# Exploring $CO_2$ measurement

Before Covid, carbon dioxide ($CO_2$) was mainly thought of as a greenhouse gas with a sideline of making fizzy drinks. We all knew we breathed the stuff but nobody talked about that. Covid made us aware of the risks of breathing in air that someone else has breathed out, and the realisation that masks and distancing won't protect you from aerosol particles that float in the air made ventilation a big issue, and it turned out that measuring $CO_2$ concentration has for a long time been a routine way to assess the quality of ventilation in buildings.

It seemed obvious that whenever it came 'the new normal' would be different because the virus is likely to be around for a long time. It also seemed that we would probably move from having 'one size fits all' rules imposed on us by the Government and/or Church, to being expected to 'apply common sense' to coexist safely with the virus.

Ventilation is obviously part of that, but our tower is not easy to ventilate. It has some natural ventilation, but how much? And is it 'enough'? We had no way of knowing. When talk of $CO_2$ meters first popped up it looked like a way to learn more about how the air in our tower behaves.

We are fortunate that one of our band was able to borrow a professional $CO_2$ meter so we could start to make measurements, gather data and explore how the tower air behaves in a range of conditions. That knowledge should help us to make more informed decisions about how to manage ringing, and what restrictions if any we ought to apply during possible future periods of higher risk.

In this article I am sharing what we did and what we learnt from it. It isn't advice or guidance, since all towers are different, but I hope it will be of interest, and maybe stimulate further questions and debate.

### The tower

Although our tower has no windows or doors opening directly to outside it has several relevant features:

- The ringing room is high, with a volume over 80 m$^3$. So there's plenty of air to dilute what we breathe out, and to slow the rate at which anything ($CO_2$ or virus) builds up.
- The stairs to the ringing room are quite short and connect us to the church porch, which has large doors.
- There is an openable vent (~0.5m$^2$) into the nave. It is shut during service ringing to avoid interference from the organ (and the church heating when it is on) but it is open at other times.
- There is some leakage through the rope holes – quite small but every little helps.
- We have a very large stained glass west window. You might not think that relevant but a lot of air leaks through the leaded joints of stained glass windows, something I learned when the church heating system was installed, since it injects hot air under pressure and relies on such leakage to help distribute it round the building.

But how much ventilation does it all add up to?

### Using all the air

The first time we used the meter during ringing $CO_2$ level rose quite quickly. I wondered if that was in the whole volume of air or just the bottom part where we and the meter were, so I turned on the fan in the air conditioning unit (which is above us) to stir up the air. The $CO_2$ reading went down and remained much lower. The data from that session were lost but I repeated the experiment later with the result shown in Figure 1. Before the fan was switched on $CO_2$ concentration was rising at around 30ppm per minute whereas with the fan running the concentration rose at a significantly lower rate, presumably because our breath was being dispersed through a larger volume of air.

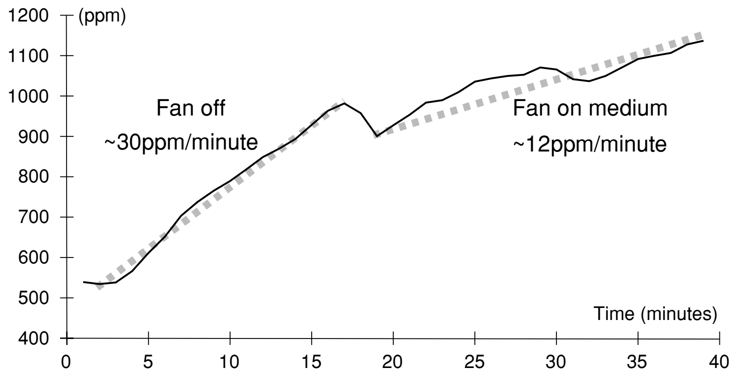


*Figure 1: Effect of air mixing on the rise of $CO_2$ concentration*

### Leakage testing

One of the ringers had a small cylinder of $CO_2$ that he used for home brewing but no longer needed. With it screwed into its fitting the valve can be opened and closed by turning slightly. I used this to raise the $CO_2$ level in the empty room artificially and then measured the time it took to decay from natural leakage (with the fan running to ensure good mixing). I was being quite cautious, standing near the door when releasing the gas, given the warnings about doing it in an enclosed space. But it took quite a while, and I had to release a lot of gas to get the concentration up to 900ppm, which was still well below the 1100ppm in my dining room when I first switched on the meter to see how it worked.

For the test I used a 'worst case' with both the door and vent closed, but a week later I did two more tests (which emptied the $CO_2$ bottle), one with the door open and vent closed (as for service ringing) and one with both open (as for practices). The worst case gave between 1.5 and 2 air changes per hour (ACH), while the other two gave much higher values: door & vent open ~5 ACH and door only open ~4.5 ACH.

To get a feel for what this meant in practical terms I built a simple model that assumed $CO_2$ was produced at a fixed rate per ringer and used the higher and lower air change rates I had measured. Figure 2 shows the result (with 1.5 ACH dotted and 5 ACH solid) for four, six & eight ringers.

As expected, for a given air change rate more ringers equates to higher $CO_2$ concentrations, but the interesting thing is the different shape of the two sets of curves. To understand that think what happens as the $CO_2$ concentration rises. The more there is in the air the more of it will leak out, until eventually enough is leaking out to balance what is being produced. With a low air change rate the concentration has to get very high before there's enough leaking out to achieve a balance, which takes a long time. But with a high air change rate the balance happens sooner and at a lower concentration. Figure 2 shows that with 5 ACH the concentration hardly rises after about half an hour, so it would be constant during most of a peal, but with only 1½ changes per hour the concentration would still be rising slightly at the end of the peal, and by then would be around three times higher than with 5 ACH.

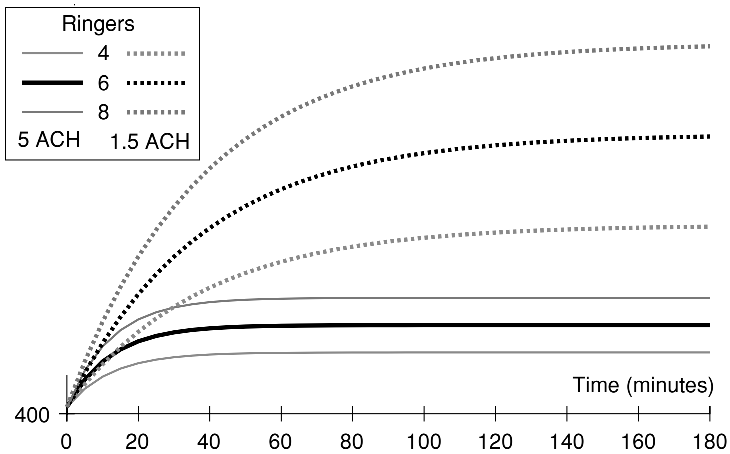


*Figure 2: Modelled $CO_2$ concentration over time*

## Measurements during ringing

I used the meter during all ringing sessions for several weeks after the restrictions were lifted in May, and the results are plotted in Figure 3. Data for 23 & 24 May were recorded at five minute intervals but all others were at one minute intervals. I set up the recorder shortly before the session started, and the readings varied somewhat as the instrument settled down and ringers arrived. To avoid these initial readings complicating the picture I adjusted the nominal start time to make the curves appear to come from a similar point.

Most sessions had six ringers but the curves shown dotted were for sessions with only four or five ringers.

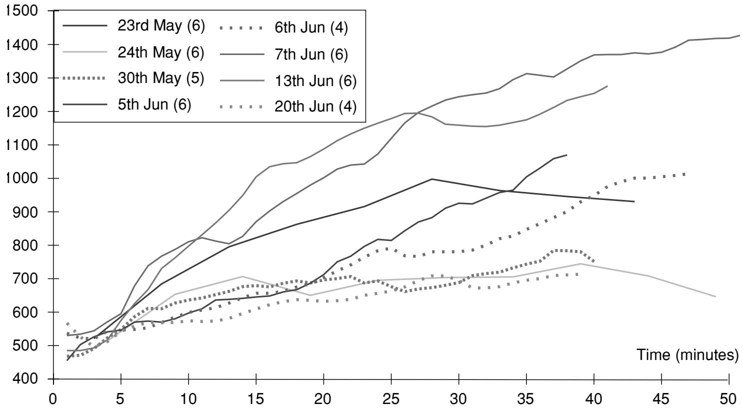


*Figure 3: $CO_2$ (ppm) measured during ringing sessions*

## Why so variable?

The most striking feature of Figure 3 is the enormous variability. Some of that was because of the different number of ringers so to put all curves on the same basis the graphs with the excess $CO_2$ scaled up as if there were six ringers, as shown in Figure 4. That moved a few curves but still left a lot of variation to explain.

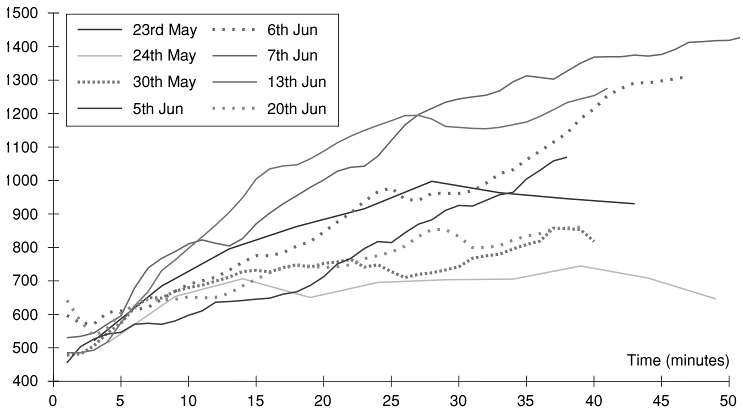


*Figure 4: $CO_2$ (ppm) during ringing sessions adjusted to be equivalent to 6 ringers*

Many factors that might have affected ventilation varied between sessions, so I looked at each in turn to see whether it could explain the differences:

- The stair door was open for all sessions but the porch door was closed for practices and open during service ringing. That might limit air flow up the stairs – though the west door is very ill fitting.
- The vent to the nave was closed for service ringing and open for practices. That could limit the flow of air – but it only made 10% difference when I tested the leakage rate.
- The sound control shutters were closed for practices but open for service ringing. When open they could provide a much easier way out for any air passing up through the rope holes.
- The fan in the air conditioning unit was run to help mix the ringers' air with the empty space above, but for some sessions it was only on

half speed, which might have made the mixing less effective.

- The air conditioning unit has moving vanes that deflect the air horizontally and vertically, but for some sessions the vertical movement was turned off. That might have limited the mixing and increased concentration where the ringers and the meter were.
- Most sessions only used the air conditioning unit as a fan but on a couple of sessions it was also cooling slightly. Cool air sinks, and that might have helped to reduce mixing.

Checking each factor against the results for different sessions showed no consistent pattern, with good and bad cases for each condition.

### External conditions

Having found no satisfactory explanations inside the tower I looked at conditions outside.

The external temperature can affect ventilation because the difference between outside and inside air temperature drives the ‘chimney effect’. When it’s cooler outside the warmer air inside the tower will rise and draw in more fresh air at the bottom, and when it’s hotter outside the cooler air inside will be drawn down by the reverse chimney effect. I didn’t record external temperature at the time but thanks to a local meteorologist who has been recording the weather since the mid 70s I could download them from his website.

Figure 5 plots $CO_2$ concentration 30 minutes and 40 minutes into each session against the external temperature. Up to 17C there is a strong correlation, with $CO_2$ concentrations rising (ie ventilation reducing) almost linearly with temperature. Above 17C the concentration falls though the correlation is less clear. This rise and fall is consistent with the chimney effect getting weaker when the external temperatures is similar to the internal temperature, which was around 17–18C.

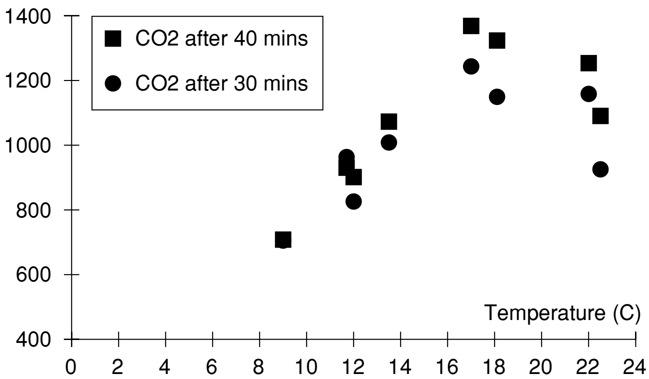


*Figure 5: Adjusted $CO_2$ concentration (ppm) plotted against external temperature*

Wind will also have an effect on air leakage, and Figure 6 shows some correlation with wind speed but it’s much less clear than with temperature.

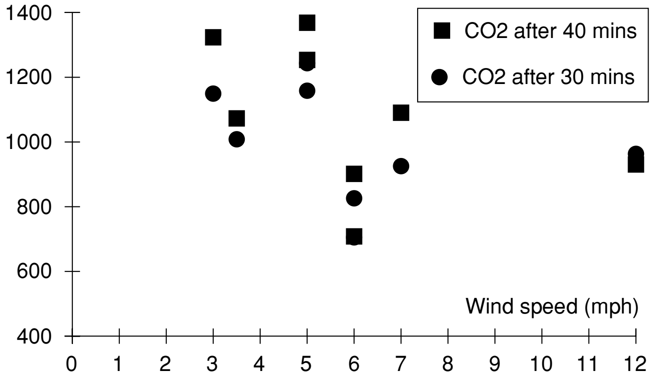


*Figure 6: Adjusted $CO_2$ concentration (ppm) plotted against local wind speed*

### What did we learn, and what next?

Measuring $CO_2$ was a means to an end – understanding how the air in our tower behaves. In particular since we don’t have windows to open we wanted to know how much natural leakage there was. The number of air changes per hour is a key input to models of infection transmission, and without it you are just guessing.

From the measurements made we know the air change rate varies quite a lot, and even leaving doors open has limited effect if the outside air isn’t either a lot colder or hotter than inside. That’s something we can’t control.

Next we intend to explore whether we could mechanically augment the ventilation. Again the features of our tower add complications. A fan could draw air from the ringing room into the clock room but where would it go then? There’s a small window that could be opened. During service ringing leakage through the rope holes and between loosely fitting boards would provide another path the bell chamber, but not during practices when the sound control shutters are closed. There are other possible air pathways, and we need more work to be sure there wouldn’t be any unintended effects, for example air going back through the rope holes or down the stairs into the Ringing room.

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