

Disinfection

Session Objectives

- To introduce the principal disinfectants that may be used and highlight key advantages and disadvantages of each
- To emphasise the use of chlorination for routine disinfection.
- To describe the process of chlorination and discuss the concepts of breakpoint chlorination, chlorine demand and outline basic chlorine chemistry.
- To discuss the types of chlorine available and how these may be used for routine disinfection.

Disinfection

Introduction

All water supplies should be disinfected. This is aimed both at inactivating remaining bacteria before distribution and providing a residual disinfectant to inactivate bacteria introduced by any subsequent ingress of contaminated water during storage or distribution. At present, the principal disinfectant used worldwide is chlorine, although alternatives are being increasingly investigated and process such as ozonation are becoming more common.

Chlorine is generally the disinfectant of choice as it is reasonably efficient, cheap and easy to handle. In all but the smallest water treatment plants, chlorine is added to water as either in aqueous solution (calcium hypochlorite or sodium hypochlorite) or chlorine gas. Smaller supplies may use tablets of hypochlorite.

Other disinfectants include ozone, ultraviolet light and iodine. These all have disadvantages. UV is not a particularly effective disinfectant and it is difficult to expose water for sufficient time for disinfection to be effective. Neither ozone or UV provide a residual disinfectant and therefore offer no protection against recontamination in distribution. To overcome this, in some water supplies booster ozonation stations are set up along the distribution network.

Both iodine and ozone are carcinogenic. There are also significant health and safety concerns, for operators, regarding the generation and application of ozone and chlorine (especially in the gaseous form). Iodine can also lead to thyroid problems with pregnant women and is generally more toxic than chlorine.

Selection of disinfectant

Under most circumstances, overwhelming factors will dictate selection of disinfection method. The most common major factors are: availability, cost of disinfectant, logistics (especially transport costs), and cost/availability of equipment. Under the majority of circumstances chlorine in one of its forms has been found to be the disinfectant of choice. The choice of which form of chlorine will again largely be determined by availability, cost and transport.

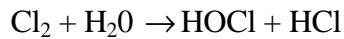
Chlorine

Chlorine is an effective disinfectant where water is not turbid (cloudy) and the pH of the water to be treated is not alkaline, for instance not above pH 8.0. However, most natural waters have a pH below 8.0 and thus disinfection is rarely compromised by pH.

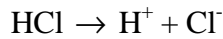
Chlorine chemistry

Chlorine, whether in the form of pure chlorine gas from a cylinder, sodium hypochlorite or calcium hypochlorite in any of its presentations, dissolves in water to form hypochlorous and hydrochloric acids. Chlorine dioxide, however, does not dissolve in water.

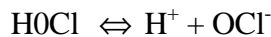
The reaction of chlorine in water follows the reaction shown below:



Hydrochloric acid dissociates in turn to form hydrogen and chloride ions

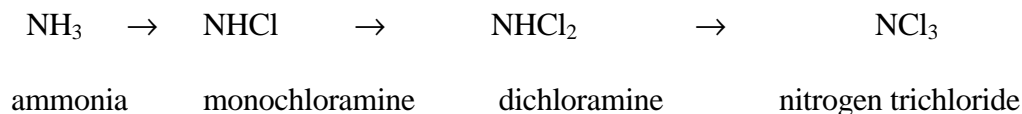


Hypochlorous acid however dissociates only partially

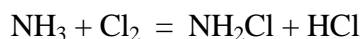


It is undissociated hypochlorous acid which acts as a disinfectant. The equilibrium between undissociated hypochlorous acid, hydrogen ions and hypochlorite ions depends on pH. At high pH (alkaline conditions, pH greater than 8), the dissociated forms predominate and at low pH (acidic conditions) undissociated hypochlorous acid predominates. For this reason disinfection with chlorine is more efficient at lower pH values and a pH of less than 8 is recommended for disinfection. Pure chlorine gas from a cylinder tends to decrease the pH of the water slightly; hypochlorite tends to increase water pH a little.

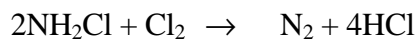
Formation of combined chlorine is due to a sequence of reactions. Hydrogen in ammonia is progressively replaced by chlorine as follows:



Where it is desired to produce monochloramine as a more stable, but less efficient disinfectant, the two chemicals may be dosed in appropriate proportions.



If a large chlorine dose is applied (relative to ammonia), as is practised in breakpoint chlorination, then nitrogen is formed.



Chlorine demand

The total amount of chlorine which will react with both compounds like iron and manganese and with organics and ammonia is referred to as the chlorine demand. The chlorine demand of different waters can vary widely.

Chlorine demand is the difference between the amount of chlorine added to the water (the chlorine dose) and the total chlorine detectable in the water. The chlorine demand for some waters, for instance some river waters, can increase dramatically, particularly after heavy rain.

Breakpoint chlorination

The type of chlorine dosing normally applied to piped water supply systems is referred to as breakpoint chlorination. Sufficient chlorine is added to satisfy all of the chlorine demand and then sufficient extra chlorine is added for the purposes of disinfection. Figure 1 shows the breakpoint chlorination curve. It indicates the effect of adding more chlorine to water which contains an initial ammonia nitrogen content of 1mg/l.

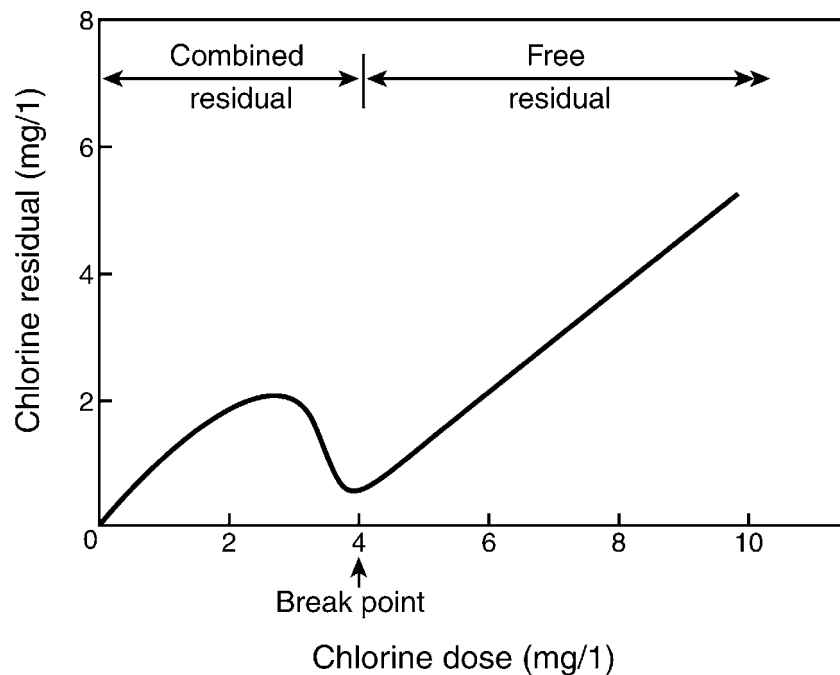


Figure 1. Breakpoint chlorination. Diagram taken from Tebbutt T.H.Y., 1992

The initial rise in residual is predominantly monochloramine (combined chlorine residual). The subsequent fall with further addition of chlorine is due to the decomposition of monochloramine to form nitrogen (the chlorine detected in this phase is also combined residual).

Finally the oxidation of ammonia is complete and any additional chlorine will cause an equal increase in the free chlorine residual.

Contact time

Disinfection with chlorine is not instantaneous. Time is required in order that any pathogens present in the water are inactivated.

The time taken for different types of microbes to be killed varies widely. In general, amoebic cysts are very resistant and require most exposure. Bacteria, including free-living *Vibrio cholerae* are rapidly inactivated by free chlorine under normal conditions. For example, a chlorine residual of 1mg/l after 30 minutes will kill schistosomiasis cercariae, while 2mg/l after 30 minutes may be required to kill amoebic cysts. Thus it is important to ensure that adequate contact time is available before water enters a distribution system or is collected for use.

Contact time in piped supplies is normally assured by passing the water, after addition of chlorine, into a tank from which it is then abstracted. In small community supplies this is often the storage reservoir (storage tank). In larger systems purpose-built tanks with baffles may be used. These have the advantage that they are less prone to "short circuiting" than simple tanks.

The pH of the water also affects the efficiency of chlorination and contact time is therefore also related to pH.

Chlorine residual

Chlorine persists in water as 'residual' chlorine after dosing and this helps to minimize the effects of re-contamination by inactivating microbes which may enter the water supply after chlorination. It is important to take this into account when estimating requirements for chlorination to ensure residual chlorine is always present.

The level of chlorine residual required varies with type of water supply and local conditions. In water supplies which are chlorinated there should always be a minimum of 0.5mg/l residual chlorine after 30 minutes contact time in water.

Where there is a risk of cholera or an outbreak has occurred the following chlorine residuals should be maintained:

- At all points in a piped supply 0.5mg/l
- At standposts and wells 1.0mg/l
- In tanker trucks, at filling 2.0mg/l

In areas where there is little risk of a cholera outbreak, there should be a chlorine residual of 0.2 to 0.5 mg/l at all points in the supply. This means that a chlorine residual of about 1mg/l when water leaves the treatment plant is needed.

Problems of taste and odour

The taste of chlorine in drinking water may lead the population to reject a source of water which is actually safe to drink. They may then choose to use a better-tasting source of water which may in fact present a greater health risk. Chlorinous tastes in water are most often due to over-dosing or the presence of chlor-phenols.

Over-dosing may be due to error (which should be prevented by proper monitoring and control); may be deliberate (for instance, in response to contamination of the supply, which should be corrected as soon as possible and chlorine levels returned to normal); or may be due to high-level dosing to ensure adequate concentrations in remote parts of the distribution network (in this case consideration should be given to re-chlorination during distribution).

Chlor-phenols are formed where chlorine reacts with phenolic substances in water. These may be derived from algae, thus chlor-phenol formation is more common where the source is surface water than when groundwater sources are used. Chlor-phenols have a very strong chlorinous taste and very small amounts of chlorine can therefore give rise to very strong tastes. Problems

with chlor-phenols are often transient and are best overcome by improving the intake and source.

Although chlorine itself can give rise to problems of taste and odour, chlorination can also help to improve taste and odour by the reduction of organic materials and iron.

As disinfection with chlorine is less effective in turbid water, water to be chlorinated should be clarified. This can be done by natural filtration as is the case with groundwater from wells and springs, or by filtration during water treatment. Filtration should also remove the cysts and eggs of protozoa and helminths which are resistant to chlorine.

Types of chlorine

Chlorine is available in various forms, including calcium hypochlorite, sodium hypochlorite and as pure chlorine gas in cylinders.

Calcium hypochlorite (chlorinated lime, tropical bleach, bleaching powder, 'HTH') is a powder containing between 30 and 70 per cent available chlorine. It must be stored carefully to prevent deterioration, and although it can cause burns, is generally safe to handle and transport. The Capital (equipment) costs of using calcium hypochlorite for disinfection are generally low. Calcium hypochlorite is most commonly used in solution for the disinfection of rural and small community water supplies and in diffusion hypochlorinators or in tablet form for household use.

Sodium hypochlorite (including household bleaches) is a solution. Sodium hypochlorite solutions contain about 1 to 18 per cent chlorine and are thus mostly water. The solution must be stored carefully to prevent deterioration, it can cause burns and is inefficient to transport, since it is mostly water. Sodium hypochlorite is most commonly used for disinfection in the home and in water supplies where transport of the solution is not a problem.

Pure chlorine gas in cylinders, is used widely. Specialized transport, handling and dosing equipment are needed. However, as chlorine in cylinders is not normally subject to deterioration it is an efficient means of storing and dosing chlorine. Leaks of chlorine gas are very dangerous and installations storing cylinders should be well designed, monitored and maintained. Chlorine in cylinders is most commonly used for dosing at water treatment plants, at the head of wells from which water is mechanically pumped and at re-chlorination plants in large distribution networks.

For more detail on the technologies of chlorination please refer to Volume 3 of the Guidelines.

Chlorine dioxide

Chlorine dioxide is a more powerful oxidizing agent than chlorine, the disinfectant action of which is less pH-dependent than chlorine. It leaves a long-lasting residual. However, chlorine dioxide is an inefficient disinfectant for viral agents and therefore its use is limited.

Chlorine dioxide is mainly used for the control of tastes and odours. It does not combine with ammonia to a significant extent and therefore is more efficient than chlorine in waters with raised levels of ammonia.

Chlorine dioxide is unstable and must be generated on-site by the action of chlorine or an acid on sodium chlorite. In general the two chemicals are dosed together into the water; this process requires constant, vigilant monitoring and control. Chlorine dioxide is much more expensive than chlorine.

Iodine

Where water is not turbid, iodine is an effective disinfectant and is more stable than chlorine in storage. Iodine is mostly used for disinfecting small volumes of water for personal use. It is generally too costly for dosing into community water supplies. Iodine reacts less with organic matter than chlorine and does not react with ammonia.

A dose of two drops of a 2 percent solution of iodine in ethanol, per litre of clear water has been recommended for disinfecting small volumes of water for personal use. However, 1-2 mg/l with a contact time of not less than 30 minutes is normally recommended for public water supplies. Most people begin to detect the taste and odour of iodine at concentrations in the range 1-2 mg/l.

Iodine in solid form is easy to store and deteriorates less rapidly than chlorine. If dissolved in ethanol however, iodine will deteriorate rapidly. Stable iodine compounds for dosing into water supply systems, such as tetraglycine potassium tri-iodide are available as tablets.

Iodine is rarely appropriate as disinfectant for long-term use in community water supplies, especially because of its cost. Nevertheless, because of its stability and effectiveness, it is very useful for disinfection of drinking water, especially in small volumes in emergency, or disaster situations.

At high doses (for instance above 4 mg/l) iodine may produce allergic reactions in some individuals and doubts exist regarding the advisability of long-term use of iodine for drinking water disinfection.

Ozone

Ozone (O₃) is an unstable gas which is only slightly soluble in water. It is an efficient disinfectant, but because it is unstable does not leave a residual in water unlike chlorine. For this reason it is effectively impossible to over-dose with ozone. Ozone contributes to the bleaching of colour and removal of tastes and odours.

Ozone is produced by passing dry oxygen or air through an electrical discharge. It is manufactured on-site using specialized equipment. Whilst ozone is overall the most effective disinfectant and is more effective than chlorine in inactivating cryptosporidium oocysts and viral agents, there are significant disadvantages in its use. These are primarily that ozone does

not provide residual protection against recontamination during distribution and as ozone affects biological stability, it may encourage regrowth of bacteria.

However, given the concerns about the use of chlorine in many countries, the use of ozone is increasingly investigated and the lack of residual may be dealt with by employing regular booster ozonation during distribution. However, far less is known about ozonation and the effect of ozone on human health and it should be remembered that ozonation is much more expensive than chlorination.

Ultraviolet radiation

Ultraviolet (UV) radiation has been used fairly extensively for disinfection of small community water supplies.

The efficiency of UV disinfection is dependent on the intensity and wavelength of the irradiation and the exposure of the microorganisms to the radiation. UV radiation therefore decreases in efficiency as contamination (especially turbidity and some substances in solution such as iron and organic compounds) increases.

UV disinfection of water is normally achieved by passing the water through tubes lined with UV lamps. This gives efficient disinfection after a contact time of a few seconds. A typical power requirement would be within the range 10-20 W/m³h. The lamps used disinfect using a wavelength of light around 254nm. The lamps may continue to produce blue light when they are worn out and no longer produce disinfecting irradiation.

Disinfection with UV irradiation does not give rise to tastes and odours. There is no requirement for consumable chemicals, maintenance is straight forward and there is no danger of over-dosing. UV irradiation does not leave a residual effect in the water. The equipment and consumables are expensive and water to be treated must be of consistently high clarity.

References

Anon. (1989) *Disinfection of Rural and Small Community Water Supplies: a manual for design and operation*. Water Research Centre. Medmenham, England.

Anon (1996) *Guidelines for Drinking Water Quality Volume III - 2nd edition*. World Health Organization. Geneva.

Tebbut, T.H.Y. (1992) *Principles of Water Quality Control*. 4th edition. Pergamon. Oxford.

Disinfectants and Disinfectant By-Products

Table 1: Summary of C.t values (mg/L. min) for 99% inactivation at 5° C (Clark et al, 1993)

Organism	Disinfectant			
	Free chlorine, pH 6 to 7	Pre-formed chloramine, pH 8 to 9	Chlorine dioxide, pH 6 to 7	Ozone pH 6 to 7
<i>E. coli</i>	0.034-0.05	95-180	0.4-0.75	0.02
Polio virus 1	1.1-2.5	768-3740	0.2-6.7	0.1-0.2
Rotavirus	0.01-0.05	3806-6476	0.2-2.1	0.006-0.06
Bacteriophage f ₂	0.08-0.18	-	-	-
<i>G. lamblia</i> cysts	47->150	-	-	0.5-0.6
<i>G. muris</i> cysts	30-630	-	7.2-18.5	1.8-2.0 ^a
<i>C. parvum</i>	7200 ^b	7200 ^c	78 ^b	5-10 ^c

a Values for 99.9% inactivation at pH 6-9.

b 99% inactivation at pH 7 and 25°C.

c 90% inactivation at pH 7 and 25°C.

Disinfection

Presentation Plan

Section	Key points	OHP
Introduction	<ul style="list-style-type: none"> • all water supplies should ideally be disinfected to inactivate any • pathogens in the water and to provide residual protection • a wide range of disinfectants have been evaluated in the GDWQ • principal disinfectant used world-wide is chlorine, although other • disinfectants such as ozone are also used • chlorinating involves addition of chlorine to water and although there are some health concerns about the use of chlorine, it is generally the disinfectant of choice • other disinfectants include ozone, ultraviolet and iodine • neither ozone or UV provide a residual and both iodine and ozone are carcinogenic • ozone is principal alternative to chlorine, however it does not provide residual protection and affects biological stability possibly increasing the risk of re-growth of bacteria 	OHP 1 Tab. 1
Selection of disinfectant - Chlorine	<ul style="list-style-type: none"> • chlorine is effective provided water is not turbid and the pH is below 8 <p><i>chlorine chemistry</i></p> <ul style="list-style-type: none"> • chlorine dissolves in water to form hypochlorite ion and hypochlorous acid • hypochloric acid dissociates, but hypochlorous acid only partially dissociates • disinfectant is undissociated hypochlorous acid; at high pH dissociated forms predominate and this reduces efficiency • as tends to increase pH and hypochlorite decreases pH; it is important that the pH remains below 8 • chlorine reacts with ammonia to form amine compounds - nitrogen is formed during breakpoint chlorination <p><i>chlorine demand</i></p> <ul style="list-style-type: none"> • the total amount of chlorine in water which reacts with other compounds • chlorine demand varies considerably and is the difference between amount of chlorine added to water and free residual detectable in water 	2, 3, 4, 5

Section	Key Points	OHP
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**Chlorine
(cont.)**

breakpoint chlorination

- this is the usual method of chlorination
- sufficient chlorine is added to satisfy the chlorine demand, then extra chlorine added to provide a residual
- initial rise of breakpoint curve is due to monochloramine formation; subsequent fall is due to decomposition of monochloramine to form nitrogen
- once oxidation of ammonia complete, any additional chlorine leads to an increase in free residual

contact time

- disinfection with chlorine is not instantaneous
- different microbes take different length of time to be inactivated by chlorine, therefore need an adequate contact time; this is usually 30 minutes
- contact time is usually assured by passing piped water through a tank
- contact time is also related to pH

chlorine residual

- residual is required to provide protection against recontamination
- level of residual depends on water supply and local conditions
- there should be 0.5 mg/l free chlorine after 30 minutes contact time
- during outbreaks residuals should be maintained as follows: 0.5 mg/l all points in the supply; 1.0 mg/l at standposts and wells; 2.0 mg/l in tanker trucks at filling

taste and odour problems

- chlorine tastes may cause rejection of water supplies by consumers
- bad tastes generally caused by over-dosing or presence of chlor phenols
- over-dosing may be through error (easy to rectify);
- over-dosing may be deliberate because contamination of supply (cause should identified and remedial action taken); or to ensure residual maintained at remote ends (consider booster chlorination)
- chlor-phenols caused by reaction with phenolic substances, often derived from algae, therefore surface water more likely to give problems than groundwater
- chlor-phenols have strong taste and should improve intake and source to reduce formation
- chlorine can also improve taste by reduction on organics and iron

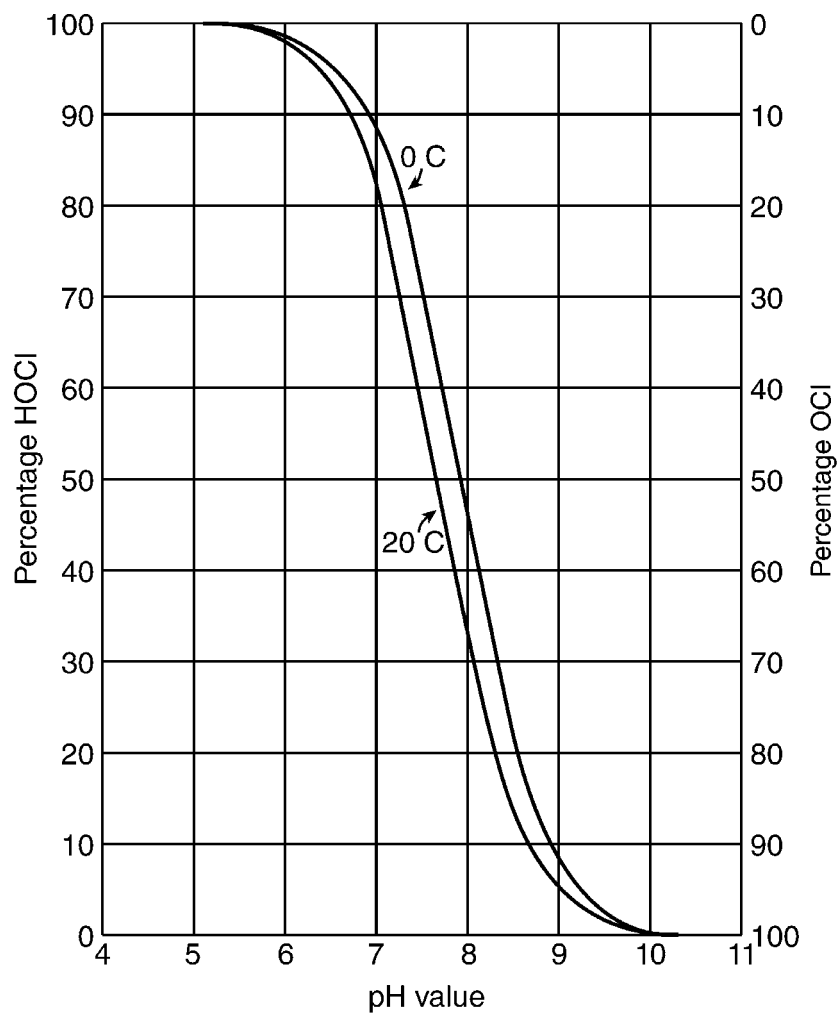
Section	Key Points	OHP
Types of chlorine	<ul style="list-style-type: none"> • chlorine comes in various forms <p><i>calcium hypochlorite</i></p> <ul style="list-style-type: none"> • powder containing 30-70% available chlorine; capital costs are low and commonly used for rural and household disinfection <p><i>sodium hypochlorite</i></p> <ul style="list-style-type: none"> • solution containing 1-18% available chlorine, used for household disinfection <p><i>gaseous chlorine</i></p> <ul style="list-style-type: none"> • pure chlorine gas and most effective and efficient form of chlorine • storage is important and safety measures must be in place 	6
Chlorination approaches	<ul style="list-style-type: none"> • in piped water supplies chlorine is added to ensure that any microbes in water leaving the source/treatment plant are inactivated and to provide a residual protection for the distribution system • under usual circumstances always maintain 0.2-.5 mg/l free chlorine residual • during epidemics or risk of epidemics, residual should be 0.5 mg/l at all points in pipe and 1mg/l at standposts • in point water sources, usually only disinfect during an epidemic or where risk of epidemic great • residual should be 1 mg/l at all times • chlorination may be by direct addition of HTH or by diffusion from a porous pot chlorinator • continuous chlorination of point sources is expensive • it is preferable to identify and remove the source of contamination that to commit to long-term continuous chlorination • household chlorination may also be practised • this involves addition of solutions or tablets in the home • household chlorination is a short-term solution and rarely effective in the long-term • should never place an over-reliance on chlorination alone for treatment of water as can get outbreaks despite adequate disinfection, treatment and source protection are vital • - chlorination efficiency should never be compromised by concerns regarding risks from by-products 	7, 8, 9, 10, 11

Disinfectants Evaluated

- Chlorine
- Chloramine
- Chlorine dioxide
- Ozone
- Iodine



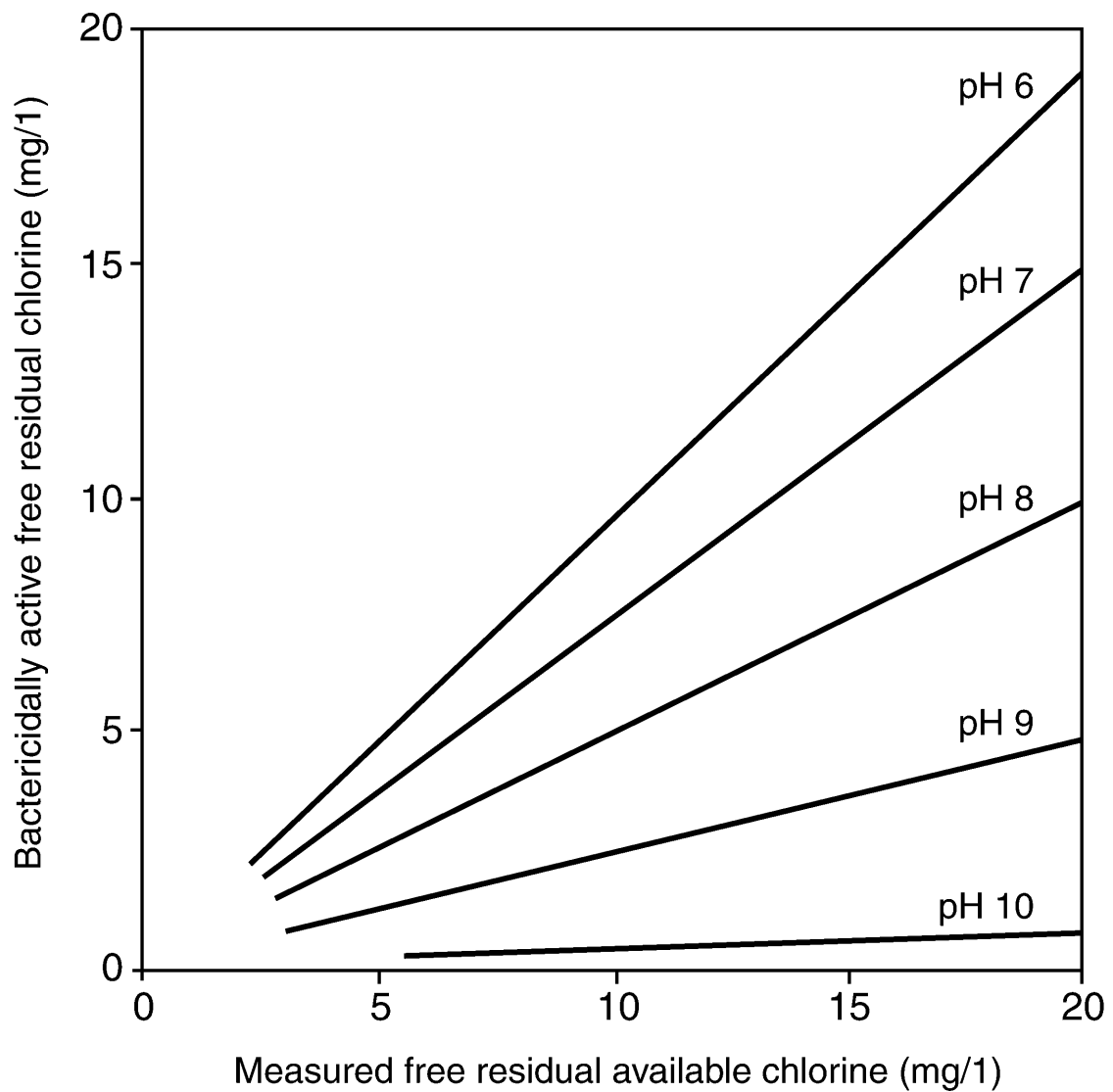
Distribution of Hypochlorous Acid and Hypochlorite Ion in Water at Different pH Values and Temperatures



(Morris, 1951)



Relationship between Measured Free Residual Available Chlorine (HOCl^+ , OCl^-) and Bactericidally Active (HOCl)



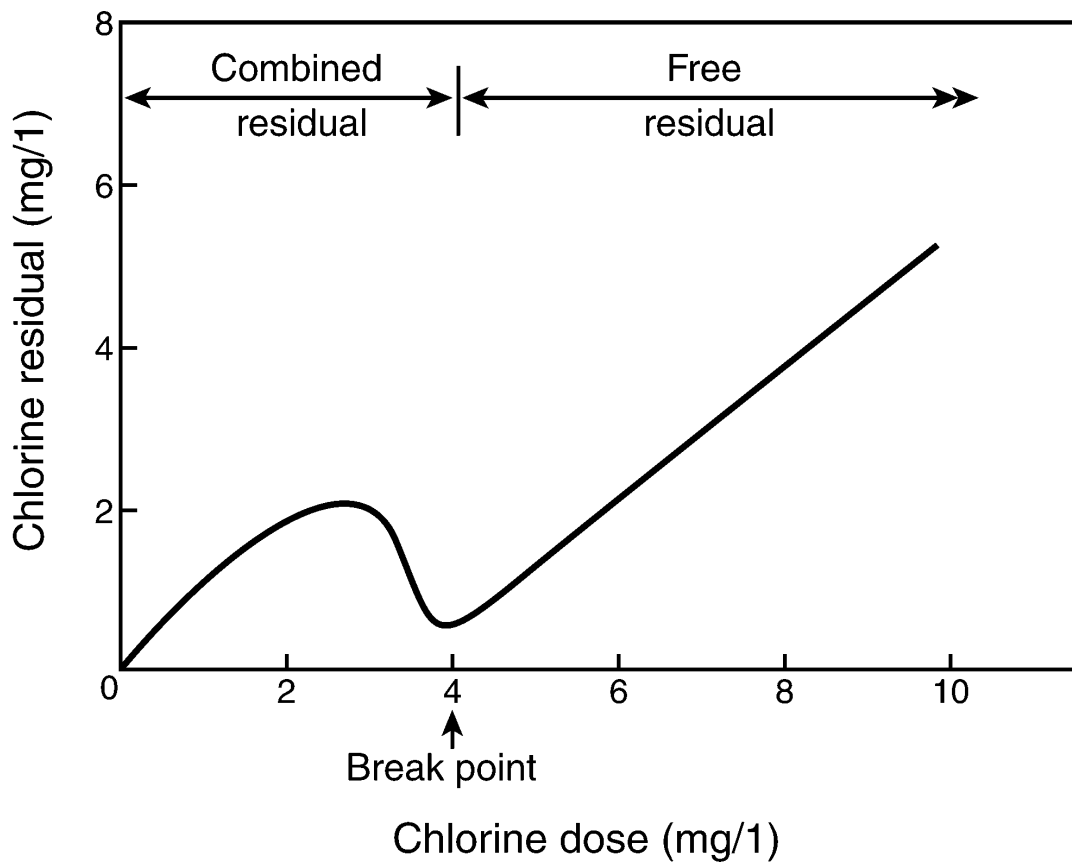
Chlorine Demand

- 1 Make 1% chlorine solution
- 2 Add 6 drops of solution to 1 litre of clean water
- 3 Mix well & leave for 30 minutes
- 4 Free residual should be 1.5-2.0 mg/l, if not either add more drops or dilute with clean water until this range is reached (this is original chlorine)
- 5 Measure out 500 ml into second container
- 6 Add 500 ml of water to be tested, mix well and leave for 30 minutes
- 7 Test water for free residual
- 8 Chlorine demand

$$= \frac{\text{Original chlorine} - \text{Residual chlorine}}{2}$$



Breakpoint Chlorination



Source: Tebbutt, 1992



Types of Chlorine Commonly Available

- Calcium hypochlorite:
 - powder containing 30-70% available chlorine
- Sodium hypochlorite
 - solution containing 1-18% available chlorine
- Gaseous chlorine
 - pure chlorine gas in cylinders



Chlorination in Piped Systems

- Chlorine is added post-treatment/post source
- Maintain a residual at all points in network
- There should always be at least 0.2 mg/l free chlorine
- In time of cholera or other outbreak minimum is 0.5 mg/l in network and 1 mg/l at public standposts
- May get a reduction in residual during storage and distribution
- Therefore may need booster chlorination



Chlorination of Point Sources

- Chlorination usually only in times of outbreak
- Use shock chlorination and maintain free residual of 1 mg/l
- Chlorine may be added by direct addition:
 - HTH
 - Tablets
- Chlorine may also be added through a porous pot diffuser
- Can routinely chlorinate point sources if contamination always present **but** it is preferable to reduce contamination
- Point source chlorination may be difficult and expensive



Household Chlorination

- Only usually done in outbreaks
- May be from tablet dosing or through solution
- Must be supported by health and hygiene education and risk reduction
- Household chlorination is expensive and rarely fully effective
- Household chlorination should be a short-term solution

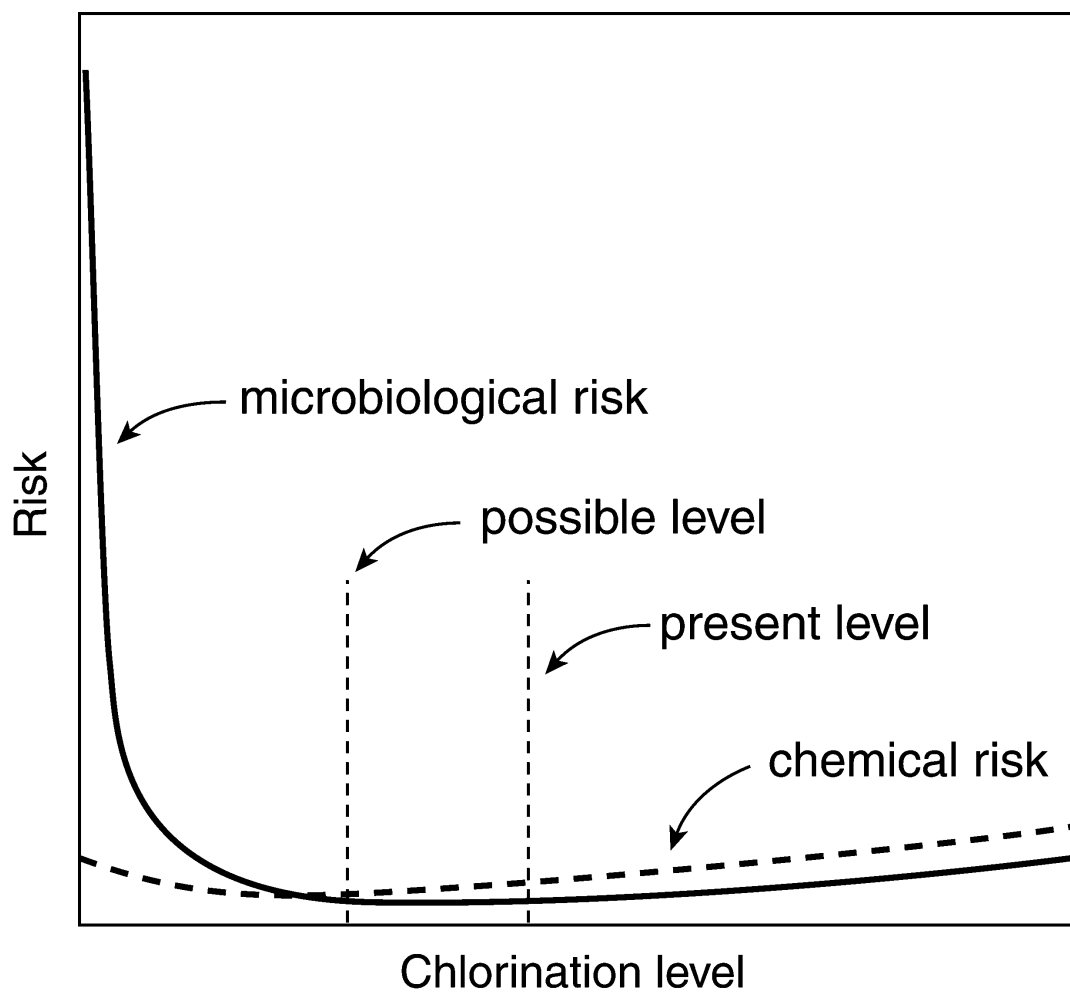


Effectiveness of Disinfection

- 1966 - New Delhi Hepatitis outbreak despite adequate chlorination
- 1966 - Scotland 40-50% Dysentery
S.sonnei/viral. Due to switch failure
- 1961-1970 26,546 cases of GI due to contaminated water supply in U.S.A.
- 1971-1972 5,615 outbreaks of GI due to Rotavirus and Parvovirus in small water supplies
- Paris Poliovirus detected in water supply despite adequate treatment
- U.K. 20% of water sources in Wales have virus contamination



Risks and Benefits of Water Chlorination



(Morris, 1978)

