What is ultrasonic plethysmography and how can we use it in airway disease?

Christian Buess

ndd Medizintechnik AG, Zürich, Switzerland
Background

Until approx. the year 2000 mainly the following flow sensor principles were used in lung function testing:

- Differential pressure (variable or fixed resistance)
- Turbines (rotation speed)
- Heated wires (cooling effect)

All these principles have potential limitations:

- Hygiene: Difficult to clean
- Unable to measure very low flows
- Need of regular calibration
- Dependency on gas composition and/or temperature
Operating Principle

Ultrasonic flow measurement is commonly used for liquid flow. It is now also used for air flow measurement in lung function diagnostics.
Operating Principle

Ultrasonic transit-time measurement. Please note that the principle differs to the Doppler principle used for blood flow measurement.
Sound transmission and reception is repeated every 1 to 5 ms. Sampling rates 200 to 1000 Hz.
Measurement principle (simple)

Time difference is proportional to speed of Jet stream

Ultrasonic flow sensor: Time difference up to 1 \( \mu s \)
Measurement principle: Flow

Flow measurement depends only on flow and geometry

- No dependency on temperature, gas composition, humidity or pressure

Flow

\[
\begin{align*}
    t_d &= \frac{L}{c - u \cdot \cos \varphi} \\
    t_u &= \frac{L}{c + u \cdot \cos \varphi}
\end{align*}
\]

Speed of sound depends on temperature and gas composition

\[
    u = \frac{L}{2 \cdot \cos \varphi} \cdot \frac{t_d - t_u}{t_d \cdot t_u}
\]
Molar Mass measurement depends on transit-times and temperature along the sound transmission path.

- Molar mass measurement ‘for free’ – no additional sensor required.
- Molar mass measurement is not specific.

Measurement principle: Molar Mass

\[ t_d = \frac{L}{c - u \cdot \cos \varphi} \]

\[ t_u = \frac{L}{c + u \cdot \cos \varphi} \]

\[ c = \sqrt{\frac{\kappa \cdot R \cdot T}{M}} \]

\[ M = \frac{4\kappa R}{L^2} \cdot T \cdot \left( \frac{t_u \cdot t_d}{t_u + t_d} \right)^2 \]
Strengths and Weaknesses

- No calibration since flow measurement depends only on time measurement and geometry of sensor
- Completely open, unobstructed tube
- Good hygienic solution
- High resolution and dynamic range
- Molar mass measurement “for free”
- Relatively high cost of sensor
Spirometry: Devices

Examples of devices using ultrasound technology

- Standalone spirometer for office use
- Flow sensors for spirometry and exercise testing
- Flow sensor for Intensive Care application
The technology can be used for a large range

**Neonatology**
- Resolution: < 1 ml/s
- Range: 500 ml/s

**Adult**
- Resolution: < 10 ml/s
- Range: 18 l/s

**Horses**
- Resolution: < 80 ml/s
- Range: 100 l/s
Spirometry: Studies

Performance of 70 devices over 3 to 6 month period
R. Pérez-Padilla et al.: Long-term stability of portable spirometers. (Respir Care 2006)

Performance of 6 devices over 200 days

- Ultrasonic spirometer used by world-wide BOLD study (Burden of Obstructive Lung Disease).
- Ultrasonic spirometer used by Platino study in Latin America.

- Expiratory side-stream MM trace
- Start of tracer wash-in
- Wash-in of tracer gas
- Computation of FRC, LCI ...

☑️ Main stream molar mass signal is synchronous with flow signal
☑️ Simple instrument setup compared to mass spectrometry
☒ Best results are only achieved with side-stream MM sensor
FRC Measurement: Setup

- Valve in ‘open’ position
- Valve in ‘closed’ position
- Test gas supply
- Ultrasonic Flow / MM Sensor
- Side-stream sampling tube
FRC Measurement: Studies

Direct comparison of ultrasonic system with mass spectrometer

$r^2 = 1.00$, mean difference -0.2%

- Setup Problems: Gas leaks etc.
- Most devices and most software are in **prototype stage**!
- The above results were obtained using a **side-stream** MM sensor
- If applied carefully results compare well with mass spectrometers
- Additional studies: J. Pillow et al., Schibler et al. etc.
Tidal Breathing Analysis: Background

Comparable to capnography the molar mass analysis of tidal breathing shows the expiratory molar mass curve vs. expired volume.

Several parameters can be computed from the curve data:

- Slope of phase 2 \( S_2 \)
- Slope of phase 3 \( S_3 \)
- Dead Space volume \( V_d \)
Tidal Breathing Analysis: Method

90 seconds of tidal breathing recording flow and molar mass

Determination of mean expiratory MM curve

\{S_2, S_3, V_d, V_i, V_e, f, \ldots\}_1, \{S_2, S_3, V_d, V_i, V_e, f, \ldots\}_2, \ldots, \{S_2, S_3, V_d, V_i, V_e, f, \ldots\}_9

Statistical Analysis

Diagnosis

ERS 2007 - 17/19
Tidal Breathing Analysis: Studies

Studies analyzing the Molar Mass Index in side-stream

$\text{MMI} = \frac{S_3}{S_2} \cdot 100$

- Normal controls
- Very severe to moderate COPD
- Restricted

Beckert, Buess, Magnussen: Not yet published

Correlation of MMI and LCI, both determined by ultrasonic flow sensor

Fuchs, Gaultier, Buess, Gappa: ERS 2007.
Conclusion

- Ultrasonic flow measurement is a new technology with many advantages: No calibration, good hygienic solution and high accuracy.

- Ultrasonic molar mass measurement is the mass spectrometer for everybody – its use may have a large potential for measuring multi-breath FRC.

- Analysis of expiratory molar mass curve during quiet breathing: Potentially interesting for analysis of gas distribution in the lungs. Further investigations are required.