RESEARCH ARTICLE

Gas in scattering media absorption spectroscopy on small and large scales: Toward the extension of lung spectroscopic monitoring to adults

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Abstract
Numerous natural materials are porous, contain free gas and are scattering light strongly. Scattering brings about a strong trapping of light and an associated prolonged transit time for photons through a medium. In contrast to the matrix materials, gas enclosures require very narrow-band laser radiation for probing. We have in the present study used the gas in scattering media absorption spectroscopy method to study free oxygen in thin (cm) samples utilizing a tunable diode laser, while a pulsed dye laser was employed in corresponding measurements on larger samples, up to the meter scale. Time-resolved spectroscopy was in both cases used to assess the temporal distribution of the detected photons, mapping the path lengths through the media, which ranged between few centimeters up to 100 m. This study explores the feasibility to extend recent successful monitoring of gases in neonatal infant lungs to the case of larger children or even adults, which could have very important applications, for example, in ventilator setting optimization for severely ill patients, suffering, for example, from SARS-CoV-2. The conclusion of our work is that this goal most realistically can be reached by applying intratracheal laser light illumination at the 1 W power level, employing a tapered amplifier, injected with a distributed feedback diode-laser oscillator output and combined with wavelength-modulation spectroscopy.

KEYWORDS
GASMAS, laser spectroscopy, lung monitoring, oxygenation, SARS-CoV-2, ventilator

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1 | INTRODUCTION

Monitoring of free gases is of great importance in many different contexts, and laser spectroscopic techniques have proven a great capability for high specificity and sensitivity, as well as for nonintrusive measurement with data available in real time. Monitoring can be performed locally/in situ, or even with remote-sensing techniques at considerable distances. Areas of application include the environmental, industrial and medical fields. Environmental and industrial monitoring can regard constituents, which influence global warming (CO₂, CH₄, H₂O, etc.) and the UV protective ozone layer (O₃, ClO, BrO, NO, NO₂, SO₂, Hg, etc.). Physiological gases of medical interest include O₂, H₂O, CO₂, CH₄ and NH₃. In situ monitoring systems frequently take advantage of the practicality of low-power semiconductor tunable lasers, including quantum cascade lasers (see, e.g., [1–5]), while, for example, combustion research frequently uses high-power, pulsed systems, which more easily can overcome the inevitable background from flame light [6]. Remote-sensing systems, for example, of the lidar (light detection and ranging) type, could utilize pulsed dye or solid-state lasers, or continuous-wave (CW) semiconductor lasers [7–9].

Gas concentrations, C, are mostly evaluated in absorption spectroscopy, utilizing the Beer-Lambert law, which is readily applicable once the optical path length, l, is known and the absorption cross section, σ, is available, or can be eliminated by calibration measurements on known concentrations. These observations reflect the fact that the product σCl determines the fractional absorption of the transmitted light, that is, the ratio of the signal intensity reduction at the absorbed wavelength to the light intensity next to the absorption line. This is a measure of the prominence of the gas absorption imprint. A situation with known values of σ and l frequently pertains in the measurement situations discussed above. Then, the gas concentration can be determined with the same relative error as reflected in the signal-to-noise ratio in the gas absorption signal.

More recently, it was realized that free gas can also be present and of substantial interest in cases, when no well-defined absorption path can be defined, but the interrogating light rather propagates diffusely, encounters distributed gas-filled pores or larger cavities, finally to arrive at the detector, located somewhere around the medium. Then only the product of C and the “effective path length” l_eff can be determined, and the result of the measurement can be expressed as the percent meter (%m) value. For example, 21%m would be the signal pertaining to a 1 m path length in 21% oxygen, or a 3 m path length in 7% oxygen. Since the emerging light is weak and nonlocalized, a large-area detector combined with extremely sensitive detection electronics is needed to pick up the faint gas imprints [10]. This type of spectroscopy, denoted gas in scattering media absorption spectroscopy (GASMAS), has since found a lot of applications in many areas [11, 12], regarding, for example, materials [13–15], pore-size analysis [16–18], food packages [19, 20], fruits [21, 22], pharmaceuticals [23] and medical diagnostics [5, 11].

The medical diagnostic possibilities are of particular importance. In situ GASMAS studies of free gas in organs are clearly different from diagnostics by breath analysis, where the gases are analyzed in a well-defined absorption cell outside the body [24, 25]. Human sinus cavities have been extensively studied in relation to rhinosinusitis [26, 27], and phantom studies related to middle-ear infection (otitis media) have also been pursued [28]. Such investigations reveal if the cavity, which normally should be air-filled, actually instead contains liquid, such as pus. Further, if free gas is detected, the technique allows the measurement of the oxygen concentration, which provides the status of ventilation—a good indicator of the expected development of the infection. The hope is that data obtained could have bearing on the reduction of the alarming spread of antibiotic resistance [29], propelled by widespread, frequently unnecessary administration of antibiotics even for patients with adequate ventilation. Since such drugs are ineffective for virus, which is the most frequent cause of infection, possible correlations between the GASMAS signals recorded for oxygen and water vapor, and laboratory analysis of pathogens, will be sought.

A further direction is to use GASMAS for lung monitoring, related to the respiratory distress syndrome, which is common in prematurely born infants [30]. Successful feasibility studies have been performed on healthy neonates [31, 32]. In a quest to improve signal quality, and extend the techniques to larger children, or even adults, where much longer optical path lengths through strongly attenuating tissue pertain, an approach was proposed, where external laser-light chest illumination is replaced by fiber-optical internal light administration [33]. This can be achieved, for example, through an endotracheal tube, which anyway would be in place for many intensive care patients. By reducing the optical path length strongly in this way, a much higher probing light flux is received. In addition, the specific gas absorption fraction of the total light received is enhanced, since all detected photons must have passed gas-filled lung structures, and not only surrounding normal tissue. The advantages have recently been demonstrated in phantom work [34] and in a study on anesthetized piglets [35].

While a 24-hour noninvasive cot-side monitoring of lung function in preterm neonatal infants is now being
developed, a long-term goal would be to achieve direct lung monitoring in larger children and also adults, with possible feedback control to optimize the operation of a connected ventilator [33]. In the adult setting, many of the patients treated in Intensive Care Units suffer from severe respiratory disorders, for example, pneumonia, chronic obstructive pulmonary disease, lung fibrosis and of course the novel SARS-CoV-2 [36–38]. Direct optical measurements on, for example, lung lobe volumes (related to GASMAS water vapor signals) and oxygen concentrations could lead to prompt detection and treatment of disease progression and complications. The world-spread pandemic has brought great challenges with patients displaying symptoms of severe respiratory distress, and also an awareness of the limitations in the health-care system. The progression of a severe SARS-CoV-2 infection does not quite resemble well-known states of respiratory failure. In order to properly treat these patients, increased knowledge, for example, on how lung aeration differs throughout the disease progression is needed. Recent studies show that once hospitalized, approximately 25% of the SARS-CoV-2 patients require mechanical ventilation, advanced circulatory support and/or renal replacement therapy [39]. The case fatality rate is extremely age dependent with an increase from <0.6% to 2.2% at age 60 and increasing to 9.3% at age 80 [40].

The ability to monitor dynamic changes regarding the air and oxygen distribution, as well as prompt detection of anomalies, would certainly improve the medical treatment of these patients. The patients, who are in need of ventilator support due to SARS-CoV-2 infection, present symptoms like shortness-of-breath, severe hypoxia and respiratory fatigue, often together with high fever and reduced general condition. The severe respiratory deterioration often emerges around one week after initial SARS-CoV-2 symptoms occur. The condition presents itself as a pneumonitis, with dysregulation of the pulmonary perfusion, loss of pulmonary vasoconstriction (a normal physiological mechanism, reducing the blood perfusion in less ventilated lung regions, avoiding shunting of deoxygenated blood through the lungs) and microembolism (small thrombi in the pulmonary vessel system, leading to increased dead-space ventilation). With disease progression, a more classical ARDS (Acute Respiratory Distress Syndrome) status arises—consisting of pulmonary edema, inflammation and consolidated lung regions [41]. The lungs are now “stiffer,” and high airway pressure in the ventilator is required to oxygenate the patient and to remove the carbon dioxide. During this phase, pulmonary embolism, a well-known complication to severe SARS-CoV-2 infection, further deteriorates the respiratory function.

The many critical aspects of lung function in severely ill patients, as illustrated above, call for optimized monitoring of lung-lobe status, even with desirable feedback to the ventilator operation. The need is present in the whole range of patients, ranging from prematurely born infants to adults.

The present GASMAS work relates to the exploration of the scaling up of dimensions from the cm scale toward the meter scale, and evaluate what technological approach would be the most feasible. In particular, we explore the best way to achieve noninvasive monitoring of lung gases in children or even adults. We have, using two different experimental arrangements, located in Lund, performed monitoring of the gas content in samples of increasing dimensions, as well as studied the temporal distribution of the detected photons following pulsed laser excitation, that is, mapping the distribution of the total path lengths of the photons diffusing through the sample. The latter type of experiments is referred to as time-of-flight spectroscopy (TOFS). For small samples, this distribution was recorded using the time-correlated single-photon counting (TCSPC) technique, following ps-pulse laser excitation. The corresponding gas imprint was assessed with a GASMAS setup, operating with a low-power, CW distributed feedback semiconductor laser. The resolving of the absorptive imprint of free gases requires a probing laser line-width of the order of 0.001 nm, or better, while condensed matter, including the gas-containing material studied in our investigation, have absorption features, which are typically 10 000 times broader. The reason for the need of two different setups for studies of small samples is the fundamental Fourier-transform limitation of spectral resolution for pulses short enough to provide temporal resolution on the short timescale, associated with small samples. Then, two separate arrangements are required, one CW high spectral resolution system matching the line-width requirement for gas monitoring, and one pulsed system for photon propagation studies. The first one did not provide path-length information, while the second one, operating with 100 ps pulse length, did not have gas monitoring capability. In contrast, for large samples, where longer pulses are tolerable due to longer propagating times, sufficient spectral as well as temporal resolution can be obtained in a single system. Then, the approach is very similar to differential absorption lidar (DIAL) [8], where gas mapping, for example, of air pollutant concentrations as a function of range, is performed by rapid switching of the laser wavelength from an absorbing one to a close by nonabsorbing one. Actually, a remote-sensing study of gas, but now in a strongly scattering material, demonstrated such combined monitoring [42], and the potential application to the localization of
**Small-scale GASMAS**

![Small-scale GASMAS](image)

- GASMAS transmitter/laser unit
- Diffuser
- Sample
- GASMAS detector

**Large-scale GASMAS**

![Large-scale GASMAS](image)

- Nd: YAG 532 nm
- Dye laser 760 nm

**FIGURE 1** Experimental setups used in the measurements. A, Photo of the small-scale setup with the GASMAS arrangement to the left and the time-of-flight arrangement to the right. B, Photo of the large-scale setup with the Nd:YAG laser pumping a dye laser, and the polystyrene block (to the left). An oscilloscope screen dump is inserted, with the trigger ($t = 0$) signal (violet), a time-of-flight graph (green) and a repetitive wavelength scan through the oxygen line (yellow). C, Schematic diagram of the diode laser-based GASMAS setup (MCU denotes the main control unit, a PC). D, Schematic diagram of the pulsed diode laser time-of-flight setup (TOFS denotes time-of-flight spectroscopy). The presence of a diffuser in both the GASMAS and TOFS setup is for reducing unwanted interference fringes. E, Schematic diagram of the pulsed DIAL-GASMAS system (PMT denotes photomultiplier tube, and PD photodiode).
avalanche victims imbedded in strongly scattering snow was discussed.

Monitoring of the physiological gas oxygen is clearly of major interest related to lung function assessment. Human tissue, while clearly heavily scattering, has comparatively low absorption around 760 nm, where the molecular oxygen absorption band is located, exhibiting a number of sharp (half-width <0.001 nm) rotational-vibrational lines [43]. Unfortunately, the lines are weak. For the strongest line, the R7Q8 component, ~0.44 m of air is needed to produce a 1% absorption [43]. A very high sensitivity for minute gas absorption imprints can be achieved by wavelength-modulation spectroscopy (WMS) using a semiconductor laser, where the lock-in detection is pushed to high-frequencies with associated 1/f noise reduction [44, 45]. The use of pulsed lasers strongly reduces the ability to discern small differential absorptions, as is well-known in the lidar community. The reasons are related to, for example, shot-to-shot fluctuations and detector nonlinearity. However, this is then partly compensated by the longer path length through gas in the larger sample, leading to a larger fractional gas imprint and thus less requirements regarding the signal-to-noise level. Our present study aimed at experimentally elucidating the factors of relevance, to give directions in the construction of an optimum clinically relevant large-scale GASMAS monitoring system. Our measurements were largely performed on oxygen gas in polystyrene foam, where scaling could be adequately studied, and then on organic samples partly simulating a lung, including a 2 kg chicken broiler, with the interior filled with porous sponge, and a small block of polystyrene foam with pork slabs on both sides. Planned measurements on fresh, resected wild boar lungs, as investigated in our first lung study [46], could unfortunately not be accomplished due to the severe SARS-CoV-2 outbreak.

We will describe our experimental arrangements more in detail in the next section. Then, in section 3, our measurements and results are presented. In the final section, we discuss the results with special emphasis on possible ways to reach the final goal of achieving 24-hour continuous lung monitoring in older children or even adults as an extension of successfully pursued neonatal lung monitoring. The scaling up is not trivial—the higher powers and better signal-to-background advantages in pulsed systems are counter-acted by higher noise levels and resolution limitations due to spectral Fourier-limitation for short pulses, also with associated safety issues. Likewise, continuous and narrowband lasers are normally of low power, and penetration depths are limited, since the competition of detector background noise is more severe, even if the average power would be similar.

2 | EXPERIMENTAL ARRANGEMENTS

In our exploratory work, we utilized two different experimental setups for the small- and large-scale GASMAS measurements, as motivated in the introduction. The systems are schematically shown in Figure 1A-E.

2.1 | Small scale setup—the GASMAS and TOFS approach

The small-scale instrument, which is manufactured by GASPOROX AB, Sweden, is shown in Figure 1A, where both the GASMAS and TOFS parts are combined into a single system, named GPX-Porosity, because of its intended use. To the right of the photo, the TOFS part, with the photomultiplier tube (PMT) detector and the fiber illumination from above, is seen. To the left of that, the GASMAS part of the instrument is shown (basically a GASPOROX GasSpect) with the laser transmitter unit on the top and its separate large-area semiconductor detector below, collecting light diffusively transmitted through the sample. In the photo, a sample is seen in position for GASMAS measurement, laying on the sample plate, which is moved by a translation stage from a load position (where the sample is put on the sample plate), to TOFS and GASMAS measurement positions. The TOFS and GASMAS measurements are thus performed in succession.

Schematic block diagrams of the GASMAS and TOFS parts of the instrument are seen in Figure 1C and D, respectively. The laser light in both the GASMAS and TOFS parts are made diffuse with a divergence of around 6° (FWHM), by sending the initially collimated beams through diffusers, prior to the sample. The laser of the GASMAS setup is operating close to 760 nm and has an output power of about 5 mW. The pulsed laser in the TOFS setup is also operating close to 760 nm and has a repetition rate of 80 MHz and a pulse length of about 100 ps. The main control unit used for both parts is a PC with a user interface. The detection in the TOFS setup is based on TCSPC, using a card installed in the PC. A variable attenuator is used in the TOFS setup to ensure that photon “pile-up” is avoided.

2.2 | Large-scale setup—the GASMAS/DIAL approach

A schematic of the experimental setup for the large-scale GASMAS/DIAL approach is shown in Figure 1E. The second harmonic output at 532 nm of a pulsed Nd:YAG
laser (Spectra Physics, PRO 290-10, 10 Hz) was used to pump a narrowband dye laser (Sirah, PRSC-D-18, operated with the dye LDS765), in order to generate tunable laser radiation around 760 nm and with a pulse duration of 6 to 8 ns. The pulse energies used in these experiments range from 2 to 60 mJ, depending on the size of the samples. The main laser beam was directed to the porous sample. The light scattered through the sample was detected with a PMT, while a small part of the laser beam was split off onto a photodiode (PD), and the signals from the PD and PMT were displayed on an oscilloscope (LeCroy, Waverunner 6100). The photodiode signal was used both as a trigger for the oscilloscope, and as a reference point for the shape and timing of the incident laser pulse. To filter away the surrounding background light, the PMT was equipped with an interference filter (750 ± 20 nm), which transmitted the 760 nm light but blocked most of the ambient light and the stray light from the Nd:YAG laser.

The sample in these measurements were either blocks of polystyrene foam, of dimension 40 × 60 cm with different thickness, or a chicken broiler/pork samples as described later in connection with Figure 6. The side of the white polystyrene foam block is seen to the left in the photo in Figure 1B. To avoid interference from light scattering in the room, the block was shielded with black plastic during the measurements. An oscilloscope screen dump is also shown in Figure 1B, with the trigger (t = 0) signal (violet), a photon time-of-flight graph (green) for a particular, fixed laser wavelength and a separate, five times repetitive wavelength scan through the oxygen line (yellow). The DIAL recordings were made with the laser emitting typically 500 pulses at the absorption peak, and then emitting the same number of pulses just off the absorption line. The recorded transients, each due to numerous photons produced by the high-energy pulses, were averaged before forming the DIAL ratio curve. Because of the interface between oscilloscope and PMT, the green signal trace is shown as a negative signal, and the absorption lines (yellow) are shown as peaks in the yellow spectrum. The sharp lines between each yellow absorption peak mark the start of each repetitive scan of about 30 second duration over the R9R9 O₂ line, which was chosen for our study.

3 | MEASUREMENTS AND RESULTS

Our measurements were all intended to be exploratory in view of extending neonatal lung monitoring toward larger children and adults, where attenuation due to longer path lengths requires other approaches than those used so far. Lung tissue is quite porous and containing small alveoli as well as channels of different dimensions pertaining to the bronchial tree. Our final goal would be to obtain data from the five individual lung lobes by using multiple detectors suitably placed on the chest wall. Because of strong scattering, detailed imaging cannot be expected.

Initial measurements were performed with both experimental setups in studies of strongly scattering structures, while a final measurement series with the large-scale setup approached a more realistic phantom situation, with sponges inserted in the interior of a large

![Figure 2](image-url)
chicken broiler, or a small block of polystyrene foam surrounded with slabs of pork.

3.1 Small-scale GASMAS and TOFS setup recordings

The GASMAS technique using a low-power tunable semiconductor laser is very suited for monitoring weak absorptive imprints due to gas in scattering media of small extension. We studied a 10 mm thick slab of polystyrene foam of the same type that we later used for pulsed laser studies. We show in Figure 2A the imprint from two molecular oxygen lines, the R11Q12 and R13R13 components, at 13150.2 and 13 151.4 cm\(^{-1}\), respectively. By calibration, we notice that the absorptive imprint corresponds to an effective path length through air of 16 cm. The remaining oxygen imprint due to the 35 mm open air path between the laser and the detector is removed from that value. The residual oxygen curve can be seen superimposed on an undulating background, which we interpret as due to residual interference fringes between partially reflecting surfaces in the setup. The removal of such fringes is frequently an important issue in tunable diode laser spectroscopy and has been discussed in several publications; see, for example, [47–50].

![Figure 3](image-url)

**Figure 3** Time-of-flight recordings (A) and corresponding oxygen GASMAS recordings (B) for cotton pads, placed in a transparent plastic box of inner height 17 mm. Recordings for 5 and 10 pads, compressed to increasing degrees are shown. Recordings for an empty box are also included (blue curves).

![Figure 4](image-url)

**Figure 4** Time-of-flight recordings (A) and corresponding oxygen GASMAS curves (B) for 4-mm-thick very porous crackers. Recordings for 1, 2, 3 and 4 crackers placed on top of each other are shown, as well as the recordings with no cracker in place (blue curves).
In our case, the use of optical diffuser and slight mechanical vibration was implemented. A time-of-flight recording on the same polystyrene slab is shown in Figure 2B.

We note that the maximum distribution of arrival times is delayed by about 0.7 ns, corresponding to 15 to 20 cm average passage length divided up between air and polystyrene, but with air accounting for the main path length in this extremely porous material. Thus, the data from the GASMAS and the TOFS setups are compatible.

As a further small-scale GASMAS example, we show in Figure 3 the case of an increasing number of cosmetic cotton pads placed in a transparent plastic box, with 17 mm height inside. Five or 10 pads all fill up the space, but with increasing compression of the fiber material. Figure 3A shows the TOF recordings and Figure 3B the resulting oxygen absorption signals. We notice that the TOF curves display increasing effective photon path lengths due to increased scattering (some photons finally travelled more than 100 cm) at the same time as the oxygen absorption increases. However, gas absorption increases due to a longer path length through gas could be partly counter-acted by photons also increasingly travelling inside cotton fibers, which become more and more compressed and thus brought in tighter contact with each other, facilitating internal light conduction.

Similar recordings are shown in Figure 4A,B for a more organic sample. Here, 1 to 4 quite porous crackers with pale yellow color were studied. The interrogation distance was matched to the resulting total thickness. We also here see the residual oxygen signal (blue curve) for the case of no sample, also showing an oscillating background due to interference fringes, which are clearly more likely in the case of the absence of a scattering medium.

3.2 Large-scale GASMAS/DIAL setup recordings

As discussed earlier, for larger samples, time-resolved recordings are compatible with range-resolved gas concentration recordings as applied in normal atmospheric DIAL air pollution monitoring. We will in this section present results from our pulsed narrowband dye laser setup. The approach could then be designated as small-scale DIAL, or as large-scale GASMAS. We first performed measurements on large blocks of polystyrene foam of the same kind as used in the small-scale GASMAS measurements shown in Figure 2. Time-resolved recordings with the laser tuned off the oxygen absorption line are shown in Figure 5A for 10, 20, 30, 40 and 60 cm of polystyrene. The average path length travelled by the photons in the sample strongly increases, and for the thickest block we notice that some photons travel over 100 m before reaching the detector. The recordings were made by adding rectangular blocks of size $40 \times 60 \times 10$ cm back-to-back and placing the
detector on the back side, opposite the light injection point. For the 40 cm thickness, one recording was made by stacking four $40 \times 60 \times 10$ cm blocks together, and another one was made by using a whole $40 \times 60 \times 80$ cm block, aligned so the detector was placed opposite the light injection through 40 cm polystyrene foam. We note that both arrangements resulted in very similar recordings, indicating that the optical contact between individual, very flat blocks was very good. The 60 cm recording was made with the same whole block but aligned so the detector was opposite the light injection point through 60 cm polystyrene foam.

Time/range-resolved differential absorption recording yielding range-resolved concentration data could be obtained by first positioning the laser wavelength on an oxygen absorption line (the R9R9 line at 13144.5 cm$^{-1}$) and reference it to a close-by off-resonance wavelength. A repetitive wavelength sweep through the line is shown as the yellow trace on the computer screen in Figure 1B. Data for a 40 cm thick polystyrene foam block are shown in Figure 5B, together with the divided, DIAL curve for on- and off-resonance recordings. A clear slope for increasing time delays/path-lengths is observed, reflecting the 21% oxygen content in the atmospheric gas inside the material pores. We note that the oxygen absorption over 30 m of gas is about 25%. Corresponding DIAL curves for all block thicknesses are shown in Figure 5C. The curves closely overlap in the regions where photons can be detected. The slope is expected to follow an exponential for this case of a constant oxygen concentration, as a reflection of the simple Beer-Lambert law.

Since the limitations in medical diagnostics using CW GASMAS systems operating with semiconductor lasers with few mW output are known, with loss of useful tissue penetrating light beyond few centimeters [11, 24, 31], we here wanted to explore what type of upscaling might be achieved using a high-peak power pulsed laser system of the kind typically used in DIAL measurements. We thus exchanged the polystyrene blocks for easily available animal food-stuff samples and pursued exploratory test recordings. Figure 6A shows a 2 kg chicken broiler, where house-hold sponges (total thickness about ~6 cm) were introduced in the interior of the broiler, while Figure 6B shows a 3 cm thick piece of polystyrene foam surrounded by ~2 cm thick pork slabs on
each side. Light injection and detection were in both cases
done in transmission geometry, with laser beam entry point
and the detector lined up and located at opposite sides of
the sample.

Examples of time-resolved recordings for these samples
are shown in Figure 7. Figure 7A presents data for the
chicken broiler with internal air-filled sponges. A delay of
$<0.1 \text{ ns}$ is observed between the peak intensities of the cur-
ves with and without the 15-cm-thick sample. No clear dif-
ferential absorption effect is observed for the resulting short
pathway through the sponges, and there is no significant
broadening of the temporal curve. We note that the tempo-
ral curve is broadened by $<0.1 \text{ ns}$. Panels B and C show
data for the polystyrene foam/pork composite target studied
in ambient air, and with the whole sample flooded with
nitrogen gas, respectively. In this case, the delay of the peak
is observed to be $1.5 \text{ ns}$, and the temporal distribution is
increased by $2 \text{ ns}$, larger values than for the broiler, indicat-
ing a longer effective path length through the composite
sample, most likely due to the foam component. Clearly,
the foam/pork composite sample is a considerably more
realistic phantom with regard to scattering than the broiler/
sponge one. Real lung tissue is expected to have about a fac-
tor of 5 less scattering than polystyrene foam, but the geo-
metrical size is larger, which also makes the foam/pork
sample adequate for the present purpose. The stronger scat-
tering observed in this sample is consistent with the obser-
vation of a small additional reduction in peak intensity for
the on-resonance wavelength in the case of ambient air
monitoring, apart from a larger reduction due to surround-
ing ambient air, present also when flushing nitrogen.
Divided, range-resolved DIAL curves make little sense in
this case when the recorded signal is heavily convoluted
with the laser pulse itself, and the influence of scattering is
hardly noticeable. Clearly, a very high sensitivity to small
trigger errors will also pertain for these cases, and actually,
occasional recordings of erratic data are believed to be due
to such problems. While such problems should be reduced
when the sample linear size would be increased by a factor
of 2, pertaining to the larger children/adult lung case, there
are clear issues with the high-energy pulsed laser approach
as evidenced in our study. These include trigger jitter,
pulse-to-pulse fluctuation, the scattering of light always ten-
ding to be heavily convoluted with the laser pulse shape
itself and also laser safety issues in medical use.

4 | DISCUSSION AND
CONCLUSIONS

We note that lung oxygen measurements in adults using
GASMAS has so far not been possible, due to longer path-
lengths/larger geometries, leading to extremely low light

intensities reaching the detector, as compared to the suc-
cessful measurements on neonatal lungs, previously
reported by our research group [31, 32]. The possibility to
promptly identify severe lung complications, for example,
pneumothorax (collapsed lung due to air leakage in
the space between the lung and the chest wall) or atelecta-
sis (collapsed lung due to deflated alveoli), using the
GASMAS technique in an animal model has also been
demonstrated [35]. The need for a noninvasive, harmless,
continuous lung surveillance technique for preterm/ill
infants is clear, and there is, of course, a corresponding
need for adults, where many patients suffer from severe
respiratory disorders, for example, pneumonia, chronic
obstructive pulmonary disease, lung fibrosis and more
recently the SARS-CoV-2 viral infection. Bedside contin-
uous monitoring of the dynamic pulmonary processes, with
regard to oxygen content, spatial air distribution and also
detection of severe complication, such as pneumothorax
and atelectasis, could lead to quicker detection and treat-
ment of immediate life-threatening conditions. There
would be a possibility to “tailor” the respiratory support
for the individual patients, with regard to in which phase
of the disease progression they are.

In scaling up lung monitoring from newborn to
larger children or adults, internal light administration
is clearly advantageous over light injection from the
surface of the chest [33–35]. Internal fiber-optical light
administration would not present any major complica-
tion, since the patients mostly in need would anyway
be intubated with an endotracheal tube, connected to a
ventilator. Clearly, high laser intensity in repetitive
pulses would allow signal photons to be better distin-
guished over background noise as compared to the sit-
uation if the same average power would be delivered
from a CW laser source. However, as illustrated in our
measurements and well-known in the general lidar
community, when the absorption imprint is a very
small fraction ($<1\%$) of the detected light, pulse-to-
pulse fluctuations and other error sources make the
detection uncertain, resulting in a less viable approach.
Also, short energetic pulses, like the $<10 \text{ ns}$ dye laser
pulses used in the present experiments, can cause dam-
age to the transmitting optical fiber, and the tissue
exposure safety regulations would be hard to meet.
Then, the longer pulses ($>100 \text{ ns}$) from a tunable alex-
andrite laser, which operates in the spectral region of
interest, would be a possibility for fiber-optical trans-
mission and lower tissue load, as earlier utilized for
inducing fluorescence in a clinical endoscopic imaging
system [51]. The potential for range-resolved monitor-
ing would then be lost due to the longer pulse length.
Further, such a laser system is very bulky and complex,
which would reduce the applicability.
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CONFLICT OF INTEREST

PL is employed by GASPOROX AB, which manufactured the small-scale equipment, and KS and SS have minor shares in this company. EKS, KS and SS are minor shareholders in the company GPX Medical AB, which pursues lung monitoring of neonatal infants; KS is also a board member of that company.

DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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