How do these pressure variations affect any gas bubbles that are present in the tissues? As the pressure increases, the bubbles are compressed and so they reduce in size. As the pressure decreases they expand. In some situations this oscillation of the bubbles is stable. This is known as “non-inertial” cavitation. At other times, however, the bubbles will implode (i.e. collapse very rapidly), generating a shock wave and exposing the tissues in the immediate area to high stresses. This “inertial” cavitation is potentially very damaging.

What are the main factors affecting the risk of cavitation? First, cavitation can only occur when gas bubbles are present in the tissues. Second, the risk of cavitation increases as the ultrasound intensity increases, as we would expect. Third, as shown by the equation below, the risk of cavitation is greatest at low frequencies, decreasing as the ultrasound frequency increases.

By its nature, cavitation cannot be quantified in the same way as the temperature increase. Instead the “Mechanical Index” (MI) has been defined as follows:

$$MI = \frac{P_r}{\sqrt{f}}$$

$P_r$ is the peak rarefaction pressure (expressed in Pascals), i.e. the greatest negative pressure (see Figure 11.1) and $f$ is the ultrasound frequency (expressed in MHz).

Instead the MI should be seen as a number designed to indicate the risk of cavitation. The maximum acceptable value for the MI is generally agreed to be 1.9.

Apart from cavitation, have any other non-thermal bioeffects been identified? Yes, “radiation force” has been shown to be capable of causing bioeffects. This term refers to the force exerted on any object that reflects or absorbs ultrasound. Indeed, there are devices which use radiation force to measure the output power of ultrasound systems (see Figure 11.3).

A common result of ultrasound radiation force is movement of liquids such as blood which contain particles that reflect or absorb ultrasound. In general this “streaming” is considered harmless at diagnostic intensity levels.
More importantly, however, it is believed that radiation force is likely to be the explanation for the bleeding that has been observed in the capillaries of lung tissue exposed (in research settings) to ultrasound at moderately high intensities.

Researchers have suggested that the incident ultrasound generates sufficient force when it reflects from gas in the alveoli to damage adjacent tissues and cause some of the capillaries to bleed.

The Mechanical Index is believed to be a reasonable guide to the likelihood of harm due to radiation force effects (and other non-thermal effects that may exist), as well as being an indication of the likelihood of cavitation.

In summary, a number of mechanical (i.e. non-thermal) bioeffects have been identified. Of greatest concern is cavitation, which can occur in the presence of gas bubbles and can cause localised tissue damage. Radiation force is also of concern given the likelihood that it is the cause of capillary bleeding seen in lungs exposed to moderately high exposure. The Mechanical Index is designed to indicate the risk of harmful effects from non-thermal mechanisms. The accepted safe limit for the MI is 1.9.

**Suggested activities**

1. As you are scanning, note the displayed Thermal Index and Mechanical Index values.
2. See whether the displayed TI type (i.e. TIs, TIb or TIc) changes depending on the clinical application area selected.
3. Compare the TI and MI values in different operating modes (grey scale imaging, colour Doppler, pulsed Doppler etc).
4. Change some of the machine's parameters (e.g. the transmit power and frequency, depth of focus, pulsed Doppler velocity scale, colour Doppler box width etc). Note any changes in the TI and MI. Are these changes consistent with what you expected?

### Characterising ultrasound exposure

An earlier chapter introduced the concepts of energy, power and intensity (see Table 11.1). Since we want a measure of tissue exposure, intensity is the most useful parameter, since it specifies how much energy flows through a given volume of tissue each second (see Figure 11.4).

![Figure 11.4 The term "intensity" specifies the amount of ultrasound energy (blue arrow) flowing through one square centimetre of tissue.](image)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>total &quot;work&quot; done</td>
<td>Joules</td>
</tr>
<tr>
<td>power</td>
<td>energy per second</td>
<td>Watts</td>
</tr>
<tr>
<td>intensity</td>
<td>power per square</td>
<td>W/cm²</td>
</tr>
</tbody>
</table>

*Table 11.1 Definitions of the parameters used to measure ultrasound exposure.*

When we start to look at just how to calculate the intensity, however, we quickly realise that there are complicating factors that must be taken into account. The transducer does not transmit continuously (except in CW Doppler). Instead it transmits short pulses of ultrasound with substantial intervals between them to allow echoes to be received. We refer to this as the temporal variation of the ultrasound exposure (see Figure 11.5).

![Figure 11.5 Temporal variation of the transmitted ultrasound. PRP is the pulse repetition period (i.e. the time from one transmit pulse to the next), \( \tau \) is the transmit pulse duration and \( I_{tp} \), \( I_{pa} \) and \( I_{ta} \) are the temporal peak, pulse average and temporal average intensities respectively.](image)
The ultrasound intensity also varies both with depth and across the beam at any given depth. This is the spatial variation of the ultrasound exposure (see Figure 11.6).

A useful concept is the duty factor (sometimes called the “duty cycle”). This is simply the fraction of time for which the transducer is transmitting, that is:

\[ DF = \frac{\tau}{PRP} \]

where \( DF \) is the duty factor, \( \tau \) is the duration of the transmit pulse and \( PRP \) is the pulse repetition period (you may remember that the PRP is simply equal to \((1/PRF)\)).

Typical values for the duty factor in grey scale imaging range from 0.1% to 1%. They are somewhat higher for pulsed Doppler due to the longer transmit pulse duration used in Doppler.

The pulse average intensity \( I_{\text{pa}} \) is simply the intensity averaged over the transmit pulse duration. It can therefore be written as:

\[ I_{\text{pa}} = \frac{P_p}{\tau} \]

where \( P_p \) is the energy per square centimetre contained in one transmit pulse and \( \tau \) is the pulse duration. As Figure 11.5 shows, the pulse average intensity is somewhat lower than the temporal peak intensity \( I_{\text{tp}} \).

The temporal average intensity \( I_{\text{ta}} \) is calculated by averaging the intensity over the entire pulse repetition period \( PRP \). It can therefore be written as:

\[ I_{\text{ta}} = \frac{P_p}{PRP} \]

Combining these equations we can see that there is a simple relationship between the temporal average and pulse average intensity values:

\[ \frac{I_{\text{ta}}}{I_{\text{pa}}} = \left( \frac{P_p}{PRP} \right) \left( \frac{P_p}{\tau} \right) \]
\[ = \left( \frac{P_p}{PRP} \right) \times \left( \frac{\tau}{P_p} \right) \]
\[ = \frac{\tau}{PRP} \]
\[ = DF \]

and therefore:

\[ I_{\text{ta}} = I_{\text{pa}} \times DF \]

Since the duty factor is typically 0.1% - 1.0%, we can see that the temporal average intensity will be very much smaller than the pulse average and temporal peak intensities.

Looking at Figure 11.6 we can see that the maximum intensity (the spatial peak intensity \( I_{\text{sp}} \)) will be found at the focal depth and on the central axis of the beam. In fact this is not strictly true. Once we take attenuation of the ultrasound into account it is clear that the intensity values will decrease progressively with depth. As a result, the spatial peak value will occur on the beam axis but somewhat closer to the probe than the actual focal point.

Yet another intensity value has been defined. This is the spatial intensity \( I_{\text{si}} \), defined as the transmit intensity averaged over the face of the transducer.

Since the focussed beamwidth is generally substantially narrower than the transducer face, the intensity within the tissues will be considerably higher than the spatial average intensity, making it a relatively meaningless parameter. Unfortunately, however, it is the easiest intensity value to measure and so it is often quoted in manufacturers’ specifications and publications.

Thus we have seen that there are a number of intensity values available. These are summarised in Table 11.2.