

## MITOCW | MITRES\_10\_S95F20\_0507\_300k

PROFESSOR: So the next important part of turbulent plume theory that we need is the distribution of concentration of particles or droplets, in this case, that are injected with the fluid at the source.

So as we've just arrived, the concentration  $C$  in this case, we could have referred to infection quanta and infectious aerosols relative to that leaving the mouth, which is we've called  $C_q$ , scales as square root of area of the mouth divided by  $\alpha x$  where  $\alpha$  is the turbulent entrainment coefficient, around 0.1 or 0.15.

And that leads to a jet which grows in size and grows in fluctuations as you see more and more eddies, and eventually might even bend due to flows in the room or thermal buoyancy effects.

And I'd like to talk about the difference between short range transmission due to really placing yourself in this jet and breathing that air directly, which is more concentrated than the background, and then compare that with the transmission in the well-mixed room that we've been talking about all along.

So obviously if we're at position 0 here right at the mouth, this is the worst case scenario.

So if we're here, let's say we're only 1 inch or 1 centimeter away.

And we put our mouth on top of the other person's mouth, that is the worst case scenario of short range transmission.

That is, relative to the background room, we're getting a much worse situation there.

But if we ask ourselves, how much worse is it, so we know that  $f_d$  is the dilution factor, that is the concentration kind of at the source relative to  $C$  sort of at infinity and the well-mixed room, so let's just say far away.

Actually instead of  $C$  infinity, I should call that  $C$  average.

Because it is the average concentration in the room.

And we've seen that the dilution factor can be written as the flow rate of the breath divided by the sort of decay rate of the concentration field at the average-- at the appropriately defined mean radius divided by the volume of the room.

So that is telling us how much more concentrated the infection quanta or viruses are here versus the well-mixed room where they're really spread out.

How big is this factor?

So this factor for the Skagit choir, which we've analyzed, the Skagit Valley Chorale.

So that was a fairly large room, 4.5 meter ceiling.

But it didn't have very good ventilation.

So that's sort of similar to smaller rooms with better ventilation.

And in that case, this number was 10 to the minus 3.

And in general,  $f_d$  for typical indoor spaces-- for offices, classrooms, and homes-- is on the order of 10 to the minus 2 to the 10 to the minus 4.

So there's quite a significant difference.

If you are right at the point of somebody's mouth and breathing in their air versus being far away, there really is a big difference.

To put it in perspective, we can ask ourselves, well, how long would you have to stay in the well-mixed room, far away, breathing the air to have the same exposure and dose of infection quanta as if you put your mouth on top of somebody else and breathed in one lung-full of air.

So if we just say that if we calculate it as a timescale, taking in the volume of a single breath and then dividing that by  $Q$  breath and the dilution factor, that is the time you would have to spend breathing the background air in order to achieve the same dose.

And this quantity ends up being for the Skagit choir that we calculated around one hour.

So if 63 people were in the room and 53 or so were infected, then that most likely happened through the airborne route, as we've discussed.

Because 53 people were mostly breathing the background air that was, perhaps, well-mixed.

On the other hand, you also could infect 53 people by taking turns one at a time putting their lips against the other person who's infected and just breathing in one full lung-full of air.

Then you would get a similar number of people infected on the order of an hour or two, which is the length of time of that choir practice.

But we know that didn't happen.

So that already tells us that short range transmission really can't explain what happened in the Skagit choir.

And as we've discussed, it has to be longer range airborne aerosol transmission.

But how much longer range?

We can also sample at different positions here.

So that's the absolute worst case scenario.

So let's consider as important numbers 3 feet and 6 feet.

So 3 feet corresponds to 1 meter, which is the social distancing guideline of the World Health Organization today.

I would also argue that 3 or maybe 2 feet is kind of close to what you might call natural social distancing.

So if you don't impose social distancing, most people prefer to have a little space bubble around them.

They don't want to be right up against somebody if they don't have to.

And they tend to stand 2 or 3 feet apart.

So somewhere in here is what I would call natural social distancing except in cases where you're in a crowd.

So if you're in a nightclub or a bar or some crowded space where you're starting to press against people, then you come closer you might be 1 foot or 1/2 foot, and you might start to get closer to this worst case.

But people tend to be about 3 feet apart.

So we can ask ourselves what happens there.

We can also look a little further.

The Center for Disease Control the United States has imposed a 6 foot rule as we have discussed.

In fact, it's been interpreted so strictly in the United States that you can find floor stickers exactly 6 feet apart in all sorts of indoor spaces even when people are wearing masks and when we aren't sure exactly what the flows are like.

And we can ask ourselves, what is the sort of level of concentration there.

It's also worth noting that we can also look at a negative value.

How about minus 3 feet?

Because it's important to note that respiratory jets do not only increase your risk relative to the well-mixed ambient, there must be regions where the risk is actually lower than the well-mixed ambient.

Because in the end, the well-mixed solution was obtained by mass balance.

So that means we've essentially counted all the infection quanta or virions in the room.

And if there is a higher concentration here, there must be a lower concentration somewhere else to account for that.

So perhaps if you're standing behind somebody at a reasonable distance, you actually have a lower concentration, although there is still mixing going on.

And you will be exposed to the well-mixed room.

Which then brings me to the way that we should really think about the role of short range transmission versus long range transmission.

And that is to compare the concentration of the respiratory jet to that of the well-mixed ambient that we calculated.

That's essentially the definition of when there's a transition from short range to long range behavior.

So where will that occur?

It will typically be somewhere here.

So there's a certain position, which we'll call  $x_C$ , and this will be defined by saying that  $C$  over the initial value is equal to the dilution factor.

So this is the point where if I follow this orange curve, I've just hit the concentration that is predicted for the background well-mixed room, which we've already calculated before.

So if you use our formula for  $C$  there, you then get a formula for this  $x_C$ , which is the square root of the mouth area times  $\lambda$   $C$  of  $r$  bar, so the decay rate of the concentration field, the volume of the room, and then  $\alpha$   $Q_B$ .

So I would argue that this is really the boundary which separates long range airborne transmission by aerosols with short range transmission, which also includes aerosols by the way.

So some of these aerosol droplets, you definitely could be inhaling anywhere in here.

But if you go long range, you're only talking about aerosol droplets.

So this is really where the dividing line is.

And if you plug in numbers for different settings, you'll find this is often larger than 6 feet.

In fact, in some cases, many cases, it's actually larger than the room.

It could be tens of meters even, because this dilution factor can be of order a factor 100 or even 10,000 lower concentration in the well-mixed room than at the person's mouth.

So you have to go pretty far away to see it actually drop back down.

What that means is that when people are breathing in a room these breaths are crossing all over the place.

They're mixing.

And you really can't think about a turbulent plume lasting out to infinity because there is another person standing here, there's ventilation flow, there are thermal flows.

All of the mechanisms we talked about mixing will take this jet and start to mix it around the room so it won't look like a perfect jet all the way.

But at least this gives us an estimate for these closer spaces here that's sort of what our risk might be.

So using this concept, I'll just mention this is typically much bigger than 6 feet, we could estimate how much worse is it to be 6 feet or 3 feet away with yourself in a worst case scenario perfectly placed in a respiratory jet.

So what we're asking here is what if we were unlucky enough to be right here and breathing in for a long period of time.

So not just for a fleeting second but you're sitting there and just over and over you're just sitting here breathing in that person's breath.

It's not an unreasonable situation.

You could imagine at a meeting when two people are sitting at a table or maybe they're having dinner.

Masks are off, they are facing each other, talking to each other.

And in fact that is a high risk situation in terms of this kind of transmission.

So let's see how much worse it actually could be.

Well, if you plug in the numbers then using a typical mouth area, in this case the concentration drops to about 6%.

In this case, the concentration since it's what goes as 1 over distance, is more like 3%.

So it's a very rough calculation.

But relative, and I should say, so relative to the highest concentration of reaching the mouth, the plume has been diluted down to 6% or 3% as you go these distances.

Notice there's not a massive difference between 3 and 6.

And it does make a very big difference in terms of decisions to reopen spaces and how people interact, whether you're strictly 6 feet apart or perhaps you can be 3.

So keep in mind that 3% to 6% dilution.

But what we're really interested in here is now, how do these fractions compare with the well-mixed room.

And so for that I actually would like to do a different comparison as I'd like to do  $C$  over  $f_d$ .

Because  $f_d$ , relative to here, is the concentration far away.

So I want  $C$  over  $C_q$ , I should say, over  $f_d$ .

And so this also can be written as  $xC$  over  $x$ .

So it's basically how much farther is that crossover point relative to where you're standing.

That's another way to think about it.

And this is then six to 600.

So this is the excess risk.

If you were to stand 3 feet away, that's the excess risk you face from short range transmission if you are 100% of the time breathing in the jet of the infected person pointing right at you all the time.

If you take this 6 foot rule, it's a little bit less strong.

You have a  $C$  over  $C_q$  divided by  $f_d$ .

It is more like three to 300.

It, again, depends on the details of the room.

But it still can be a significant factor.

So we will come back to thinking about how to handle short transmission in light of its interaction with long range.

But let me make one final comment on this discussion, which is where is this crossover point.

So notice it scales with volume.

So something you may be wondering is, don't we have airborne transmission and shortwave transmission outdoors also.

Yes.

And that is actually covered by the theoretic arguments that we're making here.

Although, as I said, these jets really can't last forever.

But we can at least say to ourselves, what happens as  $v$  goes to infinity.

So I like to call this the outdoor limit.

If you apply our safety criterion for a well-mixed room to very big room, think of, for example, a gymnasium or a sports stadium, very, very big room, then if there's only one infected person, then the dilution of those droplets in a massive space is like being outside.

You might as well be outside.

And what you find that is the crossover is very far away, which means the long range analysis is not even helpful.

It's not even valid.

Really, it's the short range analysis you'd be thinking about.

Now unfortunately, the short range analysis depends on many assumptions about how people are positioned, how they're interacting, what are the local flow fields.

But you have to deal with short range transmission.

And social distancing can play a role in how you address that threat.

But once you get to smaller rooms and longer periods of time then you actually find that this  $x_C$  is on the order of the room size.

And then you really are going to be having significant effects of long range transmission.

And I will argue that for most typical rooms that we inhabit indoors, that the long range airborne risk is the leading order first approximation and best approximation.

And the short range risk must be considered, but it's a correction to that.