheters.

- A catheter into the bladder to fill the patient.
- A catheter in the bladder to measure p_{ves}. Bladder catheters normally go in *per urethra*, but might occasionally be passed via a supra-pubic opening.
- A catheter in the back passage (or occasionally vagina or stoma) to measure p_{abd}.

In some cases, the first two catheters are combined into a single line with two completely separate lumens, but the principle is the same.

Flush the measurement lines (if using fluid-filled catheters)

Fluid-filled catheters don't work well unless filled completely with water.

- For information on why air bubbles compromise a catheter's performance, see page 10.
- For details of how to flush your catheters, see page 14.
- To check the quality of recording, see page 17.

Fill the patient, and then ask them to void

Again, largely the clinician's business. It's possible to allow the patient to fill naturally (particularly in ambulatory urodynamics), but takes an hour or more. It's therefore much more common to fill through a line into the bladder.

- For information about the filling procedure, see page 18.
- You will probably ask for regular cough tests - see page 17.

Record the urodynamic signals throughout

Throughout, you will record the urodynamic signals for later review. This might be on a chart recorder, but these days is more likely to be on computer.

- For a brief discussion of the electronic systems used in a urodynamic system, see pages 19 to 20.
- For information on data recording, see page 21.

Review and interpret the urodynamic data

Finally, you will review the recorded data to make a diagnosis.

- For some very basic information on trace interpretation, see pages 22 and 23.
- For specific information on assessing outlet obstruction, see page 24.
- For specific information on assessing bladder contractility, see page 25.

Measurement of flow rate and voided volume

There are a number of ways to assess flow rate (Q) and voided volume (V_{void}). These are described below, in approximate order of increasing complexity. There are other systems, but these are the exception rather than the rule.

The dipstick flow meter

In a dipstick flow meter, the height of urine in a collecting vessel is measured by a dipstick. Typically, the capacitance of the dipstick will be proportional to urine height. Now, if the area of the vessel is known, the height can be converted directly to a measurement of volume, and then to flow rate.

Advantages

Works with any conductive fluid, including contrast medium.

Disadvantages

The cross-sectional area of the vessel must be known.
Often produces a noisy signal because of ripples in the urine.
The vessel needs pre-loading with saline so the dipstick tip is immersed.
Quickly goes out of calibration if not cleaned regularly, as urine crystals collect on the dipstick.

To cystometry system
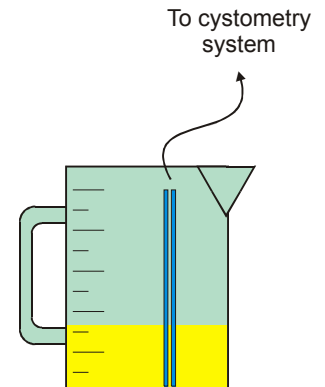
The load cell flow meter

This is currently the most common type of flow meter, and is used by the majority of flow or cystometry measurement systems on the market. The load cell is essentially a weighing scale - since the density of urine is (to within 3%) the same as water, the weight of the urine can be converted directly to volume, and then to flow rate.
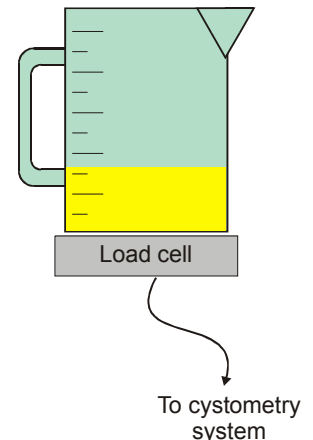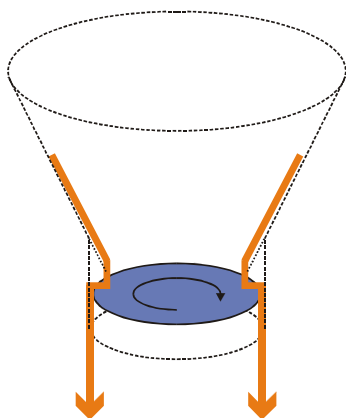
Advantages

Simple and easy to clean.
Works with any shape and size of collecting vessel.

Disadvantages

Measures weight, not volume. Hence needs calibration for contrast medium.

Load cell

To cystometry system

The spinning disk flow meter

The spinning disk flow meter is currently made by just one manufacturer (Dantec, now Medtronic), but is very popular. The urine stream falls on (and is quickly thrown off) a rapidly spinning disk, and tends to slow it down. A fairly complex control system measures the electrical power required to keep the disk spinning at a constant speed. The flow rate is directly related to the measured electrical power, and volume can be calculated thereafter.

Advantages

Does not require a collecting vessel.
Less prone to momentum artefacts (see later).

Disadvantages

Electrically and mechanically complicated, hence can be awkward to clean.
Measures weight, not volume. Needs calibration for contrast medium.

# Checking calibration of a flow meter - the milk bottle

It is good practice to check the calibration of a flow meter regularly, preferably at the start of every session. Here's a cunning gadget that works extremely well. (*J Urol 1983: 55: 21-24.*)

You will need:

- A milk bottle
- A rubber bung to fit the bottle
- A short length of metal pipe
- A longer length of flexible neoprene or silicone rubber tubing

To make the gadget:

- Bore holes in the cork to fit the metal pipe and the rubber tubing
- Fit the pipe and tubing so they are flush with the base of the cork
- Mark the milk bottle at a known volume - probably 500 ml
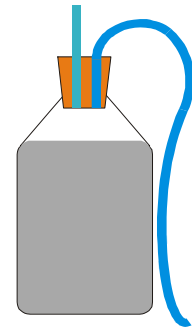
To use the gadget:

- Fill the milk bottle to the 500 ml mark
- Turn the bottle over as shown, so the flexible tubing stays filled with air
- Direct the flow into the flow meter
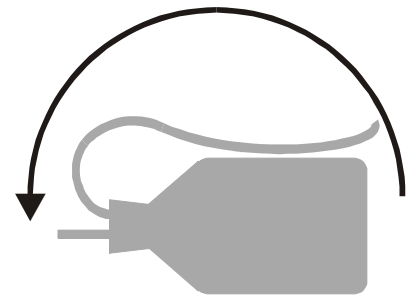
How does it work?

When water flows through a hole in the bottom of an open vessel, the flow rate will fall as the vessel empties. The head of water is reducing in height, and so the pressure driving the flow is constantly falling (*see later sections on pressure*).

In the gadget, the inside face of the cork is kept at a fixed pressure because it is vented to the atmosphere at this level by the rubber tubing. This means the driving pressure is fixed. The flow rate depends only on the length and diameter of the metal pipe. The flow from one of our milk bottles is shown below.

In principle, it is possible to calculate the flow rate from physical equations. However, it's much easier just to make the gadget, and measure the flow rate produced. By shortening the tube, it's possible to reduce the flow rate. Lengthening the tube would have the opposite effect, if you could manage it.
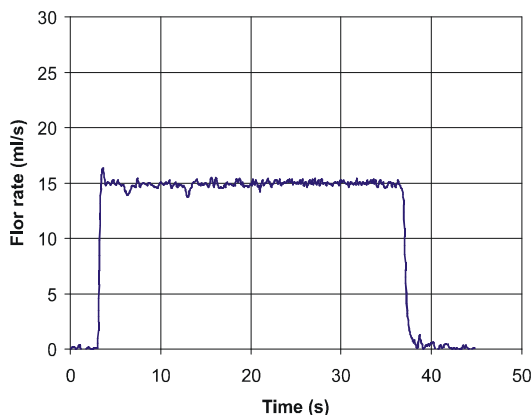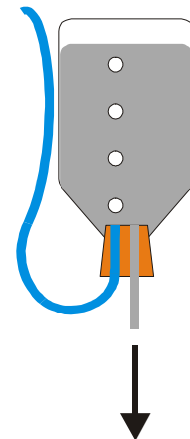
NOTE: The process of integration is used (by spinning disk flow meters, for example) to determine volume from flow rate. This process is (effectively) the same as measuring the area under the 'flow rate versus time' graph. In the case above, this area would be approximately:

$$15 \text{ ml/s} \times 34 \text{ s} = 510 \text{ ml}$$

Flow artefacts

There are a few artefacts to be aware of when making flow measurements.

Wagging

Wagging (known as cruising in Bristol, for some reason) is part of the male psyche. It's caused by the chap who alternately directs the flow down the spout, then into the funnel rim, and affects all types of flow meter.

The urine directed straight down the spout catches up with urine that fell earlier into the rim. So far as the load cell is concerned, the flow increases briefly; the effect (*right*) is to produce a peak of flow.

When the flow is directed back into the rim, the opposite happens, to create a temporary dip in flow rate. You should be particularly suspicious when (as shown) the area of the peak and the area of the trough are equal.

A funnel fitted with baffle will help reduce these artefacts.

Peak due to flow down spout

Trough due to flow into rim
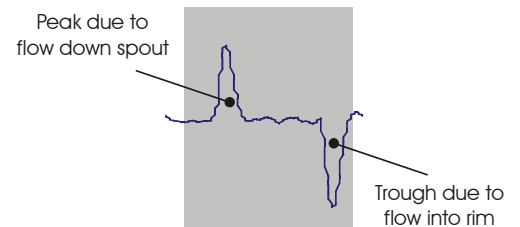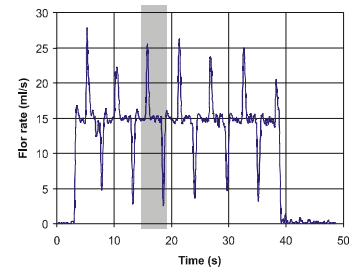
Lagging
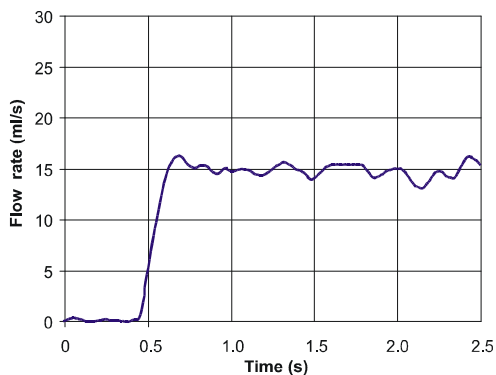
All flow meters introduce some delay to the signal. The figure shows the response of our flow meter to a step change in flow as generated by a milk bottle test. Points to note are:

- The flow meter has no response whatever for almost half a second. This is caused by the mechanical delay as the urine flows down the funnel and into the vessel, up to 1 second in the worst case.

- Thereafter, the response of the flow meter is not instantaneous. This is caused by electronic filtering in the flow meter circuit.

As a rule of thumb, assume your flow meter will introduce a delay of around 1 second in the flow trace.

Occluding the penis

For some obstructed men, it helps to pinch the penis and build up a head of steam, before letting flow commence. The flow trace thus produced will of course be intermittent.

In addition (*right*) there will be a burst of flow following each occlusion. This is caused by urine dilating the proximal urethra while the penis is occluded. You should be aware that this surge is artefactual - in the example shown, the peak flow rate is 6-7 ml/s, and not 21 ml/s.

The Americans Maryrose Sullivan and Subbarao Yalla (Neurourology & Urodynamics 2000 19: 657-69) use this effect to assess bladder obstruction. In obstructed men, you would expect a bigger surge relative to the steady-state flow rate.
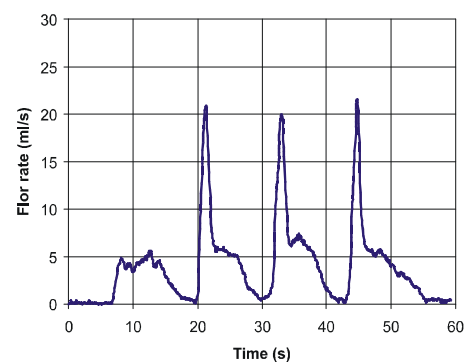
Contrast medium

Load cell and spinning disk flow meters don't measure flow directly - they measure mass and interpret that as flow by assuming the density of saline/urine is approximately 1 g/ml. If you're using a contrast medium, this isn't so - the indicated flow rate will be too high. To make the correction, you need to know the density of the medium you're using. If your flow meter doesn't offer any way to correct, then simply divide the indicated flow by the density of the contrast medium to estimate the actual flow. For example, an indicated flow of 20 ml/s with a contrast medium of density 2g/ml would mean the true flow rate was 10 ml/s.

Pressure

What is pressure?

As most people know, a pressure is a measurement of force per unit area. At the lowest level, pressure is caused by the random movements of molecules in a fluid, and can *only* be measured reliably in a fluid (liquid or gas). If you try to measure pressure when a fluid is not present (for example, in a dry urethra), the results will very likely be nonsense.

Units of pressure measurement

The SI unit for pressure is the Pascal, defined as 1 Newton per square metre. By phys iological standards the Pascal is tiny; there are (approximately) 100 Pascals to 1 cm H_2O. Therefore in urodynamics, the *cm H_2O* is used, because:
- The pressures involved are typically in the range 0 to 250 cm H_2O, which are convenient sizes to handle;
- The fluid in question is (very nearly) water.

The importance of this second point will soon become clear.

## Some useful bits of hydrostatics

Hydrostatics is the study of fluids (especially, water) when not moving. Much of the physics behind urodynamic measurement can be understood from three basic principles. Here they are:

THESE RULES APPLY ONLY WITH NEGLIGIBLE FLUID FLOW - AS IN A MEASURING CATHETER
When there is appreciable flow, effects due to turbulence, frictional loss and Bernoulli's principle are intr oduced.

1 Fluids transmit pressure changes

Water has no structural strength, so a difference in pressure can't be supported. Suppose you connect two balloons (*right*) by a horizontal tube. Any pressure applied to one balloon will be transmitted along the tube to the other balloon. The same pressure would be measured in both balloons.

Any pressure change at one point will be transmitted, causing the same change everywhere else in the system.

Same pressure
in both balloons
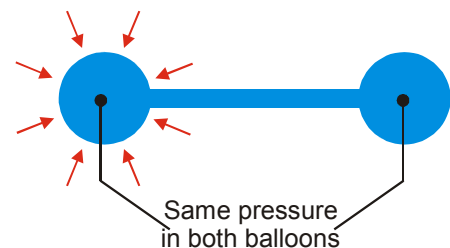
2 Pressure varies with height

p = zero

p = 20 cm water

20 cm

40 cm

p = 40 cm water
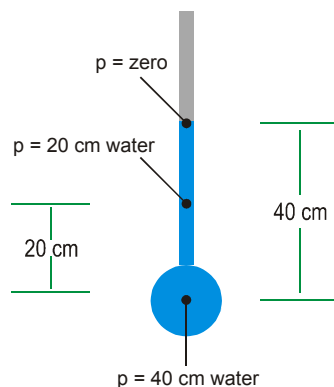
As anyone who ever went swimming will know, pressure increases with depth. At the surface, pressure is the same as atmospheric - which will become our definition of 'zero pressure'.

Descend 20 cm, and the pressure increases by 20 cm H_2O. The increase in pressure is caused by the weight of water above.

Descend a further 20 cm, and the pressure will be 40 cm H_2O. This is, of course, the origin of the *cm H_2O* as a unit of pressure.

3 At a given height, pressure is equal everywhere in the system

This follows from rule 2:
- Start half way down the thin tube - pressure is 20 cm H_2O.
- Descend 20 cm into the bulb - by rule 2, pressure is 40 cm H_2O.
- Climb 20 cm up the fat tube - by rule 2, pressure is 20 cm H_2O again.

This rule becomes particularly important when using external transducers.

p=20 cm water

40 cm

p=40 cm water
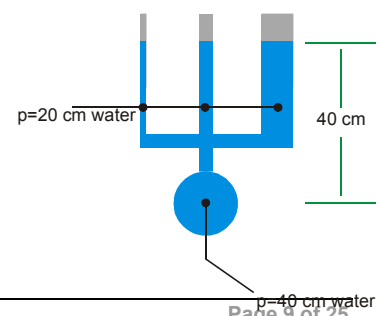
Some more (relatively) interesting things about pressure

Pressure as height of a column of liquid

A simple demonstration of pressure can be made by tying a fluid-filled balloon to the bottom of a vertical pipe. If you now squeeze the balloon, the water will rise in the pipe. As mentioned earlier, the height of the water column is an indication of the pressure in the balloon, in this case 40 cm H_2O. The fluid-filled balloon is not such a bad model of the bladder, and this gives a hint as to how early urodynamics were performed.

40 cm

p = 40 cm water
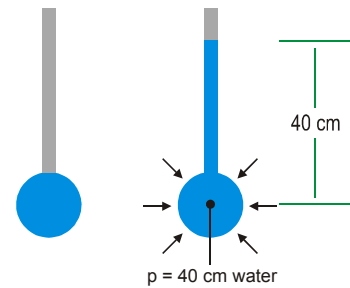
The effect of tube diameter
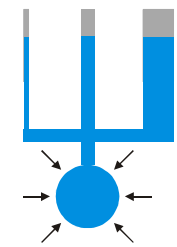
There is a saying that *water always finds its own level*, as illustrated (*left*). In this case, the pressure in the balloon is supporting three columns of different widths. It seems likely that the water will travel higher in the narrower tube. However, this normally isn't so - the height of water in each column will be identical. This follows from the 3rd rule presented earlier.

If the tube is so narrow that capillary action comes into play, then the water may behave differently to what is described here.

The effects of density and gravity

A similar idea is, of course, the origin of the unit *mm mercury* in blood pressure measurement. In the sphygmomanometer, mercury is used simply because of its high density, about 13 times higher than water. A blood pressure of 150 mm Hg would require a water column 2 m high. Therefore (*right*), the density of the fluid is important when making pressure measurements in this way.

In addition, gravity is important. If you performed the experiment (*right*) on the moon, the water would rise to 240 cm, and the mercury to 18 cm, because the moon's gravity is one sixth that on earth. The effect of gravity isn't likely to cause practical problems in the Urodynamics laboratory.

water   mercury

40 cm

3 cm

Same pressure in both balloons
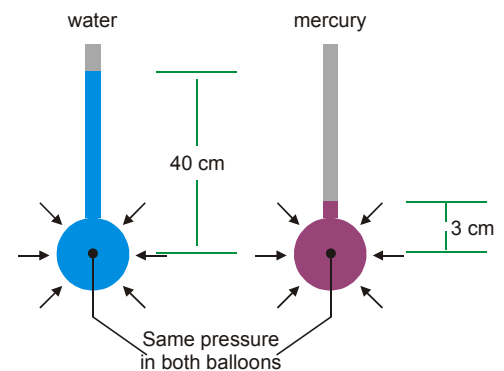
Why are bubbles a bad thing?
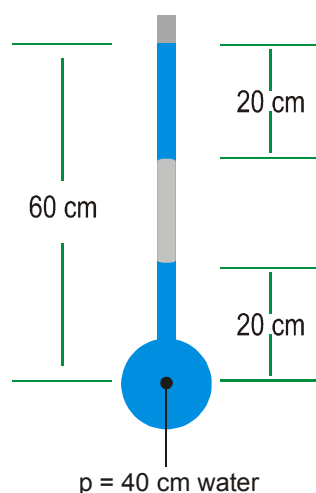
There are two problems with air bubbles. First (*left*), the weight of a column of air is (effectively) zero. You might think the water column is 60 cm tall, but the pressure in the bulb at the bottom will only be 40 cm H_2O, because only 40 cm of the column is filled with water. Any bubble in a catheter that isn't completely horizontal will introduce an offset to your pressure measurements.

20 cm

60 cm

20 cm

p = 40 cm water

The second problem is more subtle. Water is essentially incompressible, and pressure changes are transmitted very quickly along a water-filled catheter *without any flow of water*.

Air bubble shrinks
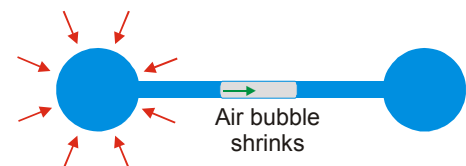
Air (*right*) is compressible - an increase in pressure *will* be transmitted eventually - but only after fluid flows into the catheter to compress the air bubble. This will *dramatically* slow down the response of the catheter. In effect, the catheter acts as a *low-pass filter* (see the later discussion of filters).

The measurement of pressure

The most obvious way to measure pressure in (say) the bladder might suggest itself from what went before (*right*). Just arrange for the bladder to be connected to a vertical catheter. Ask the patient in question to void, then measure how far up the column the urine reaches. The height *h* gives the bladder pressure in cm H_2O.

This would work (and indeed, used to work[☺]), but there are a couple of difficulties. First, the obvious one - the idea isn't particularly practical, and certainly doesn't lend itself to making a permanent record of bladder pressure changing over time.

Second, a more subtle problem. Unless the patient has an exceptionally strong bladder so that urine can reach the top of the tube, the urine has nowhere to go. The patient will maintain a bladder contraction without any flow - a so-called *isovolumetric bladder contraction*. While *isovolumetric bladder pressure* might be useful, this measurement isn't particularly representative of a normal voiding cycle.
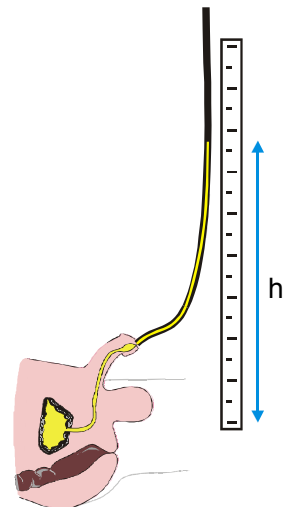
Clearly, a simpler method of measuring pressure during voiding would be desirable.

Pressure transducers

The term *transducer* can be used to describe any device that converts a physical quantity (temperature, sound, pressure) into an electrical signal (normally a voltage). In urodynamics, you'll be concerned with:

- Load cell transducers (converting weight to an electrical signal in the flow meter);
- But particularly, pressure transducers.

The strain gauge transducer
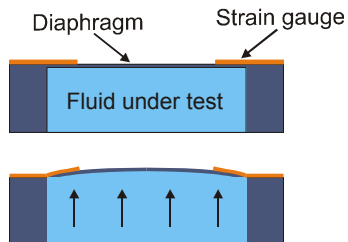
The transducer contains a flexible diaphragm, one side exposed to the fluid you're trying to measure the pressure in. When the pressure in the fluid increases, it will displace the diaphragm a little way. That is usually detected using a strain gauge built into the diaphragm; a strain gauge is a strip of some material whose resistance increases when stretched. Many materials (all metals, for example) have this property, but silicon is often used because it produces a relatively large yet predictable change in resistance for a given stretch. While there are improvements, most modern pressure transducers used in urodynamics are variations on this theme.

Properties of a transducer

The blue trace on the graph (*right*) shows how you would like the transducer to behave. The output (in suitable electrical units, typically milliVolts) is a linear function of the applied pressure. The urodynamics system can convert back to a pressure simply by knowing the appropriate scaling factor.

The *sensitivity* of the transducer is an important characteristic, and is given by the slope of the graph - 1 milliVolt per 50 cm H_2O.

Generally, you'd like a sensitive transducer to measure small changes accurately. However, more sensitive transducers have a lower range of operating pressure (the *dynamic range*). The system designer makes a compromise between sensitivity and dynamic range.
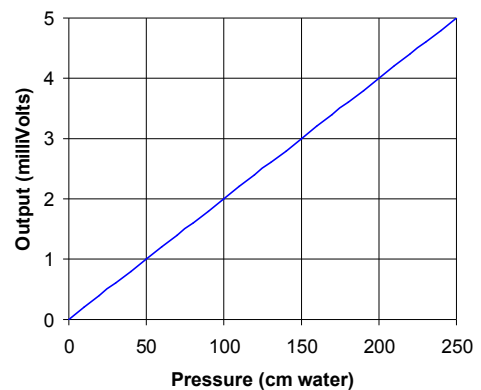
[☺] *Piccie of early urodynamics is courtesy of Doug Small's excellent web site at www.sghurol.demon.co.uk/urod*

Non-ideal transducers

Of course, transducers don't always behave exactly to plan - a few sources of measurement errors are described below. These should be quantified in the transducer's documentation, and are normally expressed as a percentage (the effects at normal temperatures and pressure will typically be around 1%).
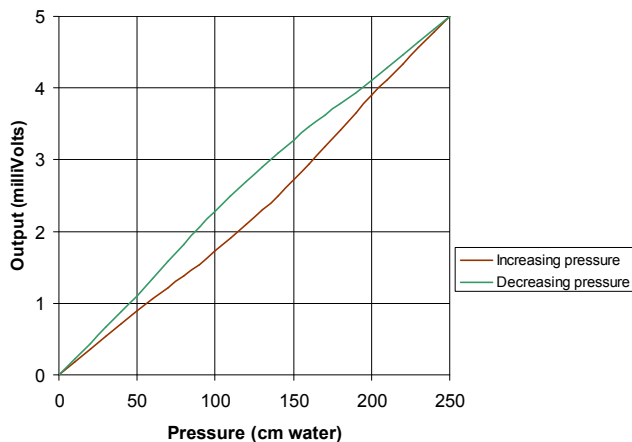
Non-linearity

The red line (*right*) shows (in exaggerated form) how a transducer might really behave. This transducer is non-linear, and it's therefore not easily possible to convert back to an exact pressure measurement.

All transducers will be non-linear to some degree, because the materials used to make the strain gauge are fundamentally non-linear. For small strains the deviation from linearity is small, typically < 1%. The problem will be more manifest if you use a transducer near the limits of its operating range.
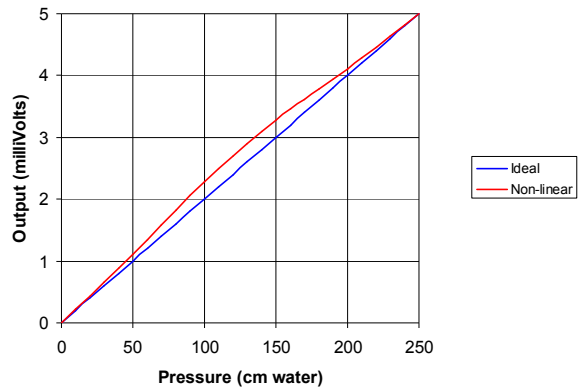
Hysteresis

Hystereis is a particular form of non-linearity where the transducer behaves differently depending whether the pressure is increasing or decreasing. It is typically due to visco-elastic properties in the transducer itself.

In modern transducers, hysteresis does not normally pose a large problem.

Temperature dependence

Most transducers are made from silicon strain gauges these days, and the properties of silicon are extremely sensitive to temperature. While this can largely be compensated, most transducers are sensitive to some degree (*right*). In particular, the offset from zero is prone to drift. The best advice here is to switch on the equipment some time before use, and (as much as possible) control the temperature of the environment.
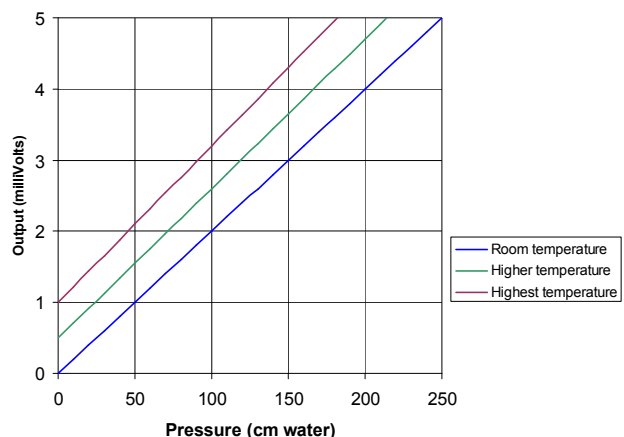
More about pressure measurement

Sites of pressure measurement
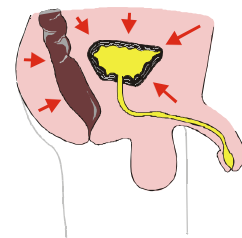
If you're doing urodynamics, you will clearly be interested in the pressure in the bladder (vesical pressure, p_{ves}). However, p_{ves} has contributions from two sources:

- The pressure exerted by the bladder detrusor muscle (p_{det}).
- The intra-abdominal pressure p_{abd} experienced throughout the abdominal cavity. This is shown by the red arrows (*right, top*).
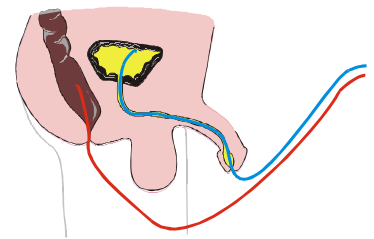

$$p_{ves} = p_{det} + p_{abd}$$

To assess the bladder function we're really interested in the pressure p_{det} due to the detrusor muscle itself. By a bit of rearranging:

$$p_{det} = p_{ves} - p_{abd}$$

So, as shown (*right, bottom*):

- You can measure p_{ves} within the bladder.
- You can measure p_{abd} within the rectum (or in the vagina, or via a stoma).
- You then subtract one from the other to calculate p_{det}.

The two types of pressure transducer

In urodynamics, the sites where pressure needs to be measured (the bladder, and also the rectal cavity) are not readily accessible to the outside world. The transducer must therefore be allied to some form of catheter that can be guided to the site of measurement. The transducers used in urodynamics can be divided into two broad categories.
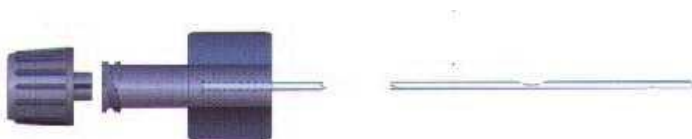
Catheter-tip transducers

Catheter-tip transducers are the simplest to understand. As the name suggests, the transducer is mounted in the tip of the catheter, and is located directly at the site of measurement. Of course, since the transducer must be passed *per urethra*, it needs to be small. The transducers are more difficult and therefore expensive to manufacture.

In the UK, the best-used catheters of this type are manufactured by Gaeltec on the Isle of Skye. They are easy to set up, and are most appropriate for ambulatory studies.

External transducers

With an external transducer, a fluid-filled catheter is passed to the measurement site (the bladder, for example). The pressure is transmitted along the catheter to the pressure transducer, which is external to the patient. The transducer can therefore be as large as needs-be. The transducer (*near right*) is usually protected by a dome (*far right*) with a thin membrane, so the transducer itself need not come in contact with the fluid.


In most cases, the catheter and transducer dome are disposable and should be discarded after each patient. In the UK it would be illegal to re-use a product marked *for single use only*. There has been a recent MDA bulletin regarding cross-infection from re-used transducer domes.

Pressure measurements with an external transducer

With an external transducer, a hollow fluid-filled catheter is passed to the measurement site; the bladder is shown, but this equally applies to the rectum. The pressure is transmitted along the catheter to the pressure transducer, which is external to the patient. This type of transducer is the most commonly used, but is the most difficult to set up properly. There are two key elements in setting up an external transducer.
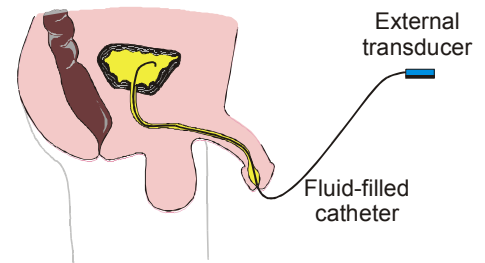

Flushing the line

A fluid-filled catheter *will not work properly i*f there is *any air* in the measuring system. You therefore need to flush the catheter line and transducer dome before starting measurements. You will need:

- A 10 ml or 20 ml syringe;
- A 3-way tap.

REMEMBER: What you are trying to expel all the air from the system. Different centres arrange the syringe and tap differently, but you must never expose the transducer to the full pressure of the syringe. A syringe can generate pressures 10 times those seen in normal use, and you can quite easily damage the transducer. Note also that a small diameter syringe will generate higher pressures than a large one!

Newcastle and Manchester use the method below, because it avoids the need to flush water across the transducer dome into the catheter:

- Isolate the catheter using the tap, and flush through the transducer dome to air.
- Isolate the transducer using the tap, and flush through the catheter to the patient.
- Isolate the syringe using the tap, connecting transducer to patient for normal use.


Flush to air

Flush to patient via catheter

In use
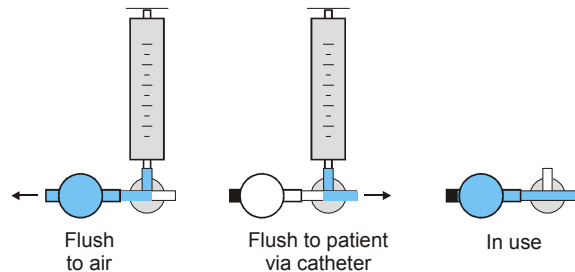
Establishing the pressure reference level

40 cm H_2O
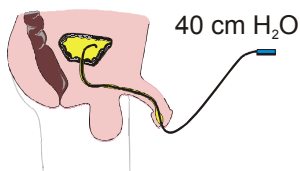
From the earlier principles of hydrostatics, remember that in a fluid-filled system the pressures at any given height are equal. The bladder, catheter and transducer all form part of the same .water-filled system This means that:

- The position of the catheter in the bladder *does not matter*.
- The vertical position of the transducer *affects the pressure measurement.*

If you lower the transducer by 20 cm, the pressure measured will increase by 20 cm H_2O.

60 cm H_2O
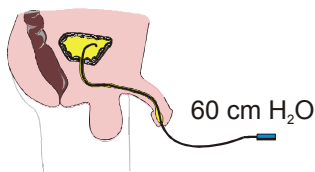
By convention, the transducer is set level with the pubic symphysis. Since pressures across the system are equal at any given height, you are effectively measuring the pressure in the bladder *at the level of the pubic symphysis*.

Measuring in the rectum

Measuring p_{abd} in the rectum is trickier because the rectum is (relatively) dry - a pressure measurement under these conditions is not particularly useful. The usual solution is to use a catheter with a small rubber balloon on the end.

These are commercially available but we use a finger cot, tied on with silk thread. The balloon is vented with a small hole. When the catheter is flushed the balloon fills with water, and provides a fluid medium around the transducer tip.

Vent hole

Catheter

FInger cot
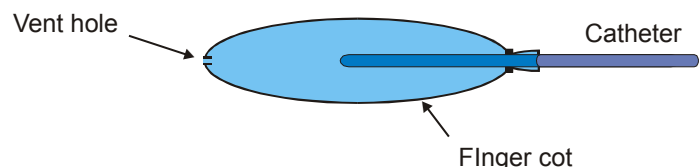
Pressure measurements with catheter-tip transducers

The catheter-tip transducer is fundamentally simpler than its cousin, but far more difficult to manufacture. This makes the catheters more expensive, and not so widespread. The key difference between this and the fluid-filled catheter relates to the effect of height on the measured pressure. To re-state the facts:

Fluid filled catheters

- The position of the fluid-filled catheter within the bladder is *not* important.
- Changing the height of the external transducer *will* affect the measurement.
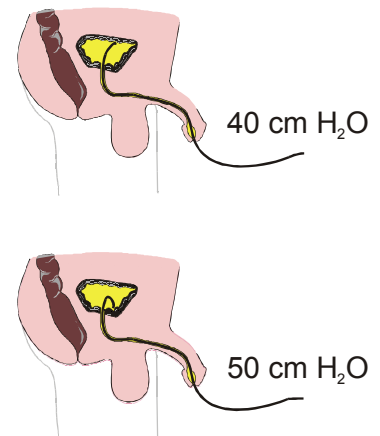
Catheter-tip transducers

As shown in the figure (*right*):
- The position of the transducer in the bladder *will* affect the measurement.
- In the roof of the bladder, the measured pressure will be relatively low;
- In the bladder floor, pressure will be relatively high.

40 cm H$_2$O

In a typical bladder, the difference between the two might be 10-15 cm H$_2$O. Of course, without using some imaging technique it's not possible to know where the transducer is sited, so this is effectively a source of measurement error.

To summarise

In both types of pressure measurement, it is the height of the *transducer* that affects the pressure measurement. This is true whether the transducer is in the bladder or external to the patient.


50 cm H$_2$O

Some pros and cons of the two transducer/catheter types

	Fluid-filled catheter with External transducer	Catheter-tip transducer
One-off cost	Medium - typically £100 for each non-disposable transducer.	High - typically over £500. Catheter might typically last >100 studies.
Disposables	The catheter & often the transducer dome are disposable - typically £10 per study.	None required.
Sterilisation	Catheter is supplied sterile. Transducer requires sterilisation if exposed to fluid.	Catheter should be sterilised before every study.
External equipment	Transducer, dome, tap and syringe for flushing.	None
Bandwidth	Relatively low - typically 30 Hz. Does not respond to rapid pressure changes.	Relatively high - 500 Hz or higher. Can respond to rapid changes in pressure.
Artefact	Artefacts from infusion pump or line tapping.	Transducer is in the bladder - therefore few artefacts.
Effect of height	None - if the transducer height is set correctly at pubic symphysis.	Random error of typically ±5-10 cm H$_2$O relative to the centre of the bladder.
Typical use	ICS standard for laboratory cystometric measurements.	Ambulatory urodynamics.

Calibrating a pressure transducer

Each transducer should be calibrated before every session. In older systems, calibration means adjusting a control on the instrument. In newer machines, it is performed electronically[*]. In either case, there will be two steps in the calibration procedure. As shown, in the figure (*right*), you will need::

- a syringe;
- a 3-way tap;
- your cheapest sterile filling line.
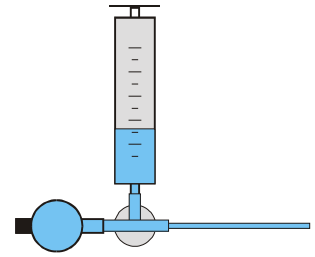
Establish the zero pressure reference

The first stage in calibration is to establish the zero pressure. In urodynamics, zero pressure is *always* defined as atmospheric pressure, and pressure measurements are expressed relative to atmosphere. To establish zero pressure:

- Flush the dome and the line with sterile water to ensure *there is no air in the system*.
- Adjust the 3-way tap, to connect the transducer to the line.
- Place the tip of the filling line *exactly level with the transducer*.
- Adjust the instrument's *zero offset* control so that the measured pressure is zero (older machines) or identify this as zero pressure (newer machines).

Calibrate at some suitable positive pressure

Next, you will establish a known pressure reference at some suitable pressure, typically 100 cm H_2O.

- Raise the tip of the filling line *to exactly 100 cm above the transducer.*
- Adjust the instrument's *gain* control so that the measured pressure is 100 cm H_2O (older machines) or identify this as 100 cm H_2O pressure (newer machines).

If you're not sure why this works, go back to the principles of hydrostatics described earlier.

A more convenient way of doing things

The way we've just described will work well, but there are a few caveats:

- The line must be *completely free of air* - the reasons were explained earlier.
- The line *must not leak throughout the calibration procedure*.

Remember that if you get the calibration wrong, then every measurement you make thereafter will be inaccurate. Using our lines, an air bubble or leak of 0.1 ml would result in an inaccuracy of about 10 cm H_2O in the calibration.

If you have access to a hand-held pressure meter, a new way of doing things is shown in the figure:

- Connect the transducer, syringe and meter - *NO WATER*.
- Now use the syringe to adjust the pressure.

Big syringes (>100 ml) work best, particularly those fancy ones with a threaded multi-turn plunger for fine adjustment. Follow the protocol above - first establish zero, then calibrate at 100 cm H_2O. We think the pros are:

- No water, and so no problem with bubbles or leakage.
- You don't need three hands to perform the calibration.

BUT REMEMBER - check the calibration of the meter periodically.
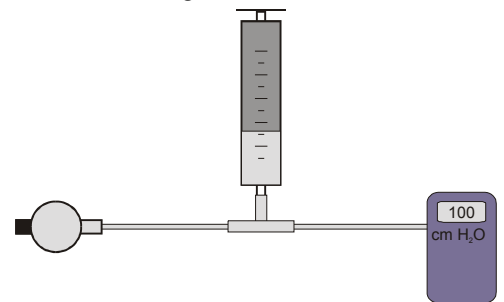
Calibrating a catheter-tip transducer

To calibration rig ← | Catheter / Seal
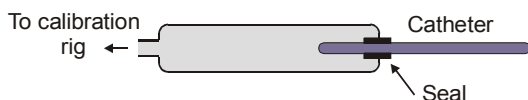
To calibrate a catheter-tip transducer, you need to expose the catheter tip to the calibration pressure. One way is to fill a measuring cylinder with sterile water, and immerse the catheter tip to a known depth.

Alternatively, you can make or buy a gadget like the one shown. This whole thing plugs in place of the dome, but beware - *this calibration procedure is not sterile*.

---

[*] *We're wary of electronic calibration - even if the transducer is completely knackered, the system will probably try to calibrate itself ... BUT your measurements thereafter will be nonsense. If you use such a system, CHECK THE SIGNALS AFTERWARDS.*

Making a pressure recording

Okay - you've done all the following:

- Calibrated the transducers;
- Passed the catheters;
- Set the reference height to pubic symphysis;
- Flushed with water;

And everything seems fine - but is it?

Resting pressures

The resting pressure in the abdomen is caused by the weight of body tissues sitting on top of the abdomen. Since the lungs and diaphragm must be at (approximately) atmospheric (zero) pressure, and the body is largely water, you might estimate a resting pressure (in an upright patient) as the distance from the diaphragm to the pubic symphysis (*below*).

- For abdominal pressure (p_{abd}), we measured a value of 38 ± 8 cm H_2O in a group of patients; this agrees with other similar studies.
- Resting vesical pressure (p_{ves}) should be similar.
- Thus resting detrusor pressure p_{det} should be low (<10 cm H_2O).
- For good physiological reasons, a negative value of p_{det} is unlikely - suspect your setup.

Lungs - zero pressure

This bit (say 30 cm) is mostly water

P=30 cm H_2O
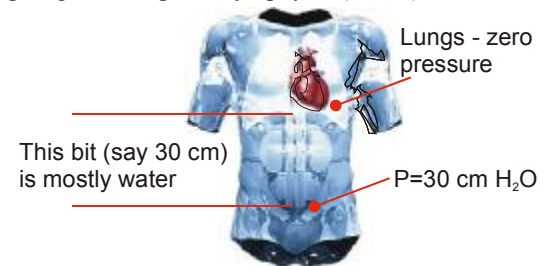
The cough test

Ask the patient to cough - the cough causes a rapid rise in intra-abdominal pressure, which ought to be recorded in p_{abd} and p_{ves}, as shown below.
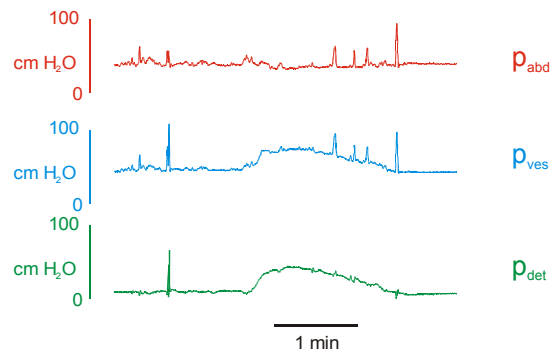

p_{abd}

p_{ves}

p_{det}

1 min
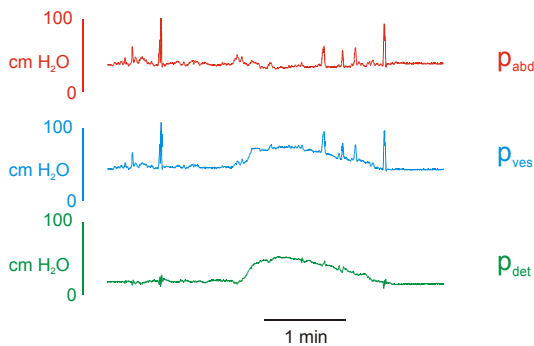
Since the pressure rises in p_{abd} and p_{det} are similar, the net effect on p_{det} is small. It's not unusual to observe a small biphasic fluctuation in p_{det}, because the pressure wave due to the cough reaches the two transducers at slightly different times.

It's generally a good idea for the patient to cough at intervals through their study - the bladder catheter can sometimes be expelled during the voiding cycle. Notice that even during the detrusor contraction (*left*), the effect of the coughs cancels out.

In the next case (*right*), there's a problem with the first cough. The rise in p_{ves} is present, but without an accompanying change in p_{abd}. The net effect is therefore visible in the subtracted detrusor pressure, p_{det}.

Remember - fluid-filled lines with air in them don't transmit fast changes in pressure. In the case shown, you would strongly suspect the abdominal line. You might flush the line again and, if that doesn't work, reposition the catheter.

p_{abd}

p_{ves}

p_{det}

1 min

Abdominal straining

p_{abd}

p_{ves}

p_{det}

1 min
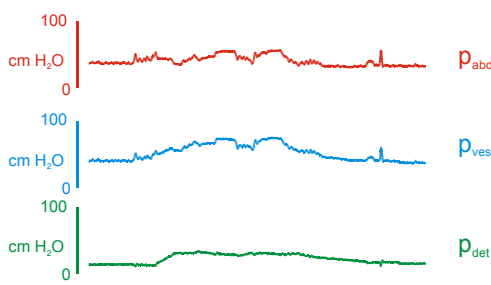
The abdominal pressure gives a clue about straining. In the example (*left*) recorded during a voiding phase, there is a clear rise in p_{abd}.

Whether straining has much effect on flow rate depends on the patient. In some cases, it certainly works. In others, the abdominal pressure is also brought to bear on the outlet, so straining increases p_{ves} but also increases the obstruction to flow.

Filling the patient

Natural (physiological) filling

For flow tests and ambulatory urodynamics, it's usual to let the patient fill naturally. Of course, the rate of filling will depend on the amount of fluid taken by the patient, but something around 5 ml/min might be expected from someone well hydrated. This means you might need an hour or so to reach bladder capacity.

Artificial (non-physiological) filling

The faster way to fill the patient is via a catheter. There are two types of catheter in common use:

Filling catheters

A dedicated filling line can be passed alongside the pressure measuring catheter. Normally, the measurement catheter is substantially finer (because it doesn't need to support fluid flow in normal use), and is piggy-backed onto the filling line.

Dual-lumen catheters

Alternatively, a dual-lumen catheter can be used. This is a single line with two completely separate channels - one for filling and the other for measurement. This makes for an easier catheterisation, but is of course more expensive than the dedicated filling catheter.

In addition, dual-lumen catheters can be susceptible to filling artefact, where the pressure generated by the infusion pump affects the pressure in the measuring line. It is normally manifested as a rhythmic signal superimposed on the p_{ves} signal, and is seen particularly at high filling rates. The artefact will disappear if the infusion pump is stopped.

The infusion pump

The infusion pump is normally of the peristaltic type. That is, a series of rollers compress a flexible tube to drive the fluid in the direction of flow. Fluid never comes directly in contact with the pump, and the pump need not be sterilised.
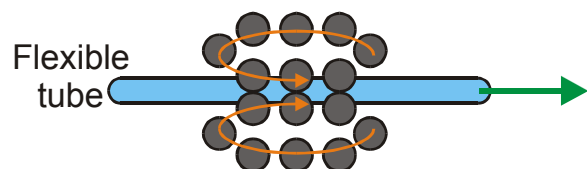
Fill procedure

A range of fill rates are in use, but the consensus seems to be that not more than 100 ml/min be infused. This is often reduced where the patient shows early signs of bladder overactivity. One useful distinction is to delimit natural and non-physiological filling rates. The ICS have proposed the upper limit of physiological filling:

Filling rate (in ml/min) = Body mass (in kg) ÷ 4

It is known that filling with cooled water can promote bladder overactivity. Following this thinking to its conclusion, some centres warm the infused fluid to body temperature, though there is no conclusive evidence that this is useful.

Measuring filled volume

Using an infusion pump, it is in principle possible to determine the filled volume by counting revolutions of the rollers. However, this is susceptible to errors, particularly in the size of tube used in the pump. It is therefore common to use a load-cell arrangement to measure infused volume by weighing the infusion bag. This is essentially identical to the load-cell measurement of voided volume described earlier, except the bag grows lighter (not heavier) as the patient is filled. Once again, be aware that contrast medium is denser than saline, and will lead to over-indication of the filled volume if not taken into account.

Instrumentation for urodynamics - amplifiers

Ultimately, you will want to make a permanent record of your flow and pressure signals - either on a chart recorder or (these days) on a computer. Chart recorders and computers are generally designed to work with signals in the range of 1 Volt, but the signal obtained from a load cell or pressure transducer is much smaller - typically a few milliVolts (mV). An amplifier increases the size of the signal to a size that the recorder can work with.

There isn't a huge difference between an amplifier for urodynamics, and the one in your hi-fi at home. In some cases, you could use one as the other. However, some key things about amplifiers for medical applications are here:

Gain

Your home stereo has a *volume* control - generally you adjust to reach a nice listening volume, without being too worried about exactly what level you've chosen. In medical applications (including urodynamics), you *do* need to know the level of amplification, because you would like to convert the measurement back into ml/s or cm H_2O.

The *gain* of an amplifier tells you exactly that:
$$V_{out} = V_{in} \times gain$$

In other words, the amplifier simply multiplies the incoming signal voltage by a factor (the *gain*), to produce the output voltage. When you calibrate the transducer on older systems, you are setting the gain of the amplifier. The simple rule is this:

Once you've calibrated the system, don't adjust the gain !!!

Saturation

Generally, a higher amplifier gain is better, because it produces a bigger signal for the rest of the system to work with. However, there is a limit - the output of an amplifier is constrained by its power supply (typically ±12 Volts). No matter how big the input signal is, the output can't go outside this range. If you supply an input that's too big, the output will *saturate* (see the figure). In this case, your measurements are distorted.

Input

Output
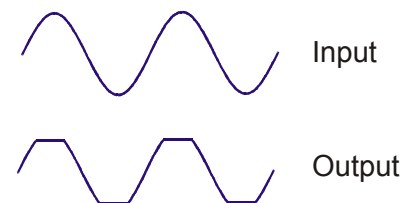
Once again, this simply shouldn't be a problem with a well-designed urodynamic system. However, you might need to be on your guard if it's home-made. In particular, be careful if you replace a transducer with a new one that is much more sensitive (ie. produces a bigger output signal for a given pressure).

Electrical isolation

Mains earth is generally a useful thing - the case of (say) a hi-fi amplifier will be connected to mains earth, so an electrical fault can't make the entire case live - the current will flow to earth and blow a fuse. It's also possible that other bits of the amplifier circuit are in contact with mains earth - the amplifier is said to be *non-isolated*.

If a non-isolated amplifier were connected to a patient, it would be safe under normal conditions. However, if the patient inadvertently came in contact with the mains supply (via a faulty light fitting, say), there is a path for current through the patient and via the amplifier to earth. The circuit is complete, and the patient gets a shock.

The input to a urodynamic amplifier is *electrically isolated* from its output - they are *completely separate electrical circuits*. The signal passes from one to the other through (usually) an opto-isolator, which transmits the signal across an air gap using a beam of light. The current has no path *through the amplifier* to earth.
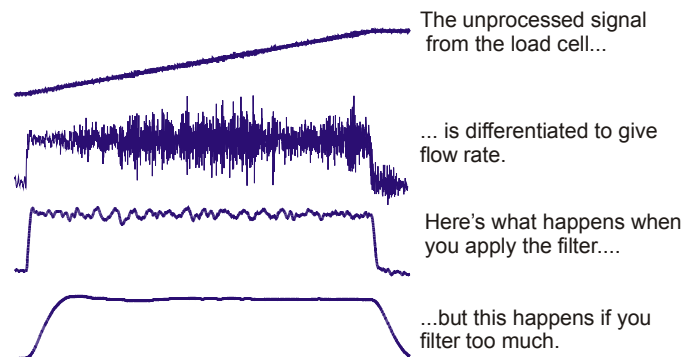
Isolation doesn't guarantee the patient's safety - they might still earth themselves through (say) touching a nearby metal water pipe, but it offers a degree of protection.

Instrumentation for urodynamics - signal conditioning

In many cases, the signal from the transducer is conditioned to make it easier to interpret. For example, an unprocessed signal from a load cell flow meter is shown (*top, right*). The signal was recorded from a 'milk bottle' test (*see earlier*).

The unprocessed signal shown relates to mass (and hence volume), but we would like to record a flow rate signal as well.

So - how do you get from the unprocessed volume to the flow rate?

The unprocessed signal from the load cell...

... is differentiated to give flow rate.

Here's what happens when you apply the filter....

...but this happens if you filter too much.

Differentiation & Integration

You'll remember from the earlier work that volume must be differentiated to determine flow rate[^1]. There is a well-understood electronic circuit to perform this operation, and the effect can be seen in the figure. Clearly, this first attempt at the flow rate is extremely noisy. This reflects the fact that flow is not continuous - by the time the stream reaches the meter, it has broken into a series of droplets.

Filters

A filter removes certain frequency components from a signal, but leaves other components. In the figure (*above*), a 1 Hz (1 cycle per second) low-pass filter was applied to the first flow signal. In simple terms, this filter will remove any features of the signal changing much faster than 1 cycle per second. This seems reasonable, because real changes in flow are not likely to take place faster then this. Indeed, the filter clearly removes much of the noise, leaving a good quality flow trace.

In the bottom trace the flow signal has been over-filtered. You are left with an acceptably noise-free trace, but the sharp changes at the beginning and end of the trace are lost. You might over-estimate the total time spent voiding, and you certainly miss the small irregularities in flow rate seen in the previous trace.

Finally, it's worth saying that for a similar reason, a similar low-pass filter is often applied to your pressure signals.

Electronic subtraction

As you'll remember, it's usual to record pressure signals from the bladder (vesical pressure, p_{ves}) and from the abdomen (p_{abd}). The difference between these two pressures is the pressure due to detrusor muscle contraction (p_{det}). Again, an electronic circuit does the trick.

In the figure (*right*) a good example is shown. The detrusor contraction half-way through the trace is genuine. However, coughs throughout the trace appear in p_{abd} and p_{ves}, and cancel to give very little effect on p_{det}.

100 cm H$_2$O 0 p_{abd}

100 cm H$_2$O 0 p_{ves}

100 cm H$_2$O 0 p_{det}

1 min
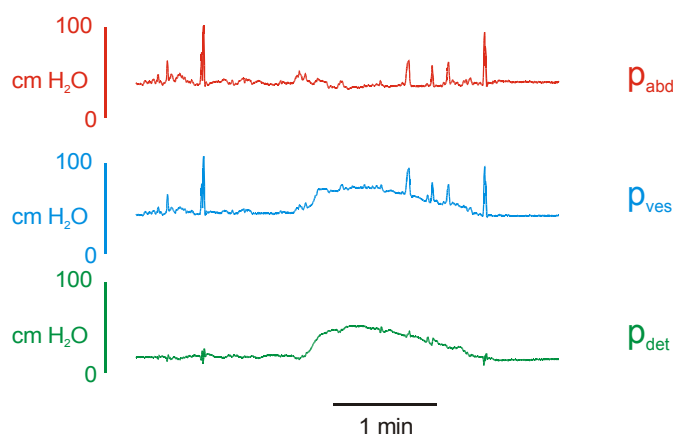
[^1]: In a spinning disk flow meter, the opposite process takes place - the flow rate is determined directly, then integrated to give the voided volume.

Data recording

Analogue chart recorders

In the early days, an analogue chart recorder would just be an array of pens, each connected to some mechanism to move the pen up and down as your signal voltage increased and decreased. Meanwhile, the chart paper moved along underneath the pens to leave a record of how the signal changed with time.

These days, chart recorders are often digital - the printing is performed as a series of fine dots, like the image on a computer screen. However, the printing quality is excellent - one we use in our Department draws 64 dots to each square millimetre, which is much finer than any pen recorder. Contrary to what you might expect, chart recorders are not losing out to computers - they're still popular because...

- You can draw on/pass round/photocopy hard copies.
- The contrast and resolution of chart recorders is very good, far better than even the best video displays. That means you can see fine detail in your signal waveforms.
- You can get continuous records on fan-folded paper - you don't need to work with a set of discontinuous pages such as you might get from a laser printer.
- Whatever anyone might tell you, it's easier to look at hard copy than a computer screen.

However ...

- Don't think a modern chart recorder is a cheap option - it will probably cost upwards of £5000. Once you've bought the recorder itself, you'll need paper. Gould charge us about £50 for a bundle.
- Even if you can afford the paper, do you have somewhere to keep it?
- Chart recorders are fundamentally mechanical instruments - the fastest can print at about 500 mm/sec. That's fine for most urodynamic signals, but (for example) a sphincter EMG would lose detail.
- You have to work out pressure and flow values manually. There is no fancy cursor placement to aid the process)

Digital recording and display

The physiological signals you're trying to record are fundamentally analogue - as time goes on, they change continuously. A digital recorder (including any computer-based urodynamics system) includes an *analogue-to-digital converter (ADC)*; it converts a signal to a series of numbers - *samples*. You can think of each sample as a 'snapshot' value of the signal at some instant in time.

It is important to remember that the signal stored on the computer is <u>not</u> exactly equivalent to the continuous physiological signal from which it is derived. There are things you have to beware of...

Speed of sampling

Sampling is a bit like a cinema film, which is just a series of still 'snapshots' of a moving scene. So long as you take the snapshots often enough, you get the illusion of continuous motion. Likewise for urodynamic signals - if you record the value of the signal often enough, then you'll end up with something very close to the original signal.

- Urodynamic pressures and flow rates don't vary much in less than 1 second. A sampling rate of 10 samples per second (10 Hz) is considered adequate to record these signals faithfully.
- If, however, you want to record EMGs (for example), you'll need to sample much faster - 1000 Hz or higher. But speed costs money.

Precision of sampling

When the computer takes a sample, the value is stored to a fixed precision - in the case of pressure, it might be (roughly) one decimal place. In the case of flow, two decimal places. Your sample values must be precise enough to be sure that small changes in the signal can be represented accurately - but precision costs money.

But…

If you're recording digitally, you need to make sure you get the sampling speed and sampling precision right. But of course, if you've bought an off-the-shelf system, the designers should have got them right for you.

Trace interpretation

This document is really about getting to this point, where you have good-quality traces to analyse. Now the data have been collected, you need to convert them to some kind of summary statistics. We don't understand all the clinical aspects of trace interpretation, but here are some useful bits and pieces. Two measures that stand out as important are:

- Q_{max} - the maximum flow rate.
- $p_{detQmax}$ - the detrusor pressure when flow is at its maximum value Q_{max}.

First…
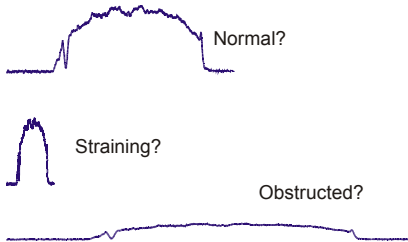
Look at the three flow traces (*left*). You might get a feeling about a different diagnosis for each of them. The three traces are actually identical, but look very different - the only differences are the horizontal and vertical scalings.
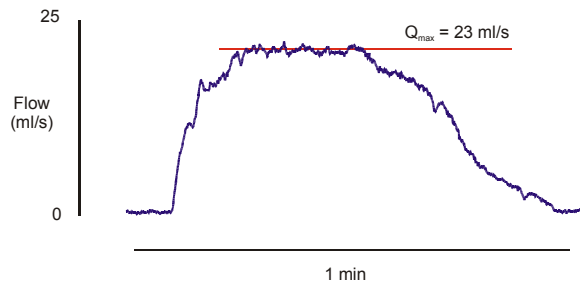
*Standardise the presentation of data at your centre,
and stick to the standard!*

If you don't, then someday someone will misinterpret one of your traces.

Reading a maximum flow rate Q_{max}

A 'normal' flow trace

This is as easy a flow trace as you're likely to analyse. The maximum flow rate is maintained for 15-20 seconds, and this trace is entirely unambiguous.

An erratic flow trace

This one is considerably more difficult. Certainly, you wouldn't measure to the absolute top of the flow trace at 16 ml/s, *but your automatic system probably would!* Once again, we worry about the automated analysis of flow and pressure traces.
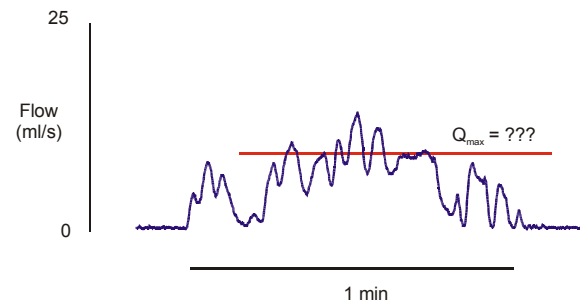
This chap was straining on cystometry - the red line at around 10 ml/s is probably more-or-less representative of his peak flow Q_{max}.

Reading a detrusor pressure $p_{detQmax}$
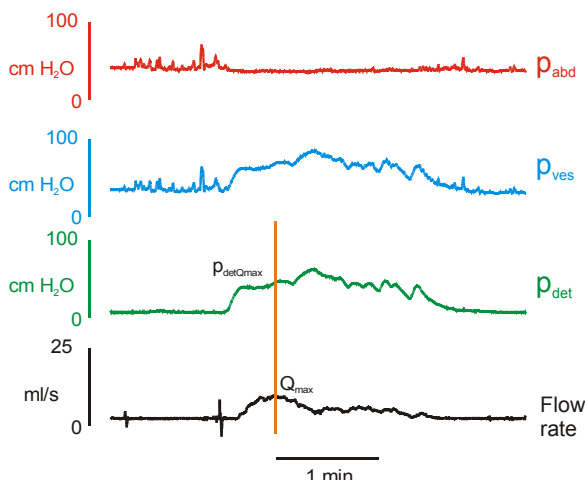
Finally, you need to measure the pressure. This is the easy bit, because you simply read the $p_{detQmax}$ at the point of maximum flow.

Since the detrusor is smooth muscle, the pressure signals tend not to suffer so much from the rapid fluctuations seen in flow rate. Since p_{det} doesn't change quickly, the delay of a second or so introduced by the flow meter isn't too important.

However, apply the same kind of common sense as for flow traces - if there's an obvious artefact, then ignore it.

Some typical cystometric traces

This document isn't really about interpreting the traces. However, what follows should give you some idea about the typical traces you will encounter in clinical practice.
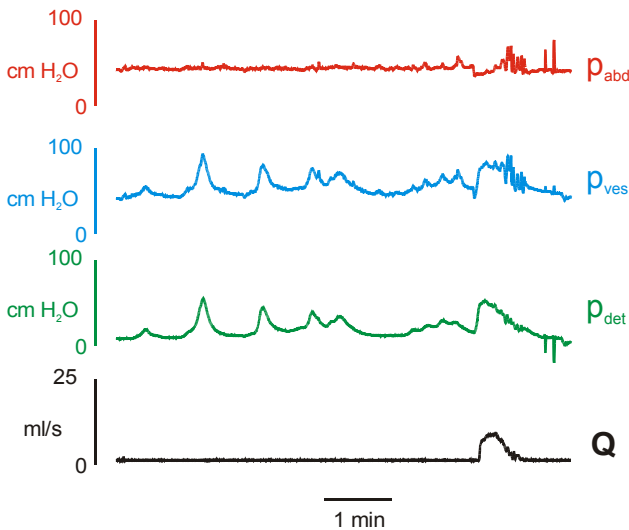
Normal cystometry

This is a normal cystometric measurement. Points to note are:

- Little activity in the detrusor (except a cough) until the voiding phase.

- Flow commences just after the p_{det} rise.

- Flow is regular, with just a hint of wagging.

- No sign of abdominal straining.
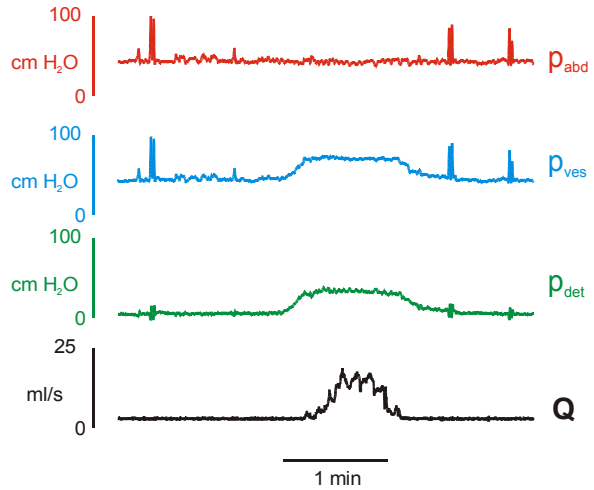
Overactive bladder

Previously called bladder instability, the overactive bladder contracts spontaneously with a small amount (in this case, < 100 ml) of fluid in the bladder. Points to note:

- Strong detrusor contractions during the filling phase, which are associated with the strong urge to void. Notice the abdominal pressure p_{abd} is stable, ruling out abdominal contractions as the source of the pressure rise.

- A low voided volume - the patient was unable to hold any more without leaking.

- Following the void, p_{ves} no longer responds to the cough test. The line was probably dislodged during the void.

Outlet obstruction and straining

This patient had bladder outlet obstruction. Points of note:

- A low flow rate, and so the patient takes a long time to void.

- Frequent abdominal contractions during the void, nevertheless having little effect on the flow rate.

Outlet obstruction is a particularly common complaint, to the extent that the ICS have published separate guidelines specifically for the assessment and diagnosis of the condition.
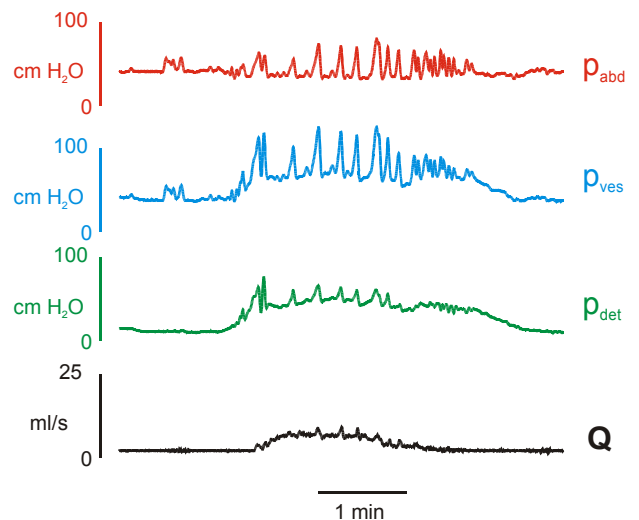
Assessment of outlet obstruction

The ICS nomogram

The ICS nomogram (*right*) is similar to earlier nomograms produced by Paul Abrams & Derek Griffiths, and by Werner Schäfer. The stages in using the ICS nomogram are as follows:

- Determine Q_{max} from cystometry;
- Determine $p_{detQmax}$ from cystometry;
- Plot a point on the nomogram using those values.

The point will lie in one of the regions *unobstructed, equivocal* or *obstructed*.

The slope to the regions on the nomogram reflects the fact that a high bladder contraction pressure would normally be associated with a high flow rate. So for example, a flow rate of 10 ml/s would be normal for a detrusor pressure of 20 cm H_2O, but low for a pressure of 100 cm H_2O.
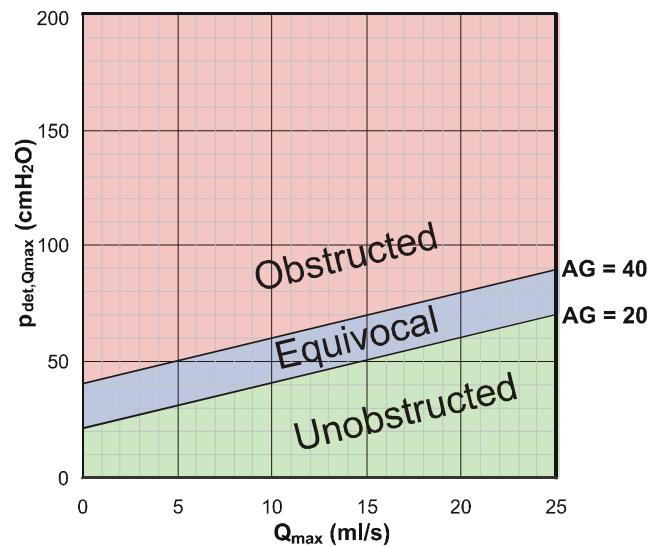
The AG number

The Abrams-Griffiths (AG) number is defined as follows:

$$AG = p_{detQmax} - 2 \times Q_{max}$$

While this may appear complicated, the formula is actually very closely related to the ICS nomogram.
- When AG < 20, the patient will lie in the *unobstructed* region of the nomogram
- When AG > 40, the patient will lie in the *obstructed* region of the nomogram
- Otherwise, the patient will lie in the *equivocal* region of the nomogram

For example:
$Q_{max} = 10$ ml/s and $p_{detQmax} = 50$ cm H_2O
AG number = $50 - 2 \times 10 = 30$
The patient is classified *equivocal*.

Urethral pressure profile measurement

The nomogram is an indirect way of assessing obstruction, but it is possible to quantify urethral function (or more specifically, urethral pressure) more directly. The Brown and Wickham method is shown.
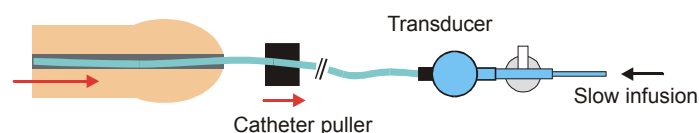
A fluid-filled catheter is slowly withdrawn from the bladder (typically at 2-5 mm/s) using a catheter puller. Meanwhile, continuous pressure measurements are made as for standard cystometry. Since the distal urethra is dry, the line must be slowly infused with saline (at typically 2-5 ml/min). In effect, the transducer measures the minimum fluid pressure required to cause the catheter to leak - this is termed the *urethral pressure*.

This so-called *urethral pressure profile* is not universally used, partly because the instrumentation is tricky to set up, and partly because the clinical relevance of the measurement is not clear.

Assessment of bladder contractility

Clearly, the measurement of $p_{detQmax}$ offers some measure of the bladder's ability to contract, but it isn't the whole story - in any bladder, detrusor pressure changes according to the flow rate.

Bladder contractility and the Hill equation

The Hill equation relates the contractile force of skeletal muscle with the rate of contraction. It starts with the assumption that the muscle can perform work at a constant rate, and introduces corrections to explain the observed behaviour. In general, the faster a muscle is being asked to contract, the less force it can muster.

A similar relationship can be proposed for the bladder (*right*). The bladder's power (its rate of doing work) is given by:

$$Power \ = \ Detrusor\ pressure \ \times \ Flow\ rate$$

If we naively assume *Power* is constant, we end up with a clearly nonsensical ideal bladder where pressure can rise indefinitely if flow is stopped. As for the Hill equation, a correction comes close to the observed behaviour of a real bladder, but the shape of the curve is similar.

What this means is this:
A bladder contracts with greater pressure when flow is obstructed.
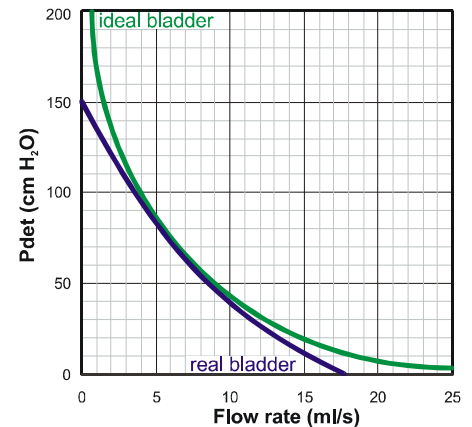
For example, assume the blue trace above represents a real bladder:
At a flow rate of 10 ml/s, the measured bladder pressure would be 40 cm H_2O.
At a flow rate of 2 ml/s, the measured bladder pressure would be 120 cm H_2O.
With no flow at all, the measured bladder pressure would be 150 cm H_2O.

A different patient's bladder would have a different relationship, but it would have a similar form:
A bladder can contract with greater pressure when flow is obstructed.
Therefore to measure bladder contractility, some correction for flow rate must be applied.

The Watts factor

The Watts factor (WF) was proposed by Derek Griffiths (*Neurourol Urodynam 10: 1, 1991*). It is derived from the Hill equation, as modified for a spherical bladder, and gives an estimate of the bladder's power. The WF can be calculated for any values of p_{det} and flow rate.

Isovolumetric pressure

The *isovolumetric pressure* is the detrusor pressure when flow is completely stopped, and is therefore an indicator of bladder contractility under a single known condition.

The figure shows data recorded from the penile cuff measurement developed in Newcastle, which we believe gives an indication of bladder contractility.

As the cuff is inflated, flow is reduced and finally stops. At this point, the isovolumetric pressure can be read from p_{det}.

The isovolumetric contraction pressure (~90 cm H_2O) is clearly higher than $p_{detQmax}$ (~50 cm H_2O). This can be thought of as the bladder's response to the increasing obstruction, but is in fact a consequence of the Hill equation and the bladder physiology.