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47

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1 Introduction

The history of vinyl chloride-associated disease, its recognition and prophylaxis is a classic example of shutting the stable door after the horse has bolted. It should help to emphasize the need to shift our attention to preventing exposure from occurring rather than to reparative measures. *In view of the large number of new and potentially hazardous* chemicals introduced each year into the workplace and the environment, this account should again alert us to the necessity of pretesting chemicals adequately for their potential health effects, even at the risk that technological progress will develop at a more modest rate.

Large-scale production of the synthetic resin polyvinyl chloride (PVC), a thermoplastic material suitable for the most widely diversified industrial use, was begun around 1930 in the United States and in Germany. The monomer, vinyl chloride (VCM), a rather simple aliphatic compound, was believed until the early 1960s to be

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2 Technological Details

2.1 Vinyl Chloride Monomer (VCM)

At standard (ambient) conditions of temperature and pressure, vinyl chloride (CH_2=CHCl: chloroethylene, chloroethene) is a non-irritating, colourless gas with a faintly sweet odour, inflammable at concentrations above 3.8% by volume in air, which is only slightly soluble in water, soluble in ethyl alcohol and easily soluble in ether and carbon tetrachloride. VCM is mainly used as an intermediate in the manufacture of plastics, as a refrigerant and in organic synthesis. It was formerly also employed as a propellant for aerosoles. It is easily liquefied under pressure and is usually handled and shipped as a liquid. Gaseous VCM condenses at −13.8°C and 760 Torr (= 101.3 kPa) to a colourless liquid of low viscosity (*Lefaux* 1966). Its physical properties are listed in Table 1, the most important of which are its low boiling point, its high specific gravity (gaseous VCM is 2.15 times heavier than air), its low solubility in water and the half-life in air, ranging from 3 to 20 h.

Table 1. Physical properties of VCM

Mol. wt.:	62.503					
B. p.:	−13.8°C (−13.7 to −13.9)					
F. p.:	−153.7°C					
Flash point:	−78.5°C (Cleveland open cup)					
Limits of flammability:	3.8%–29.3% by volume in air above −78.5°C (= 38 000–293 000 ppm)					
Autoignition temperature:	472°C					
Vapour pressure:	mm Hg	10	100	692	2300	2660
	°C	−87.5	−55.8	−15.8	+ 20	+ 25
Vapour density:	2.15 g/litre (calculated at 25°C and 760 mmHg (air = 1)					
Sp. gr. of liquid VCM:	0.9121 at −20°C/4°C 0.99 at −25°C/4°C					

Sources: *Fairhall* 1957; *Irish* 1963; *Zapp* 1964; *Lefaux* 1966; *Ostermayer* 1967; *Roubal* 1972.

2.1.1 History

The French chemist, *Regnault* (1835) was apparently the first to study systematically the synthesis and analysis of vinyl chloride. *Liebig*, who had done some earlier preliminary experiments, encouraged *Regnault* to investigate this compound when *Regnault* spent several months in *Liebig*'s laboratories. All compounds containing the vinyl group (CH_2=CH–) polymerize readily (*Fairhall* 1957). Spontaneous polymerization of vinyl chloride to a white opaque solid mass under the influence of sunlight was first described by *Baumann* in 1872; he also quotes a paper by *Sayrsev* and *Glinsky* (who

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2.2 Production of Polyvinyl Chloride (PVC)

2.2.1 Technology of Polymerization

The following description is meant to serve merely as a rough sketch of the procedures and technological details involved in the production of polyvinyl chloride.

Vinyl chloride monomer is polymerized in large autoclaves (reactors) at temperatures between 40°C and 80°C and pressures of 6–16 (8–12) atmospheres. There are usually several reactors (up to 10–30) located in one building. The reactivity of the monomer is a function of its double-bond. The second functional site of the vinyl chloride molecule, the chlorine atom, does not react easily. The double-bond of VCM is not only the site from which the polymerization originates but is also the source of the toxicity and carcinogenicity of this compound when it is being metabolized in the body. The polymerization of VCM, which is a strongly exothermic reaction (*Barnes* 1976), is initiated with the aid of compounds soluble in VCM that form free radicals at relatively low temperatures. Initiators are such compounds as lauroyl peroxide, isopropyl percarbonate, azo-bis-isobutyronitrile, and others. The free radicals react with the double-bond of the monomer, transforming it in turn into a free radical and thus propagating the growth of a chain of molecules with a terminal free radical. Chain growth is interrupted by saturation of the terminal free radical which often involves a reaction between two growing chains (*Malten* and *Zielhuis* 1964; *Lefaux* 1966; *Albright* 1967 a–c; *Dominghaus* 1972; *Slater* 1972). The random character of such termination steps accounts for the production of chains of different length and hence different degrees of polymerization, with molecular weights of the finished PVC being statistically distributed around a mean value.

Commercial PVC polymers have average molecular weights that vary from about 50 000 to 150 000 daltons (*Albright* 1967b). Degree and velocity of polymerization, which are influenced by temperature and the concentration of initiators, determine the specif · type of PVC produced (*Frey* 1973). During polymerization considerable amounts of the monomer are at first dissolved in the polymer, but most of this is later also transformed to PVC as polymerization progresses. The polymer which is not soluble in the liquid monomer precipitates out. The process of polymerization slows down towards the end of the reaction. It is terminated, depending on the method used, when approximately 80%–90% of VCM is polymerized. The timing of this termination of the process is essential for the physical properties of the resins produced. The heat generated during the exothermic process of polymerization must be removed to keep the temperature of the reaction under control. Mechanical agitation aids in transferring the heat across the colloidal system to the cooling jacket of the reactor. During the process of polymerization certain quantities of the polymer adhere to the walls of the reactor and form a slowly thickening continuous film or crust. This polymer crust on the inner surface of the reactor vessel, which contains cavities filled with unreacted monomer, impedes the conductance of heat; it has, therefore, to be cleaned away after termination of the batch process (*Barnes* 1976).

After completion of the polymerization process, the slurry is released from the reactor into a dump tank. Residual unreacted vinyl chloride monomer is partly solvated in the polymer (about 10%); the remainder is dispersed in the water phase or is present

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Solution Polymerization. This type of precipitation polymerization is carried out in organic solvents such as *n*-butane or cyclohexane. It accounts for only a small percentage of the total amount of all PVC resins produced and it is used for the production of copolymers. Copolymers are mixtures of comonomers (such as vinyl acetate, vinylstearate, vinylidene chloride, propylene, acrylonitrile etc.) and vinyl chloride. The comonomers tend to improve flexibility and limited solubility of the product in solvents and exert an influence on the temperatures required for compounding.

2.2.3 Compounding

As a next step, depending on the end use, the dried polymer, a whitish powdery or granular product, is then compounded (or dry blended) under pressure at fusion temperature with the aid of plasticizers (mainly phthalate or other organic esters) and light and heat stabilizers (heavy metal salts, organotin compounds, and other stabilizers). Lubricants or dyes can be added. Plasticizers are added for the production of flexible PVC; rigid PVC contains little or no plasticizer. These additives can also be a source of toxicity. The plasticizers may slowly diffuse out of the final product depending on its compatibility. Lead-containing stabilizers may also pollute the working atmosphere (*Smolčić* 1966; *Tola* 1975). Compounding is carried out by hot mixing at fusion temperatures below or within the softening range (120°C–160°C). Diversified compounding and processing technologies were developed about 1950.

The compounded polymers are used for the production of diverse end-products. The final conversion of the thermoplastic PVC resins into consumer end-products is accomplished by such procedures as extruding, calendering, injection or compression moulding, blow moulding, dipping (coating) and hot spraying. Temperatures used in these processes range from 100°C to 300°C. End-products include a vast number of articles used in almost every sphere of daily life. The temperatures during the fabrication operations (compounding and conversion of compound polymer into consumer articles) drive off part of the small concentrations of residual monomer still contained in the polymer. *Barnes* (1976) calculated that the final fabricated articles contained approximately 5 ppm VCM and those for foodstuff packaging (bottles, films, foils) even less.

2.2.4 Sources of Exposure to VCM in PVC Production

Both polymerization of VCM and subsequent processing (centrifuging, drying, screening, bagging) are usually carried out in closed buildings. Exceptions can be found in hot climates (*Aryanpur* 1977). Polymerization is of necessity a batch process that requires a large number of single operations. Therefore, valves, gaskets, shaft-openings and control gear are subject to heavy wear and thus to leakage. Other sources of pollution of the working atmosphere are exchange of parts and repair jobs. The degree of pollution also depends to a large extent on the quality and effectivity of monitoring equipment and special exhaust systems. Opening of autoclave vats for cleaning and control purposes resulted in larger spill-over of the tank atmosphere into the work environment. Numerous reports of workers with prenarcotic symptoms (dizziness etc.)

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States was almost completely destroyed when VCM escaping from a leak detonated (*Albright* 1967a). Another explosion in one of the two Rumanian factories operating at that time was mentioned by *Suciu* et al. (1975). Monitoring of VCM concentrations polluting the work environment was then directed largely towards preventing VCM from reaching the flammability limit.

2.2.6 The Odour Threshold

Unfortunately, gaseous VCM has no irritating or unpleasant warning properties. Its mild odour is described as faintly pleasant, sweet or ethereal. Some of the PVC workers we interviewed reported that they had even enjoyed 'sniffing the gas', which soon resulted in a feeling of light-headedness. For the early days of PVC production, when appropriately sensitive monitoring equipment was not yet available, workers' reports about perception of the odour of VCM can be taken as circumstantial evidence for a rough estimate of the actual degree of exposure. It should be kept in mind, however, that in chemical production units the presence of other odoriferous chemicals and the possibility of olfactory fatigue, as well as different levels of individual sensitivity, may render it very difficult to determine the factual odour threshold of a certain gaseous substance unless it possesses irritating warning properties.

In 1929, *Schmidt* and *Schaumann* declared that the faintly sweet gas is practically odourless at concentrations of 5%–10% by volume. *Veltman* and *Lange* (1977a, b) assumed an odour threshold of 5 000–10 000 ppm. Volunteers exposed to VCM detected a slight odour at 4 100 ppm; a distinct odour was noted at 6 600 ppm for 30 min and this was accompanied by subjective symptoms of dizziness and sleepiness (*Irish* 1963). *Gehring* et al. (1979) recently mentioned a threshold of approximately 3500 ppm. Others have claimed that a concentration of 400–500 ppm is the lower limit for detection of VCM by its odour (*Baretta* et al. 1969; *Cook* et al. 1971; *Markowitz* et al. 1972; *Lefèvre* 1975, cited by *Hublet* 1975). *Baretta* et al. (1969) conducted experiments with concentrations of 50, 250 and 500 ppm in an exposure chamber, in which 13 volunteers participated. At 500 ppm only some of them claimed that they were able to detect the odour, but this was inconstant. Table 3 shows that differences between the various estimates are at least one order of magnitude. The close proximity between the perception of the odour of VCM and incipient CNS symptoms as reported by *Irish* (1963), however, makes it likely that the actual odour threshold can be assumed at or above 4000 ppm.

In contrast to VCM, the comonomer vinyl acetate, for instance, has distinct warning properties and can be detected by its odour at a level as low as 0.4 ppm; eye and throat irritation begin upward of 5 ppm and are noted by all test subjects at a concentration of 21.6 ppm (*Deese* and *Joyner* 1969).

2.2.7 VCM as an Anaesthetic Agent

VCM was once even considered for use as an anaesthetic agent. In 1929, *Schmidt* and *Schaumann* speculated about using VCM as a supplementary narcotic at concentrations of 3%–5% (v/v) (= 30 000–50 000 ppm) in combined nitrogen oxide oxygen

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Table 4 Individual responses of volunteers to increasing concentrations of VCM

Concentration	Duration of exposure	Symptoms	Reference
500 ppm	7.5 h	(Inconstant odour detection) mild headache, dryness of eyes and throat in 2 of 7 subjects)	*Buretta* et al. (1969)
~4 000 ppm	–	Generally accepted odour threshold	*Irish* (1963)
6 600 ppm	30 min	(Distinct odour) dizziness, sleepiness	*Irish* (1963)
8 000 ppm	5 min[a] (twice on each of 3 successive days)	2 of 6 subjects 'slightly heady'	*Lester* et al. (1963)
12 000 ppm		1 of 6 subjects had reeling, swimming head, 'just like getting gas'	
16 000 ppm		5 of 6 subjects, various degrees of intoxication	
20 000 ppm		All 6 subjects had more intense symptoms of acute intoxication than at 16 000 ppm	
25 000 ppm	3 min	2 experimenters: dizziness, disorientation, burning sensation in the soles of the feet	*Patty* et al. (1963)

[a] Exposure to six different concentrations: 0 ppm; 4 000 ppm; 8 000 ppm; 12 000 ppm; 16 000 ppm; 20 000 ppm

through which non-polymerized residual VCM was pumped back into a reserve tank; another man coming to his rescue was himself overcome by the gas and only just escaped.

Two non-fatal cases of VCM gassing were reported in Great Britain in 1951 (*Spurtas* et al. 1975). A maintenance worker experienced acute narcosis while repairing a VCM leak, and a worker cleaning a polymerization vat from outside with a water jet suddenly collapsed across the open manhole. Subsequently he complained about tightness of the chest, nausea, abdominal pain and headache. Occasional loss of consciousness was also reported by *Lilis* et al. (1975) in 14 of 354 workers at Niagara Falls and by *Suciu* et al. (1963) at a Rumanian plant. VCM-induced narcosis, at least on one occasion in the past, had occurred in 46 of 58 workers (79%) referred for medical surveillance from one British PVC-producing plant (*Ward* et al. 1976), with a 100% incidence of narcosis in 28 symptomatic workers (Raynaud's syndrome and/or acroosteolysis). Successful resuscitation after VCM-induced narcosis of several hours' duration without evidence of permanent damage was mentioned by *Rety* et al. (1974).

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away from reactor walls during cleaning was placed, concentrations of up to 600 ppm were measured.

In the report of a World Health Organization (WHO) working group on vinyl chloride (IARC 1974) it was stated that in a reactor of 15 m^3 (production of 4–5 tons of PVC per cycle) a crust of 4 kg PVC containing 3%–5% VCM can be formed on the inner surface. During the cleaning procedure 30%–50% of this VCM content is liberated. It was calculated that the probable concentration of VCM within the reactor after a 1-h cleaning operation was about 2700 ppm, but that it could be reduced to 90 ppm by 30 renewals of air per hour. In the past a polycleaner used to spend 4–5 h/day inside the reactor but later the introduction of (not fully sufficient) automated cleaning reduced manual cleaning procedures to shorter periods of 10–15 min following every 20th–30th reactor cycle. A Belgian company, where monitoring in the working area was started in 1967, claimed that measurements at various sites inside a 9000-litre autoclave during the manual cleaning operations had shown VCM concentrations varying between 50 and approximately 540 ppm, with a mean of 413 ppm (*Hublet* et al. 1977). According to data provided by *Cook* et al. (1971), VCM concentrations within the reactors prior to ventilation were in the order of 3000 ppm. The reactor cleaners usually did not enter the autoclaves until an aeration period of 15–20 min had reduced the VCM concentration to what was considered satisfactory limits. In the early days, this was tested either by 'sniffing at the manhole opening' (the lower limit of detection of VCM by its odour having then been accepted as 400 ppm) or by use of a flammable vapour indicator which required a minimum of 400 ppm for positive readings, equalling 4% of the lower explosive limit of VCM. Later more sensitive methods such as gas chromatography were said to have shown that VCM concentrations inside the reactors tended to be below 100 ppm during cleaning operations, but VCM released from the residue during scraping resulted in concentrations of 600–1000 ppm measured close to the hand.

The Dow Chemical Company started monitoring the work environment in 1950 by means of grab samples; continuous monitoring was installed in 1959. While time-weighted average (TWA) concentrations ranged from 10 to 385 ppm during this period (1950–1959), excursions up to 4000 ppm occurred, agreeing with employees' reports of experiencing dizziness while loading or unloading reactors (*Ott* et al. 1975). In a second unit with modernized equipment excursions up to 600–1300 ppm still occurred during the period of 1953–1959. In 1959, when toxicological data indicating adverse effects in animals exposed to 100–500 ppm VCM had become available (*Torkelson* et al. 1961), the Dow Chemical Company introduced a new 50 ppm guideline for the work environment. Excursions and peaks up to 500 ppm did continue. Measurements of TWA exposures for various specified job categories in two production units of this plant between 1950 and 1966 were presented by *Ott* et al. (1975). In 1968 BASF (West Germany) introduced continuous monitoring by infrared absorption spectrophotometry for VCM concentrations well below 500 ppm; in 1974 more sensitive equipment was installed and concentrations were kept below 25 ppm and later below 10 ppm, with occasional ceiling values of 70 ppm (*Fleig and Thiess* 1974).

In several surveys individual jobs were grouped into three exposure categories according to job classification to evaluate past exposure experiences (*Spirtas* et al. 1975; *Williams* et al. 1976; *Blendis* et al. 1978). These exposure indices were: (a) light = less

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was reported to have been as high as 6000–7000 ppm (w/w) in some types of raw PVC, but a level of 500–1000 ppm probably was a more representative range (*Schweitzer* 1975; VKE 1974; *Karstadt* 1976). The monomer slowly escapes into the environment exponentially with time. Depending on length of storage period, temperature, size and porosity of particles and other physical properties of the polymer and, more recently, on the effectivity of special degassing techniques (*Piver* 1976; *Schutz* and *Wolf* 1977). In 1975, the Association of the German Plastics Industry announced that in future only PVC powder with a maximum monomer content of 10 ppm would be put on the market due to the development of special degassing technologies (VKE 1975). Analyses of the types of raw PVC, chiefly suspension polymer, which are now used in German plants showed that in most products the content of unreacted monomer was now less than 20 ppm but in some foreign products it still ranged between 150 and 250 ppm; it also turned out that there may be considerable variation between different batches of the same product (*Schutz* and *Wolf* 1977).

Cold and particularly hot mixing or compounding of PVC, a procedure which usually precedes fabricating processes, favours the escape of unreacted monomer and, therefore, requires special ventilation equipment. Depending on the content of residual monomer, considerable amounts of VCM could be set free during the mixing process, as was shown by *Brüder* and *Straby* (1975). Apart from hot compounding, other thermoplastic operations, such as extruding, calendering and welding of tiles, also resulted in release of unreacted monomer into the work environment. Although recently conducted measurements of the concentration of VCM in working areas of six German PVC fabricating plants have shown that in 90% of the readings mean levels integrated over 1-h periods now range below 0.1 ppm, numerous short bursts with excursions up to 60 ppm during a workshift were recorded in one instance (*Schütz* and *Wolf* 1977). Similarly low concentrations of VCM in breathing zone samples (maximum: 12 ppm) with 60% of the values ranging below 1 ppm had been found in 1974 in nine United States fabricating plants, but source samples had ranged up to 340–540 ppm (*Karstadt* 1976).

These present results, however, do not permit any conclusions as to past levels of atmospheric VCM during the years when residual monomer content of PVC resins was high and ventilation insufficient, particularly in compounding and extruding units. Whatever the extent of the risk might have been in the past, it can be safely assumed that the ambient monomer concentrations in fabricating plants have always been considerably lower than in PVC-producing plants.

When it was suspected that certain VCM-related symptoms might also have afflicted PVC process workers, this problem was investigated by our group. Although no cases of acroosteolysis, pseudoscleroderma or angiosarcoma of the liver were observed, evidence was presented which demonstrated that minor and inconspicuous lesions such as mild hepatic fibrosis, bromsulphalein (BSP) retention, thrombocytopenia and slight enlargement of the spleen could be found in 28 process workers who had been employed for years in compounding and fabricating units (*Lange* et al. 1975, 1976a; *Wegman* 1975; *Marsteller* et al. 1976). In principle, these lesions were identical with those seen after heavy exposure as we will describe, but the degree of damage attributable to occupational VCM exposure observed in these workers was not considered sufficient to entitle them to disability compensation under German law. Although the in-

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in 1970 in conformity with the proposal of *Torkelson* et al. (1961), which was based on the results of their animal experiments. In June 1974, when the carcinogenic properties of VCM had been well established, the MAK regulation for this chemical was repealed and instead a preliminary technical guideline (Technische Richtkonzentration) of 50 ppm was instituted (VKE 1975). The Chemical Industries' Liability Insurance Association (Berufsgenossenschaft der Chemischen Industrie) also issued instructions for the prevention of health hazards arising from handling of VCM in July 1974. As of July 1975, a technical guideline (TRK = Technische Richtkonzentration) of 5 ppm, defined as annual mean, for PVC-producing and -fabricating plants was instituted, permitting excursions up to 15 ppm during periods of not more than 1 h. In order to adapt operating plants, a provisional regulation was issued with reduction of the annual mean concentration to 20 ppm as of July 1975, and to 10 ppm as of July 1976 and peak concentrations over 1-h periods not exceeding 60 or 30 ppm, respectively (*Veltman* and *Lange* 1977a). The technical guideline (TRK value) was revised in 1977 (2 ppm annual mean/5 ppm per 1 h).

In the United States the threshold limit value for VCM was originally set at 500 ppm in 1947. It was reduced to 50 ppm in April 1974 as a temporary emergency standard and finally reduced to 1 ppm/8 h in 1976. *Haley* (1975) summarized the conflicting views on vinyl chloride regulations proposed by Government and industry in 1974. Table 6 shows threshold limit values in a number of PVC-producing countries.

2.2.12 Exposure to VCM Outside the Working Area

The Environmental Protection Agency estimated that PVC-producing plants in the United States discharged about 90 million kg VCM annually into the environment (4%–8% losses), most of it as air emissions and lesser quantities dissolved in water effluent streams and entrapped in sludge and solid wastes (*Schweitzer* 1975). In a pioneer study, concentrations of 1–2 ppm VCM were found in the ambient air near such a plant (IARC 1974), 2–3 ppm in the primary water effluent and 100–200 ppm in the sludge at the plant site, but sampling and analysis methods used were later found to have been inadequate so no conclusions were drawn from these figures since they could have been in error by as much as one order of magnitude (*Schweitzer* 1975). For people who live within 5 miles of monomer and polymer production facilities in the United States an average exposure of 17 ppb during the years of uncontrolled emissions was calculated (*Nicholson* 1977).

In the past VCM has been widely used as an aerosol propellant, either alone or mixed with fluorocarbons, hydrocarbons and inert organic gases, in household and cosmetic products (hair sprays, deodorants, pesticides, room disinfectants, paint sprays, furniture polish and window cleaners). In Germany, VCM was proposed as propellant for aerosols in 1958 (*Ostermayer* 1967), in Japan it has been used as a propellant since 1958, in the United States this use was probably introduced after 1962 (*Schweitzer* 1975). As an aerosol propellant, VCM has been a possible source of exposure for the public at large, particularly for women, the extent and the potential health implications of which are unknown. Use of aerosol products in confined spaces has been reported to result in air concentrations of VCM of up to 400 ppm in closed rooms, even after only short bursts (30 s) (*Gay* et al. 1975), which could persist for several

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Sources: *Sc* 73; IARC R 1977; *Schu*

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hours after repeated spraying in smaller-sized rooms (IARC 1974). *Haley* (1975) presented a list of pesticide products containing VCM as a propellant and registered for indoor use, which were banned in 1974 by the Food and Drug Administration. In Japan, the monomer was also banned as a propellant in 1974 (JAMA 1974, 229:855). There is a case on record of a worker who died from noncirrhotic portal hypertension and angiosarcoma of the liver after 14 years' employment at a chemical plant in southern Germany where he had been engaged in loading such pesticide cans (*Reinl* and *Weber* 1974). The report of a female office worker suffering from typical Raynaud's phenomenon, pseudoscleroderma, acroosteolysis and mandibular osteolysis who never had occupational contact with VCM (*Meyerson* and *Meier* 1972) is apt to make one wonder what influence the frequent indoor use of VCM-propelled spray cans (*Bridbord* et al. 1975) may have had in this unique case. Sputum samples collected from frequent users of pressurized spray cans who had no respiratory symptoms were found to contain a significant excess of moderate and marked atypical metaplastic bronchial cells compared with two groups of controls (*Good* et al. 1975).

PVC bottles, films and foils have been used for many years for packaging food and beverages (cooking oil, margarine, meat, mineral water, fruit squashes and other soft drinks, hard liquor etc.). The content of residual VCM in PVC bottles was found to have ranged formerly between 5 and 400 ppm (w/w), and in PVC foils up to 800 ppm (*van Esch* and *van Logten* 1975). The problem of migration of unreacted VCM from the PVC containers into the foodstuffs became recognized in 1973. Reports of unpleasant tastes in American brands of vodka and whisky which had been stored in PVC bottles led to the discovery that VCM had leaked into the liquors; in some samples levels up to 10–20 ppm (w/w) were found (*van Esch* and *van Logten* 1975; *Davies* and *Perry* 1975). Data available in 1974 to a group of WHO experts revealed that samples of gin and whisky had contained 0.57 and 0.62 ppm (w/w) of VCM respectively, after storage in miniature PVC bottles for periods up to 3 years; VCM concentrations in orange squash and cooking oil were found to be in the range of 0.01–0.08 ppm and 0.01–0.04 ppm, respectively (IARC 1974). Levels of 0–0.4 ppm found in British PVC-bottled liquids were mentioned by *Davies* and *Perry* (1975); in their own analyses of samples of PVC-bottled spirits supplied by British Airways they found concentrations of 0–0.25 ppm (w/w). Methods were developed for the detection of VCM in liquids with a maximum sensitivity down to the 1 ppb level (*van Lierop* and *Stek* 1976; *Dressman* and *McFarren* 1977). It was tentatively estimated that even during the years when PVC-packaged food and beverages had not been heeded as a potential source of contamination, the likely average daily human intake of VCM from this source could have been in the order of 0.1 mg/person (IARC 1974). *Schlatter* (1976) calculated that today it would be less than 0.01 mg/person (equalling 250 mg during a whole life time); in comparison, he calculated that the inhalational intake of VCM in diseased workers who had been exposed to concentrations of 500–1000 ppm during a period of 10–20 years would have amounted to at least 25 kg. The Association of the German Plastics Industry expects that the use of technology available at present for the production of PVC food-packaging materials decreases the VCM content of foodstuffs to below 50 µg/kg (50 ppb) even after prolonged storage (VKE 1975). Results of carcinogenicity assays in experimental animals after oral administration of VCM are discussed in Sect. 3.3.

3 Toxicology o

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revealed lesions similar to human acroosteolysis and also similar to the type of non-tumorous liver diseases which we observed in PVC workers 3 years later (*Marsteller* et al. 1973). *Viola* described lesions of the skin, the small arterial vessels, the connective tissue and elastic reticulum of the paws, and periosteal proliferation with chondroid metaplasis of metatarsal bones. Fibrosis of small peripheral nerves and degenerative changes of the grey and white matter of the brain were prominent, whereas the kidneys were not markedly affected. The liver showed pronounced degenerative lesions with parenchymal necrosis, cytoplasmic and nuclear polymorphism, abnormal proliferation of hypertrophic Kupffer cells and intense fibrosclerotic reactions.

3.3 Oncogenic Properties

The earliest documentation of the carcinogenic action of VCM was *Viola*'s preliminary report presented at the 10th International Cancer Congress in Houston, Texas in May 1970a. Of 26 Wistar rats exposed to 30 000 ppm for 12 months 17 developed epidermoid carcinoma, mostly in the paraauricular region; 6 also developed adenocarcinoma of the lungs and 5 osteochondroma of metacarpal and metatarsal regions of all 4 limbs (*Viola* et al. 1971; *Viola* 1974). *Maltoni* and *Lefemine* (1975) later interpreted these paraauricular tumours as arising from the sebaceous glands of the exterior acoustic duct, also known as Zymbal's glands, the cell matrix of which seems to be the target tissue of a number of carcinogens. They were of the opinion that the pulmonary malignancies were metastases from the Zymbal gland tumours. Autoradiograms of sections of whole rats dosed orally with [^{14}C]-labelled VCM revealed a discrete localization of ^{14}C in the paraauricular region (Zymbal gland?) and in the region of salivary glands and Harder's glands (*Green* and *Hathway* 1975). In this context *Neumann* et al. (1979), who analysed the peroxidase activity in Zymbal glands of Wistar rats, proposed the concept that peroxidase-mediated bioactivation of carcinogens (in their study: stilbene derivatives) might offer an explanation for these tissue-specific effects.

At the end of 1970 *Maltoni* and his group, with the support of Italian, British, Belgian and French chemical companies, started to plan and subsequently execute a large-scale carcinogenicity bioassay designed to study the effects of chronic exposure to VCM in relation to various experimental factors such as route of administration, dose level, length of treatment, and species, strain, sex and age of animals (*Maltoni* 1973, 1977; *Maltoni* and *Lefemine* 1974a, b, 1975; *Maltoni* et al. 1974a, 1975). Concentrations used in the inhalation experiments were 30 000, 10 000, 6000, 2500, 500, 250 and 50 ppm, with length of exposure ranging up to 52 weeks and observation periods up to 143 weeks. Apart from the induction of Zymbal gland carcinoma other malignancies developed, notably angiosarcoma of the liver but also extrahepatic angiosarcomas, nephroblastomas, pulmonary tumours and mammary carcinoma, as well as a number of single tumours of other target tissues. Different types of tumours were found to coexist in the same animal. On oral administration of VCM dissolved in olive oil (5 days/week) angiosarcoma of the liver was found after 50 weeks in two animals of the two groups of 80 Sprague-Dawley rats each of which had been treated with the highest doses of 50 and 16.65 mg/kg body wt. (*Maltoni* et al. 1975). *Maltoni* (1977) succeeded in demonstrating that the route of administration of this clearly multipo-

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was found in an animal exposed to 500 ppm. A few mammary adenocarcinomas, one rhabdomyosarcoma and one renal haemangiosarcoma were also seen. From their experiments *Holmberg* et al. concluded that a lower exposure over a longer period may intensify the cancerogenic response and that an inverted relationship between dose level and latency time seems to exist in the case of VCM, as had already been observed with other carcinogens. Recently the results of still another animal experiment with exposure of Wistar rats to 5000 ppm, 7 h/day, 5 days/week, for 52 months was published by *Feron* et al. (1979a, b; *Feron* and *Kroes* 1979) in an eventually fruitless attempt to elaborate suitable parameters for early detection of VCM-disease in man. Early effects were a shortening of blood clotting time and the occurrence of swollen and malformed hepatocytic mitochondria. At a later stage progessive tubulonephrotic changes in the kidneys, foci of celular alterations in the liver with reduced glucose-6-phosphatase activity in hepatocytes, strong sinusoidal activity of alkaline phosphatase and increase of smooth endoplasmic reticulum in parenchymal liver cells were observed. In the final stage areas of necrosis in the liver parenchyma, focal dilatation of sinusoids and proliferation of normal and atypical sinusoidal cells, multicentric hepatic angiosarcoma and Zymbal gland carcinoma occurred. *Feron* et al. (1979b) also observed hepatocellular carcinoma in three animals. Surprisingly, the induction of very malignant metastasizing carcinomas of the nasal cavity originating from the olfactory epithelium and Bowman's gland was noted, which had not been reported before in connection with VCM. Marked hepatic fibrosis was only seen within fully developed angiosarcoma or as a reaction to extensive necrosis of the hepatic parenchyma. The investigators were of the opinion that hepatic parenchymal changes preceded those of the hepatic stroma, but they stressed the fact that the true relationship between VCM-induced alterations of hepatocytes and sinusoidal cells has yet to be elucidated.

3.4 Toxicodynamics

Prior to 1974 very little information was available about the fate and the toxicodynamics of VCM in the mammalian organism, but the discovery of VCM-induced angiosarcoma of the liver in humans and experimental animals provoked a large number of studies which resulted in a flood of publications on the metabolism of VCM.

In 1934 *Schaumann* reported that in mammals unchanged VCM was excreted via the lungs after inhalational administration; the pulmonary route is the main excretory route of nonmetabolized VCM (*Green* and *Hathway* 1975). Blocking of nonprotein sulphydryl groups in the blood of vinyl chloride operatives, less pronounced after discontinuous contact, was observed as early as 1964 by *Gabor* et al. and indicated depletion of the glutathione pool, which has since also been found in exposed rats (*Hefner* et al. 1975a). Hepatic glutathione plays a fundamental role in protecting tissues against attack by alkylating agents. The appearance of monochloroacetic acid in the urine of workers exposed to VCM was reported in 1966 by *Grigorescu* and *Toba*, indicating that a polar excretable metabolite of VCM had been formed (*Vainio* 1978).

Toxicodynamic studies have revealed that *VCM per se* is *not* the ultimate toxin or carcinogenic. It is the process of biotransformation (metabolic activation) of VCM, primarily by hepatic microsomal enzymes (mixed function oxidases) that yields short-

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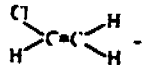
Total radioactivity 48 h after a single exposure decreased considerably in these organs, in accordance with the relatively rapid metabolization of VCM and excretion of its polar metabolites. In contrast, the amount of irreversibly protein-bound radioactivity remained constant during this time. *Buchter* et al. (1977) also showed that unmetabolized VCM possesses a great affinity for adipose tissue, in contrast to its metabolites, which are concentrated primarily in liver and kidneys.

3.4.2 Metabolism

3.4.2.1 Relation between Chemical Structure, Reactivity and Mutagenic or Carcinogenic Effect

Before discussing the metabolic pathways of VCM (monochloroethylene) and its presumptive toxic intermediates two features of the chemical structure of this compound should be mentioned. Vinyl chloride is a *monohalogenated* ethylene and its chlorine substitution is *asymmetric*. Chlorination of alkenes (olefinic compounds), in general, tends to stabilize the double bond by exerting an electron withdrawal effect on the carbon atom involved. Thus, the chemical reactivity of alkenes decreases with increasing degree of chlorine substitution, as was shown in 1968 by *Williamson* and *Cvetanović* for reaction rates with ozone. Vinyl chloride, as a monohalogenated alkene, is the least stable compound with the highest reaction rate in the series of chlorinated ethylenes and ranks next to unsubstituted ethylene.

Secondly, the first step in the oxidative metabolism of all chlorinated alkenes is a transformation to epoxides (oxiranes) which are short-lived, highly reactive electrophilic intermediates (*Bonse* et al. 1975; *Henschler* 1977b). Such chlorinated epoxides may react, by alkylation, with essential cellular constituents, a mechanism which *Rannug* et al. (1974), *Bartsch* et al. (1975a, b) and *Malaveille* et al. (1975) claimed to be responsible for the carcinogenic and mutagenic effects of VCM and vinylidene chloride. Epoxides resulting from biotransformation of *asymmetrically* substituted ethylenes, such as VCM, vinylidene chloride and trichloroethylene, seem to be particularly unstable with increased electrophilicity and thus enhanced alkylating effect. Their mutagenicity and, inversely, the nonmutagenicity of oxiranes of symmetrically chlorine-substituted ethylenes was indicated by the studies of *Greim* et al. (1975, 1977).



VCM

3.4.2.2 Metabolic Pathways

From 1974 onwards the fate of VCM has been studied extensively in vitro with rat liver microsomes in the presence of a NADPH-generating system (*Kappus* et al. 1975, 1976; *Bartsch* et al. 1975b, 1976; *Malaveille* et al. 1975; *Bolt* et al. 1976a; *Pessayre* et al. 1979), with the aid of isolated perfused liver preparations (*Radwan* and *Henschler* 1975; *Bonse* et al. 1975; *Radwan* 1977; *Henschler* 1977a) and in vivo (*Hefner* et al. 1975a; *Watanabe* et al. 1976d, 1978a, b; *Bolt* et al. 1977a, b) in both control animals and animals pretreated with various types of enzyme-inducing and enzyme-inhibiting substances.

Present biochemical knowledge strongly suggests that the first step of the predominant metabolic pathway is the oxidation of the double-bond of VCM by the hepatic

Fig. 1. Metab

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level of hepatic nonprotein sulphydryl content has been observed in rats after exposure to VCM in concentrations from 150 to 2000 ppm for 2–7 h. No depression was seen after 10 ppm and a concentration of 50 ppm caused only an inconsistent reduction (*Watanabe* et al. 1976b). Protein-bound hepatic sulphydryl content remained unaffected. Hepatic microsomal cytochrome P_{450}, the coenzyme of microsomal monooxigenases, also decreases linearly with time in animals exposed to VCM (*Reynolds* et al. 1975b). This destruction of cytochrome P_{450} may prevent further metabolism and toxicity of VCM (*Pessayre* et al. 1979).

Another mode of deactivation of the primary reactive intermediate, the epoxide, is its transformation to the inactive dihydrodiol by the inducible microsomal enzyme epoxide hydrase.

The reactive metabolite of VCM, chloroethylene oxide, is a powerful alkylating agent which covalently binds to various cellular macromolecules, notably vital proteins and nucleic acids. By binding to cellular DNA and RNA or critical proteins the metabolite may alter vital functions and the genetic information of the cell and thus exert its hepatotoxic, mutagenic and carcinogenic effect. Eventually, however, the only fraction of the formed epoxide that binds to macromolecules is the one that is not detoxified by protective scavenging mechanisms such as conjugation with cytosolic glutathione or inactivation by epoxide hydrase. Simultaneous presence of other xenobiotics which have to be detoxified will impair the effectiveness of the detoxification mechanisms. In assessing the risk of exposure to VCM, *Henschler* (1977a) concluded that there might be a greater risk in intermittent peak exposures over brief periods than might be expected from simple integration over time and that the chances for effective detoxification are greater in long-term exposure to relatively low levels.

It was shown by *Watanabe* et al. (1978a) that repeated exposures of rats to VCM do not appear to induce its biotransformation, but significantly augment the binding of the reactive metabolite with hepatic macromolecules and may thus enhance the potential toxicity of VCM. On single exposures of rats to increasing concentrations of labelled VCM ranging from 1 ppm to 5000 ppm, the amount of radioactivity covalently bound to hepatic macromolecules did not increase proportionately to the increase in concentration but followed a sigmoid curve with low and high inflection points below 50 ppm and above 250 ppm, respectively, when binding was plotted as a function of the log of the exposure concentration (*Watanabe* et al. 1978b). This correlates well with *Maltoni*'s report (1975) of a linear percentage induction of hepatic angiosarcoma in rats between 50 ppm and 500 ppm when expressed as the log of the exposure concentration.

Metabolites of VCM can alkylate nucleic acids, a commonly accepted mechanism for carcinogenesis. Covalent binding to the adenosine (*Barbin* et al. 1975; *Laib* and *Bolt* 1977), cytidine (*Laib* and *Bolt* 1978), and guanine moiety of nucleic acids (*Ostermann-Golkar* et al. 1977) has been described. But the degree of covalent binding of electrophilic metabolites of labelled VCM to hepatic nucleic acids seems to be very small (*Watanabe* et al. 1978b; *Laib* and *Bolt* 1977). *Laib* and *Bolt* (1977) presented evidence showing that the alkylating potency of VCM metabolites cannot be determined solely by measuring the incorporation of label into nucleic acids after exposure to radioactive VCM. *Watanabe* et al. (1978b) concluded that covalent binding to nucleic acids is not the preferential reaction, but they pointed out that this does not

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Table 7. Gradual emergence of evidence for VCM-associated pathology

Year	Reference	Findings
1949	*Tribukh* et al.	Hepatomegaly, more or less marked 'anicteric hepatitis', 'chronic gastritis', hypotension, anaemia, skin lesions
1954	*Smirnova*	Toxic angioneurosis
1957	*Filatova* and *Gronsberg*	Toxic angioneurosis
1957	*Kubota*	Symptoms similar to Raynaud's phenomenon
1960	*Danziger*	Two cases of accidental fatal poisoning by VCM, 1 nonfatal acute overexposure
1961	*Smirnova*	Reversible osteolytic lesions of distal phalanges. Pseudoclubbing, thickening of skin on volar side of forearms, slight haemolysis and reticulocytosis
1963	*Suciu* et al.	*CNS*: prenarcotic symptoms (dizziness, euphoria, somnolence), nervousness, insomnia, blunting of memory, general asthenia, headache *Vascular*: Raynaud's syndrome *Dermatol.*: pruritus, reversible sclerodermalike skin induration, chemical and allergic dermatitis *Digest. symptoms*: anorexia, nausea, fullness, hepatomegaly without hyperbilirubinaemia, splenomegaly *Endocrine*: hypothyroidism
1966	*Cordier* et al.	Raynaud's syndrome, sclerodermalike skin changes, acroosteolysis, pseudoclubbing, joint pain, tiredness, sleep reversal; 2 episodes of acute overexposure (loss of consciousness)
1967	*Harris* and *Adams*	Acroosteolysis, skin lesions, Raynaud's phenomenon, pseudoclubbing, involvement of sacroiliac joints and patella, hepatomegaly with persistently raised serum bilirubin, Skin biopsy
1967	*Benoit*	Arteriography. Skin and bone biopsy
1967	*Wilson* et al.	'Occupational acroosteolysis' with Raynaud's symptoms, sclerodermalike skin changes, pseudoclubbing
1968	*Antonyuzhenko*	Mentions thrombocytopenia
1971	*Dinman* et al.	Prevalence of acroosteolysis and Raynaud's phenomenon
1971	*Dodson* et al.	Vascular lesions preceding the bone lesions
1972	*Kramer* and *Mutschler*	Increased BSP retention and raised icterus index related to degree of exposure

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VCM intoxication. During a 4-year period, they examined 168 mostly young workers from two Rumanian PVC-producing plants who had not previously been employed in other industries. In their classic paper, the authors described in detail the various central nervous, digestive, angioneurotic and cutaneous symptoms (listed here in their order of manifestation). Acroosteolysis, however, was not mentioned. Episodes of acute overexposure (usually occurring at the end of a batch run, during retrieval of unreacted monomer, or at repair jobs) rapidly resulted in a state of light-headedness and transient euphoria similar to a mild degree of inebriety and were accompanied by a feeling of heaviness in the legs and disturbed locomotor coordination. Several workers claimed to have been able to identify escaping monomer by its faint but agreeable odour. Apparently during periods of particularly high ambient concentrations, workers repeatedly noticed formication in the lower limbs and a general feeling of bodily warmth. Six subjects had experienced loss of consciousness when repairing leakages, but recovered rapidly after being carried out into the open air. After a few months of work, unusual fatigue and sleepiness set in, there were complaints about persistent somnolence, even outside the work premises, and a tendency to fall asleep at the work place, particularly during night-shifts. In addition, headache, dizziness, irritability, blunting of memory, paraesthesias, and general weakness were reported; some workers noticed insomnia or sleep reversal.

A reappraisal of these nonspecific complaints (see also *Vale* et al. 1976) 6 years later, after improvement in industrial hygiene, revealed that the frequency of their occurrence had considerably decreased (*Sucu* et al. 1975). Following a prolonged period of repeated overexposure, vague nonspecific digestive symptoms also developed, such as anorexia with ensuing weight loss, nausea, fullness, upper abdominal discomfort, bloating and epigastric pains. Enlargement of the liver was found in 51 workers (30%); in 6% there was also splenomegaly. Classic Raynaud's phenomenon was found in 6%, but a tenfold higher percentage of the total work force showed evidence of vasospastic alterations on plethysmography (*Raucher* et al., cited by *Sucu* et al. 1975). Pruritus of the hands, forearms and face was an early complaint followed later by what was theought to be (allergic?) 'contact dermatitis'; finally, nodular and scleroderma- or scleroedema-like cutaneous lesions developed in some workers, involving the dorsal surface of the hands, the volar side of wrists and forearms and the face, with firm thickening of subcutaneous tissue or formation of whitish papular or slightly elevated plaquelike indurations. The cutaneous manifestations largely disappeared after removal from the work place. In addition, mention was made of features of hypothyroidism in a few workers. Also, transient loss of libido in 24% was recorded, with return to normal after a break from work or during holidays.

With the exception of acroosteolysis and the two most alarming late sequelae – noncirrhotic portal hypertension and hepatic angiosarcoma – *Sucu*'s early documentation of the prevalence of disease in PVC production workers encompassed a comparatively complete description of the various aspects of chronic VCM intoxication. Later publications supplemented the spectrum of knowledge mainly by providing additional information on epidemiological, roentgenological, thermographic, angiographic, and histomorphological aspects of the lesions encountered in subjects chronically exposed to VCM.

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4.1.1 Familial and Idiopathic Acroosteolysis

Acroosteolysis is a very rare disease. The aetiology and pathogenesis of this condition is still obscure. Osteolytic bone changes in late stages of so-called Raynaud's disease (accompanied by necrosis and gangrene), characteristically presenting as loss of part or of an entire distal phalanx of one or more fingers and also of toes, have been mentioned in the literature since 1921 (*Assmann* 1921; *Monahan* 1926; *Borak* 1927; *Kornblum* 1929). *Kornblum* attributed the lytic bone defects to vascular abnormalities and noted that he had found identical lesions in early stages of scleroderma and in leprosy. The term acroosteolysis was first introduced by *Laroche* and *Hochfeld* (1948), who held a neuroendocrine syndrome responsible for the lesions. Independently *Harnasch* (1949) reported another case of symmetrical idiopathic acroosteolysis, particularly involving the terminal phalanges of the fingers with preservation of tufts, progressive clubbing and shortening, and ill-defined symptoms of disturbed peripheral circulation. By 1952 *Giacci* mentioned that 68 cases of the familial type of acroosteolysis and 33 cases of the nonfamilial, idiopathic form had been reported in the medical literature. He added another five cases, but his case reports pertain almost exclusively to mutilating processes involving only the feet, with recurrent ulceration and discharge of bone fragments (see also *Harms* 1954). In 1957 *Lièvre* and *Gama* listed 16 observations of idiopathic acroosteolysis and commented extensively upon these lesions; the whole range of differential diagnosis (various congenital, neurogenic and endocrine osteolytic diseases, leprosy, arthritis mutilans, progressive systemic sclerosis, ainhum etc.) was considered in their study and could be rejected with reasonable certainty. In a later review, *Chency* (1965), who added another four cases of the familial type, stated that this variety and the nonfamilial idiopathic type may actually belong to the same disease entity and may be part of a degenerative bone process more generalized than the term implies. It was the puzzling character and the rarity of this peculiar bone lesion that captured the attention of site medical personnel and industrial hygienists when in November 1963 the condition was detected in two Belgian autoclave cleaners (*Lefèvre* 1972).

4.1.2 Epidemiology of Occupational Acroosteolysis

Attempts at assessing the prevalence of OAOL among personnel involved in VCM manufacture and polymerization revealed that in general this occupational type of osteolytic bone lesion was found in only 1%–3% of the work population at risk. *Hublet* et al. (1977) considered the fact that only 3% of all workers who had been engaged in manual cleaning of autoclaves at a Belgian plant suffered from OAOL and Raynaud's phenomenon to be indicative of the importance of individual factors. *Wilson* et al. (1967) observed 31 cases among 3000 employees of one large company. In 1971 *Dinman* et al. conducted a survey in 32 plants belonging to 19 corporations throughout the United States and Canada. The details of this elaborate epidemiological study, comprising a total of 5011 employees, illustrates the difficulties and limitations encountered in a retrospective study of this dimension. All of these 5011 workers had been engaged in various stages of VCM and PVC manufacturing, but 1257 of them were workers who only handled finished PVC polymer. Five of the 32 plants worked

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Occupational acroosteolysis is a condition predominantly observed in younger workers. The age range was 20—45 years and half of all cases reported fell in the 30–39 years age-group. Duration of VCM exposure prior to onset of Raynaud's phenomenon ranged from 1 to 23 months (*Dodson* et al. 1971). For OAOL the latency period was at least 12 months (*Wilson* et al. 1967): in most cases, OAOL developed insidiously within 2 to 4–6 years. There is at least one patient on record in whom OAOL was first discovered two years after termination of exposure (*Benoit* 1967). Longitudinal studies of the bone lesions demonstrated partial or complete but mostly defective restitution, resulting in shortened and deformed distal phalanges, within 2–3 years after removal from VCM exposure, but Raynaud's phenomenon and cutaneous lesions may persist (*Williams* and *McLachlan* 1976). *Stein* et al. (1973a, b) reported partial healing with restitution of tufts but progressive lysis of the proximal portion of terminal phalanges 3 years after termination of exposure.

Although OAOL developed predominantly in PVC production workers who had at least for some time been engaged in reactor cleaning, the syndrome has also been observed in association with other job assignments which were believed to carry a substantially lower risk of exposure. *Trapp* et al. (1974) reported a 31-year-old white male suffering from Raynaud's phenomenon, clubbing of the fingers and typical bilateral acroosteolysis, in whom specific inquiry revealed that his employment by an industrial chemical company had included daily handling of small concentrations of vinyl chloride (no details given). Typical OAOL was also observed in a worker after 6 years' employment as spray dryer/bagger, pre-mix operator, recovery and charging operator who had never cleaned autoclave vats (*Stewart* et al. 1975). According to routine plant monitoring of VCM levels in the past and as measured in 1973 by gas chromatography of grab samples, his average exposure had been within the threshold limit values of the day (200 ppm). Radiographs taken in 1966 at the end of his first year during an earlier survey of OAOL were normal; in 1972 he presented with Raynaud's phenomenon, pseudoclubbing, typical OAOL and dermal thickening of hands and wrists. Arteriography demonstrated narrowing of most digital arteries, even in fingers without bone defects, and abnormal collections of small vessels in the pulps of deformed finger tips, but no vascular occlusion.

Apart from the chemical insult by inhalational (rather than transdermal – *Dittman* et al. 1971; *Stewart* et al. 1975) exposure to VCM, individual susceptibility or idiosyncrasy appears to have played some (undefined) role in the development of the syndrome. It does not seem likely, however, that repeated physical microtrauma during cleaning operations (removal of polymer crusts by hand scraping or chiselling) was a decisive factor in the pathogenesis of the condition as had been speculated by *Wilson* et al. (1967).

4.1.3 Clinical and Roentgenological Features

4.1.3.1 Occupational Acroosteolysis

In the majority of cases osteolytic lesions are confined to the hands. Involvement of the feet was observed only rarely in OAOL. *Wilson* et al. (1967) believe that OAOL differs from familial or idiopathic acroosteolysis in several respects. Although the bone

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other body regions were also involved. Erosive and sclerotic changes in the sacro-iliac joints and circumscribed resorptive defects (cortical erosions) in patella, clavicle, mandible, humerus, styloid process of ulna, femoral condyles, os calcis, cuneiform and metatarsal bones have repeatedly been observed (*Cordier* et al. 1966; *Harris* and *Adams* 1967; *Dodson* et al. 1971; *Juhe* et al. 1974; *Lange* et al. 1974a; *Preston* et al. 1976; *Jayson* et al. 1976a; *Lange* and *Veltman* 1977).

4.1.3.2 Pseudoscleroderma

Concomitant with the manifestation of paraesthesias, pain, tenderness of the fingers and Raynaud's phenomenon, cutaneous lesions similar to stigmata seen in progressive sclerodema develop with thickening of the skin of fingers, hands and forearms, sometimes accompanied by swelling or puffiness and coarsening of the skin of the face (mostly on the forehead and cheeks). Raised, ivory-coloured, firm nodules or elevated, sharply delineated plaquelike skin indurations are seen on the dorsal surface of fingers and hands and on the volar side of the wrists and lower forearms. It was this combination of Raynaud's phenomenon and cutaneous lesions which first prompted a search for other symptoms of progressive systemic sclerosis in affected workers. The syndrome of OAOL, however, can be clearly distinguished (Table 10). Notably, the diffuse immobil-

Table 10. Differential diagnosis: syndrome of occupational acroosteolysis (Raynaud's phenomenon, sclerodermoid skin changes, AOL) / progressive scleroderma with (rare) osteolytic lesions

	Occupational AOL	Progressive scleroderma
Sex ratio	Exclusively ♂	♂:♀ = 1:2
Hands	Clubbing and shortening of finger tips; hyperhidrosis; no ulceration	Atrophy and tapering off of fingertips; anhydrosis; ulcerative lesions
Perioral puckering of skin	Not observed	Common
Skin appendages	Preserved	Loss of skin appendages
Telangiectases	Not observed	Common
Shortening of frenulum	Not observed	Early symptom
Subcutaneous deposits of calcium salts	Not observed	Common
Dysphagia (oesophageal involvement)	Not observed	Common
Renal, cardiac and intestinal involvement	Not observed	(Common)
Occupational history	Obligatory	–
Prognosis	Favourable (skin and bone lesions tend to heal after removal from exposure)	Usually spontaneous progression

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those observed in the dermis. The bone matrix per se was barely affected. There was minimal thinning of cortex, normal spongy bone and only mild fibrosis of the bone marrow.

Experience with histomorphology of bone lesions in the familial and idiopathic type of acroosteolysis is limited. In the few cases where biopsy material could be obtained, there was replacement of bone by nonspecific fibrous tissue, but inflammatory and degenerative changes or osteoid formation were not found (*Dupas* et al. 1936; *Elson* and *Burnstein* 1954; *Greenberg* and *Street* 1957; *Schwarzweiler* 1957).

In this context, it should be kept in mind that *Viola* succeeded in reproducing dermal, vascular, neural and skeletal lesions in the skin of the paws and in small metatarsal bones of experimental animals which were very similar to those observed in man. *Viola* exposed rats to 30 000 ppm VCM, 4 h/day, 5 days/week, for 12 months and described the histology of these lesions in detail (1970b).

4.1.5 Arteriography, Capillaroscopy, Infrared Thermography

Arteriographic evaluation of the vascular tree of the hands revealed patency of the large arteries in all cases examined. The vascular lesions were almost invariably confined to the small digital arteries, although the superficial and deep palmar arterial arch may occasionally show some narrowing and a paucity of side-branches (*Lange* et al. 1974a; *Moulin* et al. 1974). The most prominent arteriographic features were irregularities and segmental stenosis of digital arteries, ranging from localized or diffuse narrowing to subtotal or even total occlusion with development of collateral vessels. Besides, a conspicuous retardation of flow of contrast medium was noted, and peculiar tortuosities of patent digital arteries were found. Circumscribed hypervascularity of the terminal tufts and in the region of the wrists was noted in some cases (*Benoit* 1967; *Lange* et al. 1974a; *Veltman* et al. 1975; *Preston* et al. 1976; *Stewart* et al. 1975; *Gama* and *Meira* 1978). Angiographic findings in a larger group of 19 symptomatic PVC workers with either Raynaud's phenomenon and/or acroosteolysis (5/19) were recently described in detail by *Koischwitz* et al. (1980). Raynaud's phenomenon had been observed to persist in these patients for prolonged periods after termination of exposure and even after roentgenological evidence of healing of resorptive bone defects in those who had formerly suffered from acroosteolysis. In addition to varying degrees of stenosis or occlusion of digital arteries with reopening of small collateral vessels, acral hypervascularity and considerable retardation of perfusion in spite of premedication with tolazoline (Priscoline, United States), the most conspicuous features observed in the majority of these patients (14/19) were circumscribed elongations and tortuosities of digital arteries resembling cirsoid aneurysms. An example is shown in Fig. 3 of generalized tortuosity and elongation of digital arteries in a 54-year-old patient who started to complain of severe sensitivity to cold 3 years after cessation of VCM exposure (about 1 year prior to death from both angiosarcoma of the liver and hepatocellular carcinoma). The pathogenesis of these peculiar vascular alterations is not clear, but the possibility presents itself that they may be due to destruction of elastic fibres in the vessel walls in analogy to similar alterations of digital arteries seen in rheumatoid arthritis (*Laws* et al. 1963, 1967).

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British workers who were examined 6–24 months after leaving the plant (termination of exposure), the prevalence of capillary abnormalities was not less than that among those who continued work. For an evaluation of the reversibility of this condition, however, the group was considered to be too small. The same type of capillaroscopic changes was also observed in three of 4 Polish workers (2 reactor cleaners, 2 fitters) who were found to suffer from Raynaud's phenomenon after exposure for 2–5 years (*Byczkowska* and *Langauer-Lewowicka* 1974).

Infrared thermography, another non-invasive method, used by *Rey* et al. (1974) for the study of acral circulation, revealed abnormalities of surface temperature ranging from marked hypothermia of terminal phalanges (which are normally warmer than the rest of the fingers) to "complete terminal amputation" in four PVC workers suffering from OAOL. In one of them vascular disturbances as evidenced by infrared thermography persisted in spite of complete healing of OAOL. *Stewart* et al. (1975) demonstrated uneven blood flow in the fingers and patchy hyperthermia in the distal part of the OAOL-affected left index and middle finger of their atypical case. Localized acral hyperthermia seen on IR thermography corresponded to the angiographic finding of circumscribed abnormal collections of small vessels (compensatory collaterals?) in the pulps of the affected fingers. Using IR thermography in a survey involving 143 PVC production workers and 56 controls, *Williams* et al. (1977) assessed the time needed for heat return after immersion of one hand for 10 s in a water bath kept at 19°C; however, no difference between VCM-exposed subjects and controls and between groups within the exposed population was noted.

4.1.6 Immunological Studies

Early experience with the syndrome of occupational acroosteolysis suggested certain similarities between this disorder and corresponding lesions seen in progressive systemic sclerosis (diffuse scleroderma). Differential diagnosis of these two unrelated conditions is now well established (Table 10). Such similarities stimulated the search for other manifestations of a systemic collagen disease, notably immunological features, as proposed by *Marin* et al. in 1967. *Ward* et al. (1976a, b) carried out immunological studies in 58 workers from a British polymerization plant who were referred to them out of a total past and present work force of 320. Mean duration of exposure to VCM was 39 months (6–75 months). Of these 58 workers, 28 were symptomatic (Raynaud's phenomenon, 9; scleroderma of hands or feet, 6; OAOL, 2; sensitivity to cold, excessive fatigue, limb pain, paraesthesias). Slight hyperimmunoglobulinaemia, usually IgG, the presence of mixed cryoglobulins, and in vivo conversion of both C_3 and C_4 were found in 19 patients in the symptomatic group, with additional evidence of reduced T-cell population and increased B-cell proliferation. Mixed cryoglobulins, in vivo conversion of complement and depressed values for C_3 or C_4 were taken as evidence for the presence of circulating immune complexes. Autoantibody screening demonstrated low-titre antinuclear antibodies (IgG 1/20–1/50) in eight of the nine patients with Raynaud's phenomenon. Aggregates of IgG, C_4, C_3, and fibrinogen/fibrin were revealed by direct immunofluorescence in the lumen of vessels, adherent to vascular endothelium. Aggregates were similarly seen in the media and subintimal regions of small

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4.1.7 Pathogenetic Considerations

Raynaud's phenomenon as a premonitory clinical symptom, histomorphology in man and experimental animals and angiological experience suggest that the common denominator in the pathophysiology of both skin and bone lesions in chronic VCM intoxication is probably to be sought in the local impairment of blood circulation in peripheral regions, as *Benoit* pointed out as long ago as 1967. By reason of their vasculature, the distal phalanges are the skeletal segments which may be most susceptible to impairment of blood supply, particularly to disturbances of microcirculation (*Gama* and *Meira* 1978). Yet the answer to the next question, the pathogenesis of peripheral vascular injury in vinyl chloride disease, is unknown. It still remains largely a matter of conjecture how a volatile toxic compound that is taken up via inhalation, distributed throughout the systemic circulation and metabolized (bioactivated) in the liver, can bring about, apparently only in a small number of predisposed individuals, after a variable period of latency severe vascular injury and (probably secondary) damage to peripheral tissue. Some conceivable mechanisms are briefly listed in a previous chapter (see Sect. 3.4.2.2), but no conclusion can be drawn as to their relative significance.

4.2 Non-malignant Liver Disease in Vinyl Chloride/Polyvinyl Chloride Production Workers

Long before Raynaud's phenomenon or osteolytic lesions were observed in PVC production workers, *Tribukh* et al. (1949) studied environmental conditions in a Russian plant where polyvinyl chloride resins were produced and compounded. Without going into detail, the authors pointed out that moderate nontender hepatomegaly was found in a larger portion of a group of 73 workers (48 males, 25 females) mostly engaged in PVC compounding; 'anicteric hepatitis' was diagnosed in 21 of them (15 ♂, 6 ♀). Although the authors knew about the narcotic action of high concentrations of VCM (75–250 mg/litre ≈ 30 000–98 000 ppm) from the literature, which they explicitly mention, and also knew about the release of unreacted monomer from the powdery PVC resins during thermoplastic compounding, they apparently held other volatile compounds derived from halogenated aromatic hydrocarbons (such as chlorinated naphthalenes and diphenyls) used as plasticizers responsible for the systemic toxicity. They urged, however, that strict monitoring of the health of these workers should be introduced to prevent the development of severe liver damage, and they suggested the installation of ventilation facilities of sufficient capacity.

Nonicteric hepatomegaly was again recorded by *Suciu* et al. (1963) 14 years later in almost one-third of the total work population (51 of 168 employees) of two Rumanian PVC-producing plants, including 10 cases with additional splenomegaly. Liver biopsy in two of these workers revealed chronic hepatitis. Studying the prevalence of temporary disablement due to liver disease among 350 employees of the Sverdlovsk plastics industry, *Pushin* (1965) found the highest morbidity among employees of the PVC production unit, compared with other units engaged in the production of non-PVC plastic materials; 170 workers of ancillary industries served as control subjects.

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There is no longer any doubt that chronic exposure to vinyl chloride monomer can produce two different types of liver disease in man as well as in experimental animals:

1) Noncirrhotic portal hypertension

2) Angiosarcoma of the liver.

The two conditions have one feature in common: they are both rare disorders which are not easily recognized during life.

Noncirrhotic portal hypertension and (often inconspicuous) portal fibrosis are not pathognomonic. Primary splenic enlargement and gastrooesophageal haemorrhage due to marked portal hypertension in the absence of, or preceding, the development of cirrhosis was first described by *Banti* in 1894. As 'Banti's syndrome', this symptom complex and its aetiology and pathogenesis have continued to be a matter of debate. Under the designation 'idiopathic', or 'primary, portal hypertension' the syndrome has been observed notably in India and other South-East Asian regions (*Ramalingaswami* et al. 1962; *Imanaga* et al. 1962; *Basu* et al. 1967a, b; *Boyer* et al. 1967; *Sama* et al. 1971). It has been seen only sporadically in the Western World (*Rousselot* 1940; *Ravenna* 1940; *Tisdale* et al. 1959; *Polish* et al. 1962; *Miller* and *Brandt* 1962; *Siderys* and *Vellios* 1964; *Mikkelsen* et al. 1965; *Iber* 1970; *Escartin Marin* et al. 1974; *Mendenhall* et al. 1974; *Grannis* 1975; *Villeneuve* et al. 1976). *Iber* (1969) estimated that "centers throughout the world reviewing their experience with portal hypertension encounter 3 to 5% of patients who do not clearly fit into the category of cirrhosis or blockage of the portal vein."

In the absence of an identifiable aetiology it has been speculated that in noncirrhotic portal fibrosis observed in India, unknown toxins contained in indigenous drugs, herbal medicines or adulterated food might have been responsible for the condition (*Sama* et al. 1971). *Villeneuve* et al. (1976) suggested that, apart from VCM and inorganic arsenicals, other still unidentified toxins could be the cause of this syndrome. Idiopathic portal hypertension has also been observed to occur in association with known hepatotoxic agents, their common link with VCM being, so far with the exception of vitamin A, the induction of angiosarcoma of the liver. These agents are:

a) *Inorganic arsenicals* (*Zeegen* et al. 1970; *Neale* and *Azzopardi* 1971; *Knolle* et al. 1974; *Morris* et al. 1974; *Huet* et al. 1975; *Villeneuve* et al. 1976; *Cowlishaw* et al. 1979);

b) *Hypervitaminosis A* (*Muenter* et al. 1971; *Russell* et al. 1973, 1974; *Hruban* et al. 1974; *Kistler* et al. 1977); and

c) Recently, *copper sulphate* in Portuguese vineyard workers (*Pimentel* and *Menezes* 1977).

Arsenical preparations (usually prescribed as Fowler's solution – potassium arsenite) have in the past been used as a tonic in neurasthenia, as an adjunct to iron therapy for anaemia, as antiepileptic drugs and well into the 1950s for the treatment of psoriasis. In this context, Banti's remark in his original paper (1898) that anaemia accompanying primary splenomegaly responded best to arsenical preparations is of note. In a renowned German pharmacology textbook of this period (*Nothnagel* and *Rossbach* 1880) Fowler's solution is also listed as a traditional antimalarial drug of

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Table 11. 17 PVC workers with advanced portal hypertension (marked oesophageal varices, episodes of upper GI bleeding, splenomegaly)

No.	Age at diagnosis (years)	Duration of exposure (years/months)	Peritoneoscopic and histological diagnosis
1	30	5	Noncirrhotic fibrosis
2	31	5/9	Noncirrhotic fibrosis
3	32	3/6	Noncirrhotic fibrosis
4	35	4	Noncirrhotic fibrosis
5 [a]	35	9	Noncirrhotic fibrosis
6	39	10/6	Noncirrhotic fibrosis
7	39	13/6	Noncirrhotic fibrosis
8	41	7	Noncirrhotic fibrosis
9 [a]	41	18	Postnecrotic cirrhosis
10 [a]	47	18	Noncirrhotic fibrosis
11	50	6/6	Noncirrhotic fibrosis
12	51	17	Noncirrhotic fibrosis
13	52	15/3	Noncirrhotic fibrosis
14	52	11	Noncirrhotic fibrosis
15	54	6/6	Noncirrhotic fibrosis
16 [a]	58	21	Postnecrotic cirrhosis
17 [a]	61	13	Noncirrhotic fibrosis

[a] On follow-up patients 5, 9, 10, 16 and 17 subsequently developed angiosarcoma of the liver and died 3–6 years after diagnosis of portal hypertension. Patients 6 and 14 are at present (1981) under observation for suspected development of angiosarcoma of the liver, 6 and 11 years after peritoneoscopic diagnosis of portal fibrosis

associated portal hypertension, *Smith* et al. (1976a) observed later development of angiosarcoma in one of them. If a rough estimate based on these two small series were acceptable, it would appear that approximately one of five to seven individuals suffering from advanced VCM-induced portal hypertension might be expected to develop angiosarcoma later, although PVC-induced hepatic fibrosis per se is probably not a premalignant lesion.

4.2.1 Clinical Manifestations of Non-malignant Liver Disease

Physical examination is usually disappointing. In the more advanced stages of VCM-induced nonmalignant liver disease, palpable splenomegaly and a slightly to moderately enlarged liver may be the only physical signs. On palpation, we found hepatomegaly in 31 and splenomegaly in 16 of 50 selected PVC production workers who had been heavily exposed in the past (*Marsteller* et al. 1975a). *Lilis* et al. (1975) reported hepatomegaly in 15% and splenomegaly in 3.4% of 354 consecutively examined employees (267 currently employed, 87 former workers) of one PVC polymerization plant in New York State, USA, a number which included virtually the entire current production work force. A significantly higher prevalence of hepatomegaly was found in those

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these findings as an indication of toxic liver damage is not clear and the relation to previous exposure to VCM remains to be determined.

4.2.3 Gross Inspection of the Liver and Spleen

The gross appearance of the liver, as assessed by pentoneoscopy (*Marsteller* et al. 1975a, b; *Marsteller* and *Lelbach* 1977; *Lelbach* and *Marsteller* 1977) or at exploratory laparotomy, is that of a normal-sized or slightly to moderately enlarged organ with often blunted and irregular anterior edge. Inspection of the liver at peritoneoscopy also permits exclusion of partial nodular transformation as described by *Sherlock* et al. (1966). In most cases, the surface of the liver is smooth or slightly uneven with shallow indentations, but it may be finely granular, trabeculated or have a peau d'orange-like appearance. At most, there are micronodular changes but the diffuse coarse nodularity of cirrhosis is only rarely seen. Progression to frank cirrhosis with severe derangement of hepatic lobular architecture was observed by *Smith* and *Williams* (1974), and also in two of our recent cases in combination with development of angiosarcoma.

On palpation (direct or by peritoneoscopic probe), the texture of the liver is normal or only slightly firmer than usual. Indirect peritoneoscopic evidence of portal hypertension is presented by increased vascularity of the falciform ligament and the intestinal serosa or numerous dilated tortuous vessels in adhesions draining to the abdominal wall. Even in advanced stages, symptoms of pronounced portal hypertension often

Fig. 4. Peritoneoscopic view of left hepatic lobe in noncirrhotic portal hypertension (January 1979). Blunted anterior edge, smooth to finely granular surface, conspicuous patchy capsular fibrosis. (42-year-old autoclave cleaner. VCM exposure 1963–74. 1973 thrombocytopenia as first sign. From 1974 to 1979, marked progression of portal hypertension with splenomegaly and one episode of bleeding from oesophageal varices.) See also Fig. 5 (patient 6 in Table 11)

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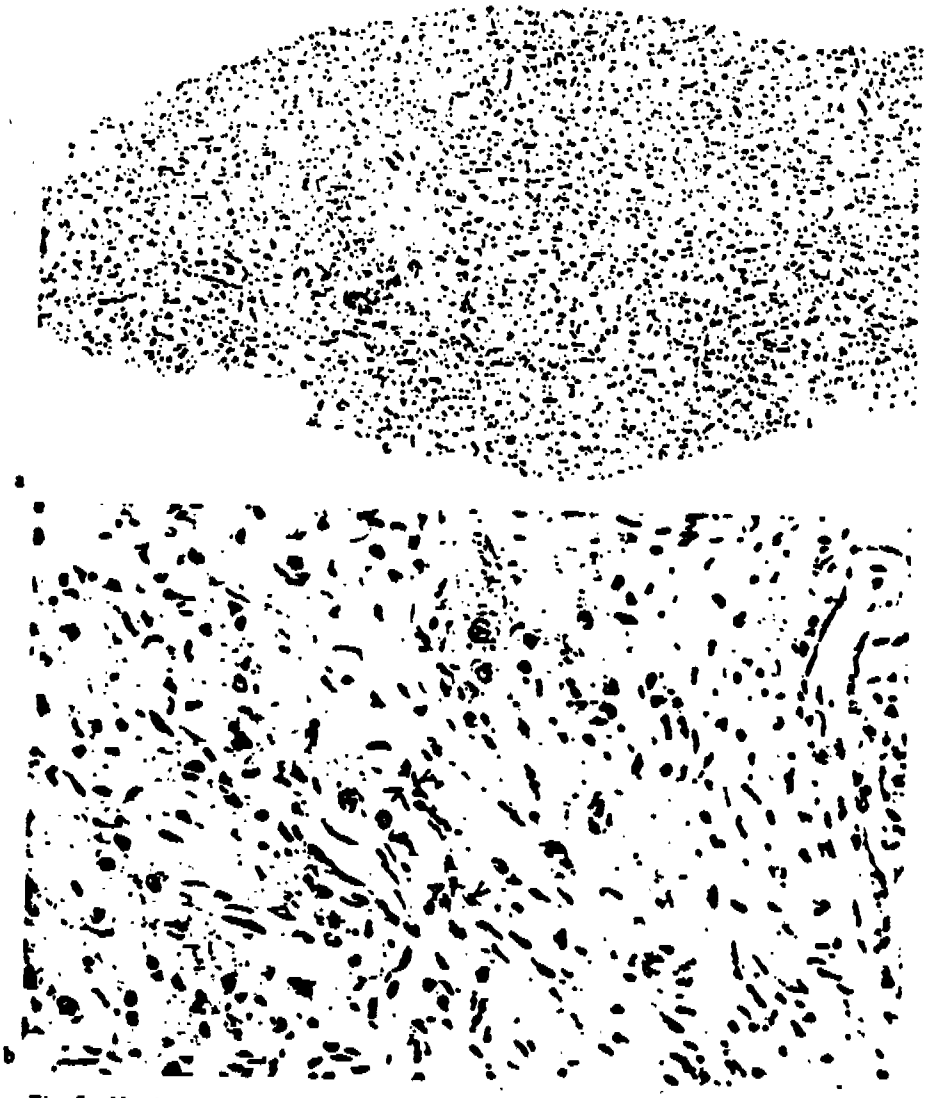

Fig. 5a. Needle biopsy specimen of the liver shown in Fig. 4. Enlargement and fibrosis of portal tracts. Moderately large droplet steatosis. Focal dilatation of sinusoids. H & E. x 80. b Close-up of Fig. 5a. Indistinct border of enlarged and fibrosed portal tract towards parenchyma *(left)*. Proliferation of capillanes (> <) with polymorphism and hyperchromasia of endothelial cells. PAS, x 400

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may be recognized only in connective tissue stains. *Triche* et al. (1975) pointed out that in one worker with severe acroosteolysis but normal hepatic function and essentially normal liver histology on light microscopy (except for a minimal and easily overlooked increase of perisinusoidal collagen in occasional lobules), electron microscopy revealed a striking centrilobular increase in collagen between hepatocytes and in Disse's spaces together with proliferation and hyperplasia of sinusoidal lining cells (see also *Kurokawa* et al. 1977). The same ultrastructural deposition of perisinusoidal collagen was observed by *Schattenberg* et al. (1977) in 15 PVC workers in whom we could obtain liver tissue for electron microscopy at peritoneoscopy. Similar changes (enlargement of Kupffer cells, abundant deposits of collagen in the Disse's space and resulting reduction of sinusoidal diameter suggesting a possible factor in the pathophysiology of 'sinusoidal' portal hypertension) were seen on electron microscopy in a number of cases of idiopathic portal hypertension of unknown aetiology (occupational histories not mentioned) (*Sommerschild* and *Kluge* 1971; *Kluge* et al. 1970; *Tandon* et al. 1970).

4.2.4.2 Sinusoidal Lining Cells

Marked focal proliferation and hyperplasia of sinusoidal lining cells with nuclear polymorphism and hyperchromasia are the most impressive features of the mesenchymal lesion. The hyperchromatic nuclei of these cells may show a bizarre shape or resemble short pegs, and are often arranged in a chainlike fashion (*Gedigk* et al. 1975). These perisinusoidal and sinusoidal cells include three types: (1) normal endothelial cells, (2) lipocytes (Ito cells), considered to be precursors of fibroblasts and (3) plump cells with spindle-shaped nuclei and PAS-positive cytoplasm. Formation of excess reticulin suggests fibroblastic activity of some of these cells. Focal dilatation of sinusoids, not explained by passive congestion, is another peculiar feature usually associated with particularly pronounced alterations of these mesenchymal cells. There is reason to believe that this combination of changes may represent a premalignant stage.

4.2.4.3 Heparocytes

Unimpressive, nonspecific, degenerative and adaptive lesions (such as minor degrees of fatty degeneration, cloudy swelling, ballooning or vacuolar degeneration, increase of lipofuscin pigment and proliferation of smooth endoplasmatic reticulum of hepatocytes in focal areas without inflammatory reactions), can be seen to disappear gradually with increasing intervals between the last exposure and the date of biopsy, in contrast to the apparently irreversible damage to mesenchymal structures (*Gedigk* et al. 1975, 1977; *Muller* et al. 1975). In poorly demarcated areas there is hyperplasia and hypertrophy of hepatocytes with polyploidy and increased number of binucleated cells. Two types of focal hepatocytic proliferation associated with varying degrees of sinusoidal cell alterations were recently described and are thought to play some as yet undefined role in the precursor stage of angiosarcoma (*Popper* et al. 1978).

4.2.4.4 Histology of the Spleen

Unless splenectomy is carried out in vinyl chloride disease, tissue specimens of the spleen are less easily obtainable than liver biopsy material. *Popper* and *Thomas* (1975)

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portal flow is obstructed at the sinusoidal or presinusoidal level. In a group of five PVC workers selected for haemodynamic studies, *Blendis* et al. (1978) could not demonstrate a direct relationship between the degree of hepatic fibrosis in needle biopsy specimens and portal hypertension. But it should be kept in mind that the distribution of fibrosis in these workers is quite irregular. It has also been suggested by *Popper* and *Thomas* (1975) and *Thomas* et al. (1975) that the increased splenic and hepatic blood flow as a result of decreased splenic resistance in splenomegaly cannot properly be accomodated in the hepatic portal vein bed owing to impairment of adaptive distension of portal veins and sinusoids by the subcapsular, portal and perisinusoidal fibrosis. *Blendis* et al. (1978) found no correlation between spleen or estimated liver blood

a b

Fig. 6a, b. Progression of noncirrhotic portal hypertension despite termination of exposure. Oesophageal varices. (Autoclave cleaner, age at diagnosis: 35 years. VCM-exposure, 1962–1972. 1972 Raynaud's phenomenon, sklerodermoid skin indurations, thrombocytopenia, splenomegaly, and grade I oesophageal varices. Gradual progression of portal hypertension. Sudden death from ruptured anaplastic angiosarcoma of the liver in June 1978. Histologically only mild perisinusoidal fibrosis in nontumorous areas)

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of the literature. *Alrenga* (1975) listed 165 published cases of primary angiosarcoma of the liver in adults. In the six autopsy series collected by *Alrenga*, ASL constituted only 1.8% (0.9%–2.7%) of all primary malignant tumours of the liver, which of themselves are rare findings in the Western World. Autopsy statistics show that the incidence of ASL ranged from 2 to 20/100 000 autopsies during different periods with a mean incidence of 12/100 000 autopsies (Table 12). According to *Heath* et al. (1975) it was estimated that in the United States the expected annual incidence of ASL is 0.014 in 100 000 inhabitants or 25–30 cases per year for the entire United States.

Table 12. Incidence of angiosarcoma of the liver (ASL) in autopsy series.

Authors	Year	Observation period	No. of autopsies	No. of cases of ASL	Region
Simpson et al.	1955	1914–1953	24 196	1	Mayo Clinic, Rochester, Minn., USA
Edmondson	1958	1918–1954	52 000	1	Los Angeles, County Hosp., USA
MacSween et al.	1973	1900–1969	– [a]	3	Western Infirmary Glasgow, U.K.
Alrenga	1975	1951–1973	39 700	6	Cook County Hosp. Chicago, USA
Rein and *Huth*	1975	1954–1974	30 079	4 (6) [c]	Düsseldorf, Fed.Rep. Germany
Byrén and *Holmberg*	1975	1958–1969	– [b]	12 (adult cases)	Sweden
Dalderup et al.	1976	1960–1975	At least 40 000	8	Netherlands (population. 10–14 million)

[a] Among 120 cases of primary malignant liver tumours studied post mortem during this 70-year period.

[b] Among 8 million inhabitants.

[c] 4 Angiosarcomas, 1 haemangioendothelioma, 1 malignant haemangiopericytoma

Accordingly, the identification of 4 cases of ASL among approximately 270 employees of the vinyl chloride polymerization section at a B.F. Goodrich plant near Louisville, Kentucky, between September 1967 and December 1973 was duly recognized as an alarming situation indicative of a serious new occupational hazard (*Creech* et al. 1974a: *Creech* and *Johnson* 1974).

Until 1974, only two carcinogenic agents were known to be associated with the development of ASL in man, i.e. the administration of a radioactive colloidal prepara-

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Table 13. Personal data of 68 polyvinyl chloride production workers with angiosarcoma of the liver reported to NIOSH up to August 1975 (*Spirtas and Kaminski 1978*)

No	Country[a]	Birth date (m/d/y)[b]	Date of death (m/d/y)	Age at death	Total years exp.	Job classification[c]
1	B (1)	01.12.13	06.29.76	63	17	1, 2
2	CND (1)	12.15.13	09.02.55	41	11	1, 2
3	CND (2)	03.06.14	12.21.57	43	14	2, 3, 12, 13
4	CND (3)	08.26.19	03.22.62	42	20	2, 5
5	CND (4)	04.05.19	01.21.68	48	22	1, 2, 5, 14
6	CND (5)	05.07.11	07.05.68	56	5	1, 14
7	CND (6)	12.15.19	04.10.71	51	23	1, 12, 13, 15
8	CND (7)	11.09.19	12.24.72	52	25	1, 9, 17
9	CND (8)	05.13.20	06.12.73	53	5	1, 12, 17
10	CND (9)	07.19.21	09.04.74	53	26	3, 12, 16
11	CND (10)	05.16.15	04.00.77	61	14	2, 16
12	ČSR (1)	00.00.28	12.00.73	45	16	1
13	ČSR (2)	00.00.26	00.00.66 (64?)	40 (37?)	15 (14?)	1
14	D (1)	06.04.30	01.25.69	38	12	2
15	D (2)	07.26.31	12.14.71	39	11	2
16	D (4)	09.04.30	11.25.74	44	17	2
17	D (5)	01.01.32	01.09.75	43	12	2, 4, 5
18	D (7)	09.29.26	11.13.75	49	12	11, (1)
19	D (8)	10.19.17	12.25.75	58	21	2
20	D (9)	12.13.34	03.24.78	42	15	10
21	D (10)	07.23.29	06.28.77	47	22	10
22	D (11)	12.29.36	03.07.77	41	16	10
23	D (12)	06.14.38	10.07.77	39	6	1
24	F (1)	04.15.24	02.19.67	43	19	1, 2
25	F (2)	06.03.11	01.24.75	63	12	2
26	F (3)	01.06.20	06.26.75	55	29	2
27	F (4)	01.27.27	01.03.76	49	26	2, 6
28	F (5)	01.29.38	05.13.76	38	11	1, 2
29	F (6)	04.14.34	09.12.76	42	13	6, 7
30	F (7)	00.00.27	07.02.76	49	22	2
31	F (8)	04.01.34	01.30.77	42	19	2
32	F (9)	10.08.14	12.25.77	62	28	2
33	F (10)	05.24.19	01.20.78	58	21	2
34	GB (1)	04.20.01	12.03.72	71	22	8
35	GB (3)	06.02.37	12.24.74	37	4 (3 1/2?)	1
36	I (2)	11.13.29	12.27.72	43	6	2
37	I (3)	03.14.20	07.10.75	55	21	
38	J (1)	08.01.22	10.24.75	52	22	
39	J (2)	08.02.29	08.10.76	37	13	
40	N (1)	12.23.15	01.04.72	56	21	

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a population of 130 000. One of the four had a history of occupational exposure to polyvinyl acetate, which has hitherto not been related to ASL. The other three may have had nondocumented exposure to arsenical pesticides, which were used for many years in this region, but such conjectural deliberations must await further investigation for confirmation.

Death certificates for the periods 1963–1973 in England and Wales and 1965–1973 in Scotland recorded 41 cases of ASL (1–9 cases per year; mean: 4 cases per year). An unexplained peak was observed in 1968/1969 (*Baxter* and *Fox* 1975). Six additional cases not mentioned on the death certificates were detected by a panel of specialists (*Baxter* et al. 1977). In reassessing 36 of these 47 patients for whom histological sections were available, the panel of histopathologists unanimously agreed on the diagnosis in only 14 cases (7 doubtful, 3 unclassifiable, 12 non-ASL). For 12 of these 14 cases occupational and residential histories were obtained which revealed one undoubtedly VCM-induced case, two cases with possible exposure to (low levels of?) VCM and one case attributable to thorium dioxide.

After the first three cases of *ASL among vinyl chloride polymerization workers* in the United States had come to the attention of the National Institute for Occupational Safety and Health (NIOSH) in January 1974 (*Lloyd* 1974), this institution continued to collect information on additional cases reported to them from nations with an important PVC industry (*Lloyd* 1975; *Spirtas* and *Kaminski* 1977). As of August 1978, data had been presented on a total of 68 cases of ASL among polymerization workers (*Spirtas* and *Kaminski* 1978, pers. comm.); another eight cases had been observed among nonpolymerization workers exposed to VCM in various jobs. On the basis of this data collection communicated to us in 1978 – for which we wish to thank Drs. *R. Kaminski* and *R. Spirtas*, NIOSH, Cincinnati, USA – we attempted to trace these cases and their individual symptomatology as well as other relevant information published in the literature up to 1979 (see Tables 13–18). The ten Canadian cases of VCM-induced ASL (cases 2–11) are dealt with summarily in the papers published by *Delorme* (1978a) and *Delorme* and *Makk* (1975); seven of them were described in more detail by *Makk* et al. (1976). Cases 19 and 23 were observed at our clinic in Bonn but details have only been published for case 19 (E.U. in *Lelbach* and *Marsteller* 1977). In reviewing the literature we could not trace cases 37–40, 43, 50, 51, 53–67 and C, F and H. According to the latest annual report of the Staatlicher Gewerbearzt, Düsseldorf (*Reinl* et al. 1978), the number of deaths from VCM-induced ASL in the Federal Republic of Germany had increased to 16 by the end of 1978, to which we now add a 17th case (Figs. 8 and 9).

In retrospect, it was discovered that the first case of VCM-induced ASL had already occurred in 1955 in a Canadian polymerization worker. For the 67 VCM polymerization workers for whom details were available, total years of exposure ranged from 4 to 31 years (mean and median 18 and 19 years, respectively). In comparison, mean duration of exposure in our group of 17 individuals with advanced nonmalignant liver disease (see Table 11) was 10 3/4 years (range: 3 1/2–21 years). The latency period (years from first exposure to diagnosis of ASL) ranged from 9 to 38 years (mean and median: 21 years). The average age at diagnosis of ASL was 50 years (range: 37–71 years).

Table 14. Clinical and morphological data on 68 polyvinyl chloride (PVC) production workers with angiosarcoma of the liver reported to NIOSH by August 1978

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Table 14 (continued)

No.	Hepato-megaly	Spleen	Oesophageal varices	Hepatic fibrosis	Thrombo-cytopenia	Acro-osteolysis	Raynaud's phenomenon	Metastases
12	+ (7300 g)	Moderately enlarged	(+)	(Cirrhosis), fibrosis	?	∫f	+	∫f
13	+ (2750 g)	?	+	(Cirrhosis)	?	∫f	∫f	Left lung
14	+	Spleno-megaly	?	?	?	∫f	∫f	4th left rib
15	+	Slightly enlarged	?	?	?	∫f	∫f	∫f
16	+ (2650 g)	Spleno-megaly (830 g)	+	Capsular, portal, septal	+ (72 000, 65 000)	∫f	∫f	1st thoracic vertebra
17	+	Spleno-megaly	+	+	?	∫f	∫f	Brain
18	?	Perisplenitis	?	?	+ (134 000, 68 000)	∫f	+	3rd lumbar vertebra
19	(+) (1450 g)	Spleno-megaly (480 g)	(+)	Progressive perisinusoidal, portal and septal cirrhosis	+ (80 000, 47 000, 30 000)	∫f	∫f	∫f
20	?	?	?	?	?	?	?	?
21	+ (1900 g)	Spleno-megaly	+	+	?	∫f	∫f	∫f
22	+	Spleno-megaly	?	Capsular, portal, perisinusoidal	+	∫f	∫f	∫f
23	+ (2700 g)	Spleno-megaly (455 g)	∫f	Focal peri-sinusoidal	?	∫f	∫f	∫f
24	+	+	+	+		∫f		+

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Table 14 (continued)

No.	Hepato-megaly	Spleen	Oesophageal varices	Hepatic fibrosis	Thrombo-cytopenia	Acro-osteolysis	Raynaud's phenomenon	Metastases
34	+ (2625 g)	Slight splenomegaly	∅	∅	+ (80 000)	∅	∅	∅
35	+ (3240 g)	Congested, firm (200 g)	+	Noncirrhotic fibrosis	?	∅	∅	∅
36	+	?	+	?	?	∅	∅	Local spread to abdominal wall and colon; lymph nodes
37								
38								
39								
40								
41	+	Splenomegaly	?	?	?	?	?	?
42	?	?	?	?	?	?	?	?
43								
44	+	Splenomegaly	+	Subcapsular and portal fibrosis	+	∅	∅	∅
45	+	Splenomegaly	+	Markedly thickened capsule; marked fibrosis	+	∅	∅	∅
46	+ (1860 g)	Splenomegaly	?	Portal fibrosis	?	∅	∅	Spread to duodenum
47	+	Splenomegaly	?	Portal fibrosis	+ (35 000)	∅	∅	Spread to diaphragm and abdominal wall
48	+	?	?	Slight focal	?	∅	∅	Tumor, large and small

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Table 15. Publications on the 68 cases of angiosarcoma of the liver listed in Tables 13 and 14

No	References	Additional relevant information
1	*Hublet* et al. (1977)	Hypertrophic, hyperchromatic and atypical endothelial cells in the *glomeruli*: foci of haematopoetic cells in liver and spleen
2 3 4 5 6 7 8 9 10 11	*Delorme* and *Makk* (1975) *Makk* et al. (1976) *Delorme* (1978a, b) *Delorme* and *Thériault* (1978)	Case no. 7. ASL associated with hepatocellular carcinoma (*Delorme* 1978b) (All cases from one plant in Shawinigan, district Trois Rivières, Quebec)
12 13	*Schmidt* and *Bátora* (1976)	At the same plant: 4 cases of VCM-induced cirrhosis of the liver plus 1 case of cirrhosis and generalized reticulosarcoma and 4 cases of carcinoma of the GI tract or lungs
14	*Lange* et al. (1974b)	See also *Reinl* and *Weber* (1974)
15	*Gedigk* et al. (1975)	See also *Reinl* and *Weber* (1974)
16	*Gokel* et al. (1976)	Foci of haematopoesis within the tumour areas
17	*Amann* (1975) *Rübsamen* (1976)	1974 portocaval anastomosis; cholecystectomy. Hypertrophic, hyperchromatic and markedly atypical endothelial cells in the *glomeruli* and in the capillaries of the *lungs*
18	*Reinl* et al. (1976)	
19	(Observed in Bonn)	Moderate hepatic siderosis; chronic fibrosing *pancreatitis*; tubular and interstitial fibrosis of the *testes*
20 21 22	*Reinl* et al. (1976) *Reinl* et al. (1977) *Reinl* et al. (1977)	
23	(Observed in Bonn)	Focal interstitial fibrosis of the *pancreas*
24	*Ravier* et al. (1975)	See also *Berrod* et al. (1978)
25	*Roche* et al. (1978)	1942 gastrectomy, 1974 splenectomy, right hepatic lobectomy (640 g). See also *Roche* (1977); *Puech* et al. (1977); *Bonneton* et al. (1975, 1977); *Berrod* et al. (1978)
26	*Rety* et al. (1976)	No autopsy (see also *Berrod* et al. 1978)

Table 15 (

No.	Re
27	*Ro*
28	*Ro*
29	*Ro*
30 31 32 33	*Ber*
34	*Le*
35	*Sm*
36	*Mc*
37	–
38	–
39	–
40	–
41	*By*
42	*Byr*
43	–
44	*Bl* (ca
45	*Blo* (ca
46	*Bl* (ca

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Table 15 (continued)

No.	References	Additional relevant information
47	*Block* (1974) (case 1)	See also *Falk* et al. (1974a) (case 2); *Makk* et al. (1976) (case 4)
48	*Block* (1974) (case 5)	See also *Falk* et al. (1974a) (case 1); *Makk* et al (1976) (case 2)
49	*Block* (1974) (case 6)	See also *Falk* et al. (1974a) (case 6); *Whelan* et al. (1976) (case 4); *Makk* et al. (1976) (case 14)
50	–	
51	–	
52	*Whelan* et al. (1976) (case 3)	Chronic alcoholic. See also *Makk* et al (1976) (case 13); *Berk* et al. (1976) (case 2)
53–67	–	
68	*Zonca* et al. (1975)	Among a work force of 180 (120. PVC polymerization: 60, production of VCM) employed at this plant, 15 died of malignant disease (2 ASL, 5 bronchogenic carcinomas, 1 case each of carcinoma of the larynx, rib, mamma, spermatic cord; glioma, melanosarcoma, leukaemia, Hodgkin's disease)

First exposure to VCM for these 67 cases of ASL dated back to the period 1939–1966 (median: 1951). Twenty-one years later, i.e. from 1972 onwards, a gradual increase in the number of new cases diagnosed and reported to NIOSH can be observed (Fig. 7). The onset of this gradual increase coincides with the calculated mean latency period of 21 years (*Spirtas* and *Kaminski* 1977). *Spirtas* and *Kaminski* also suggested that in future cases the age at diagnosis and the length of the latency period may increase as a result of the later reduction in levels of exposure.

From the synopsis in Table 13–18 it can be seen that in about two-thirds of the cases of ASL for which morphological details are available varying degrees of associated hepatic fibrosis in nontumorous areas of the liver were mentioned. Less often, evidence of portal hypertension and splenomegaly were noted. Metastasis of angiosarcoma to distant sites was observed in approximately half the published cases. It is of note that acroosteolysis and cutaneous stigmata of scleroderma have been observed in only 1 of these 76 patients, a French PVC worker who had apparently not been engaged in reactor cleaning (case 29; *Roche* et al. 1978). Another noteworthy piece of information is that strikingly atypical endothelial cells with hypertrophic and hyperchromatic nuclei have also been found in organs other than the liver (kidneys, lungs) in autopsy material from two patients (cases 1 and 17, *Hublet* et al. 1977; *Rübsamen* 1976). *Hublet* et al. (1977) also found such cells in the myocardium and in the adipose tissue enveloping the adrenals. All this may lend support to the idea that the effect of VCM metabolites is not restricted to the vascular endothelium of the liver and spleen. Angio-

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Table 17. Clinical and morphological data on eight cases of angiosarcoma of the liver among VCM-exposed personnel not employed in PVC polymerization

No.	Hepato-megaly	Spleen	Oesophageal varices	Hepatic fibrosis	Thrombo-cytopenia	Acro-osteolysis	Raynaud's phenomenon	Metastases
A	+ (6000 g)	Splenomegaly	+	Portal fibrosis	+	ø	ø	Diaphragm, gastric mucosa, abdominal lymph nodes
B	+ (3650 g)	Splenomegaly (425 g)	+	Focal capsular fibrosis, portal and centrolobular fibrosis	ø	ø	ø	Diaphragm, pleura, abdominal lymph nodes
C								
D	(+)	Not enlarged	ø	?	?	ø	ø	Lungs, pericardium
E	+	?	?	?	+ (104 000)	ø	ø	?
F								
G	+	Splenomegaly	?	?	?	ø	ø	Dura, cranium
H								

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patient with both angiosarcoma and hepatocellular carcinoma). Fibrosis of the testes was observed in three cases (19, 29, 8), and *Roche* et al. (1978) also reported fibrosis/hyalinosis in vessels of skin, heart, lungs and intestinal wall.

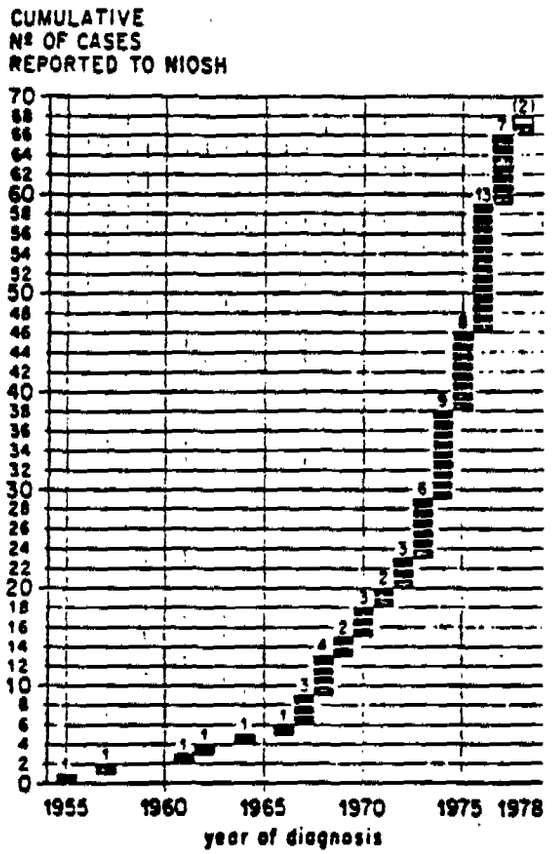

Fig. 7. Cumulative number of cases of ASL among PVC production workers reported to NIOSH up to August 1978, arranged according to year of diagnosis (data from *Spirtas* and *Kaminski* 1977, 1978)

4.3.2 Clinical Manifestations

The clinical symptomatology of usually multicentric ASL is unspecific. Gradually declining general health and loss of weight combined with ill-defined upper abdominal discomfort and slight epigastric or right upper quadrant pain are usually the first symptoms. Recurrent bleedings from oesophageal varices may have been antecedent events in patients with portal hypertension who otherwise felt fairly well. In a number

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vances during the following years with repeated episodes of bleeding which required (successful) sclerosing therapy (major surgery was declined by the patient). In August 1979 he presented again with recurrent epistaxis and slight but permanent epigastric and upper right quadrant pain, but declared that he felt otherwise fairly well. He complained about a sharp localized epigastric pain on sneezing. There was marked splenomegaly, and an ill-defined hard mass was palpable in the epigastrium. Apart from moderate elevation of alkaline phosphatase and borderline hyperbilirubinaemia, biochemistry was normal. Computer tomography showed a large irregular hypodense tumour mass in the liver, involving both right and left lobes (Fig. 8), which became practically isodense after intravenous injection of contrast medium. A liver scan corroborated the tumour defect. Shortly after this there was mounting evidence of brain involvement and rapid deterioration. Computer tomography now revealed multiple brain metastases (Fig. 9). Autopsy confirmed the tentative diagnosis of metastasizing angiosarcoma of the liver (Fig. 10).

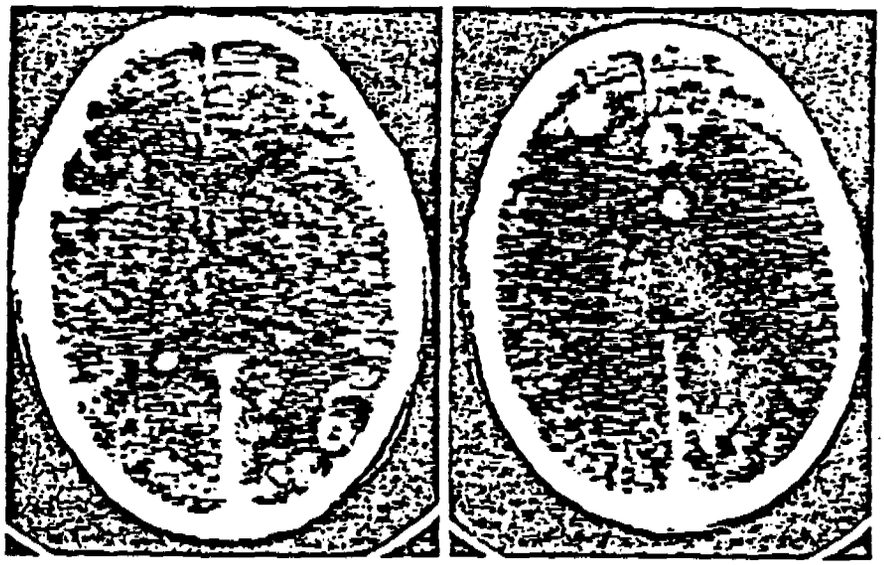

Fig. 9. Computer tomography showing multiple brain metastases of angiosarcoma of the liver. See text. Courtesy of Professor Thurn, Department of Radiology, University of Bonn

4.3.3 Peritoneoscopy

Little information is available in the literature concerning the peritoneoscopic aspect of VCM-induced ASL (*Roche* et al. 1978). It may be impossible to make a diagnosis of the initial phase of ASL in VCM-exposed workers by peritoneoscopy and needle biopsy of the liver, as documented in one of our patients who died of multicentric ASL

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11 months after peritoneoscopic diagnosis of severe hepatic fibrosis (case 19; see also *Leibach* and *Marsteller* 1977). In addition to the findings described in connection with hepatic fibrosis, there may be hypervascularized or cystic tumour formation visible on the surface of a nodular, quasi-cirrhotic liver, or a gross aspect resembling hepatic metastases if the vascular malignancy involves the superficial regions of the liver. It should be stressed here that needle biopsy is absolutely contraindicated if there is any suspicion of ASL.

4.3.4 Gross and Histological Morphology

The liver is usually markedly enlarged. Liver weight in cases of ASL ranged from 1600 to 7300 g (*Thomas* and *Popper* 1975; *Rochc* et al. 1978). The gross appearance of angiosarcoma of the live. is mostly that of large bulky, irregularly shaped cystic tumour masses; a multinodular form with numerous, sometimes umbilicated nodules, is less often encountered. Extensive haemorrhagic and necrotic areas or solid and spongy portions of tumour tissue replace much of the liver parenchyma. Rupture of large cavernous cysts may cause fatal intraperitoneal haemorrhage.

Thomas et al. (1975) and *Thomas* and *Popper* (1975) distinguished four basic developmental patterns of histomorphology of ASL, which can be found in different portions even of the same tumour and appear to represent stages of progressive evolution: sinusoidal, papillary, cavernous and anaplastic patterns. Indistinct areas of transition and merging of patterns can be observed.

Dilated sinusoidal spaces lined by hypertrophic and hyperplastic sarcoma cells with pleomorphic, elongated, hyperchromatic and often bizarre nuclei characterize the *sinusoidal* pattern, which is the most frequent type. Tumour cells of varying differentiation envelop liver cell plates and may invade enlarged and fibrosed portal tracts, accompanied by proliferation of bile ductules (Fig. 11). In *papillary* angiosarcoma atrophy of liver cells results in larger and more irregular blood-filled vascular spaces, into which loose papillary strands of surviving hepatic cords on an axis of connective tissue project, lined by sarcomatous cells (*Weinbren* 1976). Even larger blood-filled spaces are seen in the *cavernous* type, where they may be surrounded by thick fibrotic walls. In a smaller percentage of cases, solid areas or nodules of *anaplastic* sarcoma are found, resembling solid spindle-cell sarcoma, or even suggesting an epithelial type of tumour. *Gedigk* et al. (1975) also observed a reticulosarcomalike pattern. The differentiation of the tumour cells varies widely: it ranges from the inconspicuous endothelial lining cell type to irregularly shaped, grossly distorted giant-cell forms. Morphologically, vinyl chloride-related ASL cannot be distinguished from ASL associated with other aetiological factors or from the cryptogenic type (*Popper* et al. 1978).

In *tumour-free portions* of livers with angiosarcoma widely varying degrees of excess formation of fibrous connective tissue are usually observed, analogous to that seen in nontumorous livers of heavily exposed persons. Fibrosis of enlarged portal tracts with modest proliferation of bile ductules, mostly only scanty infiltration of lymphocytes and occasional formation of perilobular septa or thin connective-tissue septa extending into the lobular parenchyma can be found. A more or less conspicuous intralobular, perisinusoidal fibrosis is often detected only by special staining methods for collagen or reticulin fibres. As a rule, irregular focal or nodular fibrotic thickening of

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11 months after peritoneoscopic diagnosis of severe hepatic fibrosis (case 19: see also *Lelbach* and *Marsteller* 1977). In addition to the findings described in connection with hepatic fibrosis, there may be hypervascularized or cystic tumour formation visible on the surface of a nodular, quasi-cirrhotic liver, or a gross aspect resembling hepatic metastases if the vascular malignancy involves the superficial regions of the liver. It should be stressed here that needle biopsy is absolutely contraindicated if there is any suspicion of ASL.

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by formation of excess connective tissue or by accentuation of sinusoidal dilatation leading to primary peliosis. Involvement of portal areas in the evolution of angiosarcoma results in considerable fibroplasia and formation of hyalinized collagen together with proliferation of bile ductules. In occasional cases connective tissue bridging between portal tracts or between portal tracts and central veins with subdivision of lobules followed by rearrangement of hepatocytic plates may lead to a cirrhosislike picture.

4.3.5 Therapy

The multicentric development of ASL (*Thomas* and *Popper* 1975) as well as the diffuse spread of the tumour usually encountered by the time of diagnosis precludes effective surgical or radiation therapy in the majority of cases. A survival period of two years after surgery (*Berrod* et al. 1978) or chemotherapy (*Daunaher* et al. 1979) is a rare exception. Results of systemic chemotherapy studied in a small group of five patients showed that, at best, quality and duration of survival may improve to a very limited extent (*Daunaher* et al. 1979). At present, no generally accepted guidelines for chemotherapy are available.

4.3.6 Risk Assessment

When in the United States 13 white male cases of ASL had been detected from 1961 to May 1974, among an estimated total population of VCM polymerization workers of roughly 20 000, a risk ratio (ratio of observed to expected cases) for this population of at least 400:1 was calculated (*Heath* et al. 1975). This calculation was based on data from the National Cancer Institute's Third National Cancer Survey (1969–1971), which expected for the total United States population an annual incidence of this tumour in the order of 0.014/100 000. This would have meant only about 0.03 cases per 20 000 polymerization workers within a 10-year period. Dose-response and attendant biotransformation data on experimental animals have since been used to elaborate several different models of extrapolation to man. These were calculated with reference to relative body surface areas, for estimating the risk of ASL in human populations exposed to VCM and for establishing guidelines to assist the research for 'realistic safe doses' that do not affect the average lifespan of a person exposed (*Schneiderman* et al. 1975; *Gehring* et al. 1979, 1978; *Woods* 1979). *Gehring* et al. (1979) consider a probit percent model to be a reliable tool for risk prediction, which works without the assumption of a threshold. They predicted a cancer risk of 1.5 cases of ASL in 100 000 000 workers on exposure to the current National Standard in the United States of 1 ppm VCM 8 h/day, 5 days/week, for a 35-year working life, an incidence which does not significantly deviate from the spontaneous incidence rate. A linear model modified by adjustments for differences in the rate of inhalation, distribution, metabolism, cell proliferation and tumour latency times between rats and humans was described by *Woods* (1979). This model arrives at an incidence of 3.9 cases per 100 000 000 workers after a lifetime exposure to 1 ppm. Much controversy, however, about the validity of risk extrapolation from animal experiments to man and from high- to low-level exposure and the problem of threshold doses has been voiced (*Maugh* 1978; *Hooper* et al. 1979; *Schneiderman* 1979; *Weigert* 1979; *Reitz* et al. 1979).

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through 1974: (a) 7021 workers engaged in the production of VCM and PVC; (b) 4910 chemical workers from the same plants not exposed to VCM; and (c) 4007 workers engaged in PVC manufacture. Not included were non-German workers of Mediterranean origin. This German study permits comparison not only with the mortality ratio of the total male population but also with a comparable occupational group exposed to VCM. With regard to the 'healthy worker effect' (*McMichael* et al. 1975), overall mortality was elevated for the VCM-exposed population (group a), but not for the other chemical workers (group b). Apart from the markedly elevated standardized mortality ratio (SMR) for malignant liver tumours (1523), which proved to have been closely related to the duration of exposure, a significantly elevated SMR was found for tumours of the lymphatic and haematopoetic system (214). The group of chemical workers not exposed to VCM (b) also showed a significant elevation of the SMR for liver tumours (401), a result that deserves further investigation. No significantly increased risk was found concerning tumours of the central nervous system or the respiratory tract.

It has already been mentioned (Sect. 2.2.10) that an excess mortality from brain tumours (SMR 535) was recorded among PVC workers engaged in manufacture at one of two plants; in the second plant an elevated SMR (434) for liver tumours was found. At present, there is no explanation for the increased SMR for accidents found in the VCM-exposed population, particularly during the period 1970 through 1974, about 40% of deaths having occurred in ex-PVC workers. A recalculation of the available data would have been necessary for the evaluation of a conceivable influence of VCM on vigilance.

As an addendum it may be noted that determination of plasma carcinoembryonic antigen titre (CEA) in 200 Canadian PVC production workers (mean duration of employment: 10 years) showed a more than threefold higher frequency of levels above 10 ng/ml than in a normal healthy population (1.7% vs. 0.5%) (*Page* et al. 1976). Levels of CEA were also determined in 1363 workers of five different VCM polymerization (3) and PVC processing (extrusion) plants (2) in the United States (*Anderson* et al. 1978). After removal of possible confusing factors (smoking, alcohol intake, past medical history), it emerged that the distribution of CEA titres among the polymerization workers was significantly different from that in the extrusion plant group and in a nonexposed reference group. Significant differences were also found for two of six job categories examined (polymerization and maintenance) compared with extrusion workers and the reference group. However, the usefulness of the CEA titre as a predictive indicator of possible increased risk seems doubtful.

4.4 Miscellaneous Aspects

4.4.1 Thrombocytopenia and Platelet Function Tests

Thrombocytopenia in chronic VCM intoxication was first mentioned – rather parenthetically and without further comment – in a paper published by *Antonyuzhenko* in 1968. Later *Jühe* et al. (1973) noticed that each of the first 13 autoclave cleaners referred to them during 1972 from a West German plant because of suspected skin and

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platelet spreading), enhanced response (platelet aggregation) to addition of ADP and collagen (Born test) and increased availability of phospholipid-containing platelet factor 3 (*Bachner* et al. 1975a). This pattern was thought to be compatible with the notion of an increased turnover rate due to derangement of microcirculation (CDIC) in liver and spleen and defective reticuloendothelial system (RES) clearance of activated clotting factors (*Bachner* et al. 1974b). *Ward* (1976) and *Ward* et al. (1976) suggested that thrombocytopenia could be construed as confirmatory evidence of an immune complex disorder. *Heusermann* and *Stutte* (1977a) noted unusual focal aggregation of platelets in Klatsch preparations of spleen tissue and increased platelet pooling (platelets trapped within the subsinusoidal meshwork of pulp cords) in the red pulp of the spleen on electron microscopy as well as phagocytosis of thrombocytes by sinusoidal macrophages. *Schaffner* et al. (1976) found platelet thrombi in and around hepatic sinusoids in mice after exposure to VCM. A direct toxic action of VCM (or metabolites) on the bone marrow has not been demonstrated so far.

Although the pathogenesis of thrombocytopenia in VCM-induced disease is not fully understood, it seems at present most likely that it is caused by increased turnover and consumption of platelets within the abnormal vascular spaces of the liver and spleen. A similar type of consumption coagulopathy was described as complication of spontaneous haemangiosarcoma of the liver by *Truell* et al. (1973). A haemostatic defect more complex than mere pooling and destruction of platelets in the enlarged spleen has also been commented upon in the paper by *Gerrits* et al. (1974) in connection with splenomegaly of various noncirrhotic origin.

4.4.2 Central and Peripheral Nervous System

Miscellaneous nonspecific and somewhat indefinite symptoms have been described in connection with chronic inhalational exposure to VCM in PVC-production workers, such as dizziness, disorientation, blurring of vision and memory, headache, irritability, excessive fatigue and somnolence, sleep reversal or insomnia and other pseudoneurasthenic symptoms (*Sucai* et al. 1963, 1975; *Schottek* 1969; *Lilis* et al. 1975 and others). This prenarcotic syndrome was interpreted as a manifestation of a potentially reversible acute toxic encephalopathy. Its danger to the individual was thought to lie mainly in resultant inadequate reactions to critical situations (*Schottek* 1969). However, *Vale* et al. (1976) reported that several individuals in a group of 95 comparatively young ex-workers, the majority of whom had no other symptoms, complained of fatigue, headache, listlessness and depression, with onset of symptoms having been delayed as long as 2 years after cessation of employment.

With reference to such 'pseudoneurasthenic complaints', which may be interpreted as the mildest degree of a toxic encephalopathy, *Penn* et al. (1975) examined a group of 21 autoclave cleaners at varying intervals after cessation of exposure, all of whom presented with other (cutaneous, angioneurotic, hepatic) manifestations of vinyl chloride disease. Clinical symptoms of a more or less distinct encephalopathy (including cerebellar ataxia in 4) were found in all but one of them. EEG recordings were normal in only five of these patients; in the others, parenrhythmia, dysenrhythmia or a so-called subvigil electroencephalogram was observed. Evidence of distal polyneuropathy, found in 19 patients, was attributed in the first place to an abnormal peripheral circu-

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1969; *Szende* et al. 1970; *Vertkin* and *Mamontov* 1970; *Frongia* et al. 1974; *Darke* 1976; *Arnaud* et al. 1978). Considerable exposure to VPC dust is the rule in the drying, bagging and storage areas of PVC-producing plants. Photographs contained in *Karstedt's* paper (1976) give a general idea of the potential dust exposure. Measurements of the concentration of PVC dust at various sites of the bagging operations were reported as long ago as 1955 by *Parmeggiani* and *Sassi*. In 1969 *Broussard* mentioned the possibility of development of chronic bronchitis caused by the inhalation of PVC dust. The insoluble and inactive dust particles were thought to accumulate in the lungs blocking alveolar spaces and being taken up by alveolar cells. This could lead to elimination of these cells via lymph vessels to regional lymph nodes, with either enlargement of the hilar region or a micronodular aspect of interstitial pulmonary fibrosis without hilar lymph node enlargement but progressive respiratory insufficiency.

Szende et al. (1970) reported the case of a 31-year-old worker who presented with severe dyspnoea; a chest x-ray examination revealed diffuse micronodular pulmonary lesions. He had been engaged for only 1 year in shovelling PVC powder at a processing factory. Lung biopsy revealed moderate diffuse fibrosis and small focal granulomatous lesions containing ovoid or polygonal birefringent foreign material which could be eluted by treatment with a known solvent of PVC. Microscopic examination of PVC dust particles collected at the patient's place of work showed them to be morphologically identical with the particles found in the patient's lungs.

Another anecdotal case of pneumoconiosis after 23 years of employment in a PVC bagging area, with radiological evidence of diffuse micronodular infiltrates and granulomatous lesions found in a lung biopsy identical with those recorded by *Szende* et al., was published by *Arnaud* et al. in 1978. Histology of open lung biopsies in 1 of 14 VCM-exposed British workers, who complained of breathlessness, revealed focal alveolar wall thickening with macrophages in alveolar spaces and increased reticulin and collagen on electron microscopy (*Darke* 1976). Although chest x-ray appearances were normal and routine respiratory function tests showed only slightly impaired CO_2 diffusion in six individuals, perfusion and ventilation scans revealed strikingly abnormal pictures, including marked perfusion defects of upper lobes. *Darke* pointed out that some of the men worst affected had been engaged in the polymerization of 'plastisol', a very fine PVC powder with particle size around 0.5 μm.

Selikoff (1976) called attention to results obtained by *Frongia* et al. (1974), who observed significant histopathological changes in the lungs of guinea-pigs and rats exposed for 2–7 months to inhalation of the airborne PVC dust in a PVC bagging area. Lesions began to appear at 2 months of exposure (alveolar histiocyte-macrophage reactions); they proved to be fairly marked after 4 months, with appearance of foreign body giant cells, and proceeded to development of large interstitial granulomatous foci. *Vertkin* and *Mamontov* (1970) who examined 96 workers engaged in the manufacture of articles made from PVC powder, also found a considerable proportion of them were suffering from functional and morphological alterations of the bronchopulmonary system, which they ascribed to their exposure to PVC dust. They quoted results of earlier animal experiments conducted in 1963 by *Golovatyuk* and later by *Shlyakherskii*. These last authors had apparently shown that exposure of animals to PVC dust may lead to the development of chronic pneumonia and eventually to a sort of mild fibrosis of the lungs.

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pregnancies in women who had more than two abortions. The findings of this study raised the question of possible genetic risks of VCM to man and led to the suggestion that germ-cell damage in the father through direct VCM exposure might be a possible explanation.

No clear-cut linkage of PVC production and increased occurrence of congenital malformations (primarily CNS malformations) emerged from preliminary studies in three Ohio communities with PVC production plants. But the need for further study of possible contributary factors was indicated (*Infante* 1976). In fact, none of the parents of affected children in Painsville, one of the three Ohio communities, had ever worked at either of the two PVC polymerization plants in Painsville or lived within two miles of these plants (*Edmonds* et al. 1975).

5 Conclusion and Outlook

The combined efforts of multiple disciplines have been necessary to arrive at the full recognition of the range of pathology associated with occupational exposure to vinyl chloride. It can only be hoped that the lesson from the vinyl chloride problem may help to bring about an increased awareness of the risks and hazards which are inevitably the consequence of an ever-expanding technology.

The importance of this lesson lies in its exemplary nature. A single substance of rather simple chemical structure, which was long held to be a comparatively safe compound, even by experts, turned out after all to be a carcinogen with a very long latency period for those who were heavily exposed to it. But its carcinogenic properties would most probably still have gone unnoticed if the resulting malignancy had been any cancer other than of an exceptionally rare type. Animal experiments in the early days later proved to have been broken off before the oncogenicity of this chemical compound could have been detected.

The lesson to be learned is that in future any new chemical which is to be widely introduced into the environment should be scrutinized closely, for a sufficient length of time, and with the aid of all available methods for the detection of potential carcinogenic effects. In addition, we should keep in mind that in industrial surroundings we almost never deal with a single compound, but with a very complex occupational environment whose carcinogenic potential is still a completely unresolved problem.

If currently adopted guidelines for industrial hygiene are strictly adhered to, there is reason to hope that initiation of new cases of VCM-induced angiosarcoma of the liver can be effectively prevented. Unfortunately, however, it can be expected that in view of the long latency period for tumour promotion additional cases will appear during the next decade.

Considering the ever-increasing complexity of environmental influences, future research will be faced with almost insurmountable obstacles in its endeavour to establish 'safe' levels for potentially hazardous chemicals. Promising areas for further studies in the field of vinyl chloride and allied compounds may be the problem of the interaction

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