

Release of formaldehyde from denture base polymers

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The release of formaldehyde in an aqueous environment at 37°C from the surface of heat-polymerized, and auto-polymerized dough and pour type acrylic denture base materials was determined quantitatively. The analytical method used was based on determination of the reaction product of formaldehyde and dimedone by means of high performance liquid chromatography (HPLC), i.e. the method is specific for formaldehyde. Chemical model reactions were carried out to simulate possible reaction mechanisms for the formation of formaldehyde in denture base polymers. The quantities of released formaldehyde was dependent on the processing conditions and composition of the material. Heat-polymerized denture base materials released considerably less formaldehyde than the auto-polymerized dough and pour types of materials.

Key-words: Allergy; chemical analysis; methyl methacrylate; oxygen inhibition; dental materials

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When dentures are placed in contact with the oral mucosa, some patients develop a «denture stomatitis», i.e. a reddening of the oral mucous membrane normally confined to the area immediately beneath the denture base. This condition is often attributed to fungal infections with candida species and poor-fitting dentures including unbalanced occlusion (2, 17, 18).

Allergic reactions to constituents of the denture base polymers have been reported (6, 11): A number of reports have been presented on allergic reactions ascribed to methyl methacrylate monomer (8, 9, 16, 21). A common factor in these reported cases was that auto-polymerized resins had been used. However, hypersensitivity reactions to heat-poly-

merized acrylic dentures which had been worn for some time, have also been reported (5, 10, 15, 21). Apart from Johansen & Widnes, the authors of these reports also ascribe the hypersensitivity reaction to the leaching out of residual monomer. Cutaneous patch tests by Johansen & Widnes (10) showed that the patient was only allergic to formaldehyde and fillings from the old denture, while in five control persons no reactions occurred. After substituting the acrylic denture with one made from vulcanite, all symptoms quickly subsided.

Djerassi & Berowa (7) found a similarity in the frequency of positive patch tests among people occupied in the dental profession to trioxane, i.e. trimeric form-

aldehyde, and to acrylic denture polymers. Formaldehyde is known to cause hypersensitivity reactions (13). It is therefore justified to consider this substance when discussing hypersensitivity reactions to denture base polymers. Accordingly the purpose of this work was to study the release and the origin of formaldehyde in heat-polymerized, conventional dough auto-polymerized and pour type auto-polymerized acrylic denture base materials. For this purpose a sensitive and selective analytical method for the determination of formaldehyde in water had to be developed. The method of formaldehyde determination used in this investigation is based on the reaction of for-

maldehyde with 5,5-dimethyl-1,3-cyclohexanedione, the so-called dimedone (23).

MATERIALS AND METHODS

The nine materials listed in Table 1 were investigated. These materials comprise heat-polymerized and auto-polymerized dough and pour type resins and were selected because they contain different types and various quantities of cross-linking agents. The powder/liquid ratios used for processing and the polymerization conditions are given in Table 2. The heat-polymerized resins use benzoyl peroxide as initiator. The auto-polymerized dough and pour type resins use

Table 1. *Materials used in the investigation*

Material	Code	Batch no.		Manufacturer
		powder	liquid	
Paladon 65	PD	5062900	5061472	Kulzer & Co. GmbH, Germany
Palacast	PC	7070093	7070415	
Palapress	PP	6030545	6110357	
Swe Base	SB	605	701	Svedia Dental-Industri AB, Sweden
Swe Flow	SF	514	612	
Swebond Compact	SC	602	610	
SR 3/60	SR	22462	0701R6560	Ivoclar AG, Liechtenstein
Ivocast	IC	19593/19821	1110117503	
Quick 20	Q20	00377331	2802117246	

Table 2. *The polymerization and processing conditions used according to manufacturers' instructions*

	Powder/liquid ratio (volume)	Curing temperature (°C)	Curing pressure (kPa)	Time under pressure (min)
Paladon 65	3:1	*	*	*
Swe Base	3:1	*	*	*
SR 3/60	3:1	*	*	*
Palacast	2:1	43	220	45
Swe Flow	2:1	45	200	30
Ivocast	2.7:1	45	300	30
Palapress	2:1	40	250	6-7
Swebond Compact	2.5:1	40	250	10
Quick 20	3:1	23	200	20

* heat-polymerized resins were cured according to ISO R 1567 (June 1970), i.e. 90 minutes at $73 \pm 1^\circ\text{C}$ followed by 30 minutes in boiling water.

benzoyl peroxide and tertiary aromatic amine initiator systems, except the two products Palapress and Palacast, which have another redox initiator system.

Specimen preparation and treatment

Specimen disks, 50 ± 1 mm in diameter and 0.5 ± 0.1 mm thick, were prepared using a stainless steel mould mounted with gypsum in a denture flask. The heat-polymerized denture base materials were processed according to ISO R 1567 (International Organization for Standardization, Recommendation 1567, 1st Edition, June 1970), i.e. after mixing powder and liquid the dough was placed in the mould under pressure, submerged in water at $73 \pm 1^\circ\text{C}$ for 90 min and then immersed in boiling water for 30 min. Auto-polymerized dough and pour type resins were processed according to the manufacturers' instructions (Table 2). The specimen disks were stored for four days at room temperature, $23 \pm 1^\circ\text{C}$, in air or in an atmosphere of purified argon before they were immersed in water. The specimens were then stored for 72 hours in 31.5 ml of air saturated or argon saturated aqueous solutions of dimedone at $37 \pm 1^\circ\text{C}$. The aqueous solution had a concentration of dimedone - 5.5-dimethyl-1.3-cyclohexanedione - of 235 mg/l. Closed systems were used to avoid contamination with formaldehyde from the environment. When the release of formaldehyde was determined in an argon atmosphere, the exclusion of the atmospheric oxygen was also essential. For these purposes a Schlenk-type vessel (20) was used (Fig. 1). Careful stirring of the aqueous solution by means of a magnetic stirrer was applied. After 72 hours 30 ml ethanol was added to the mixture. After 30 min of stirring the specimen was separated from the solution. Ethanol was added to dissolve the formaldehyde-dimedone reaction product (Fig. 2) precipitated on the specimen and the wall of the reaction vessel.

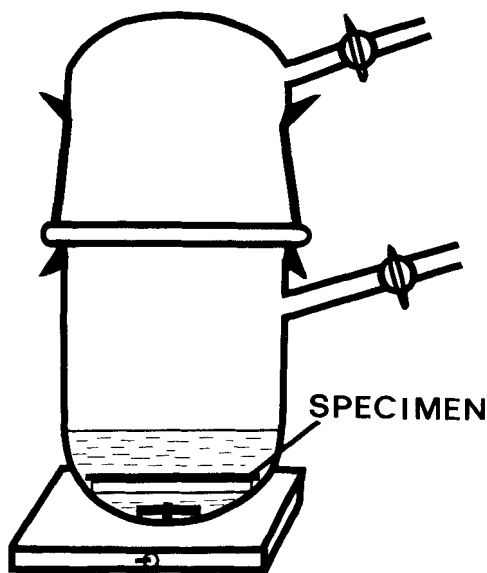


Fig. 1. Reaction vessel with magnetic stirrer, aqueous dimedone solution and test specimen. The equipment can be evacuated, to eliminate air, and the inert gas argon introduced through the side-arms.

Quantitative determination of formaldehyde released from denture base materials

The solutions containing the formaldehyde-dimedone reaction product were analyzed by means of high performance liquid chromatography (HPLC) (Liquid Chromatograph, Model 3500 B, Spectra-Physics, Santa Clara, CA 95051, USA with SF 770 Spectroflow, Schoeffel Instrument Corp., Westwood, NJ 07675, (USA). A reversed-phase partition chromatographic column (Spherisorb S5 ODS, 25 mm long, and 4.6 mm bore; Phase Separations Limited, Queensferry, Deeside, Clwyd, U.K.) was used with the solvent system comprising 65% methanol - 35% water (v/v). Representative chromatograms (Fig. 3) were run at a flow rate of 0.8 ml/min with an operating pressure of 100 atm. Samples were injected by means of a rotary valve injector equipped with a 100 μl sample loop. The UV-detector (SF 770 Spectroflow) was

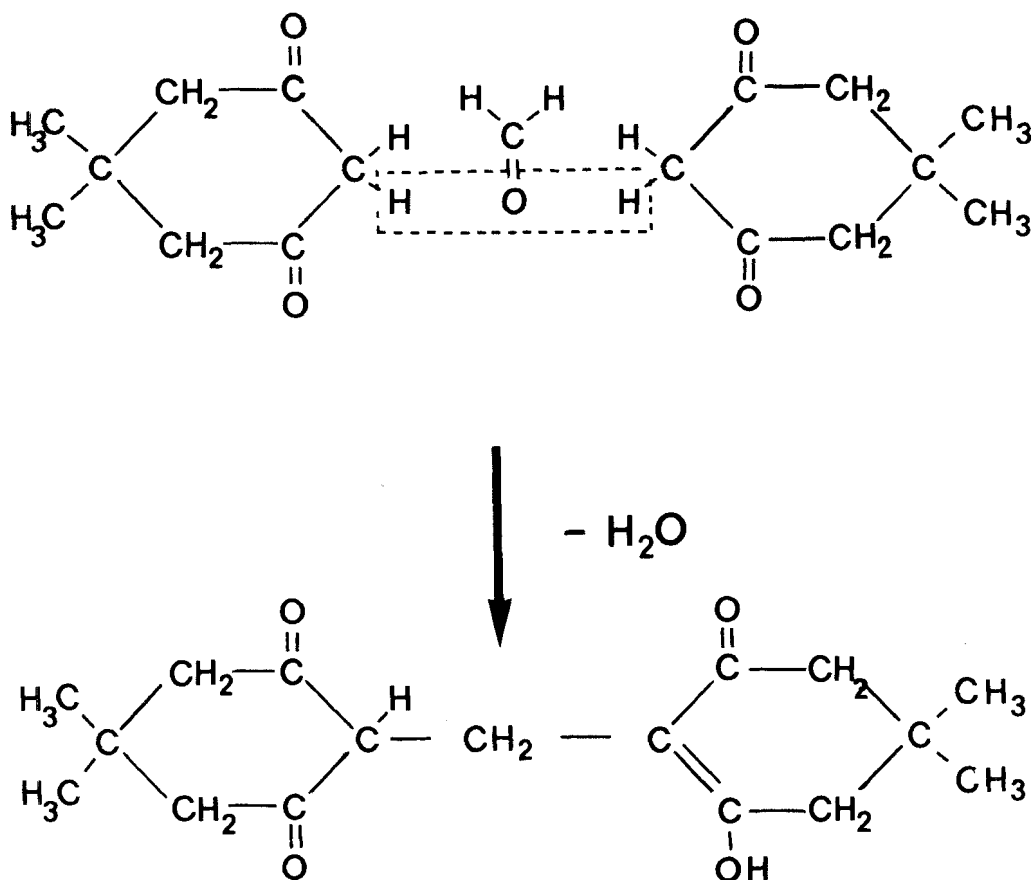


Fig 2. The reaction between two molecules of dimesone, 5,5-dimethyl - 1,3-cyclohexanedione, and one molecule of formaldehyde.

set at 254 nm. For the quantitative determinations of released formaldehyde from the specimens, a standard calibration curve was obtained by plotting the peak areas of known concentrations of formaldehyde in dimesone-water-ethanol solutions. The peak areas were measured electronically with a computing integrator (Autolab Minigrator, Spectra-Physics, Santa Clara, CA 95051, USA). Referring to the standard calibration curve, the peak areas from the HPLC-analyses of the formaldehyde-dimesone product, based on five specimens, were transformed into mg formaldehyde released per m² of the specimen surface.

Distilled water and solvents used for the experiments under inert conditions were purified from oxygen by purging with argon during refluxing and distillation (12).

The polymer powders and monomer liquids of the denture base materials were also analyzed for the content of formaldehyde. Both powders and liquids were stirred with 30 ml argon saturated aqueous dimesone solution for 72 hours under inert conditions at 37°C. To the powder-water-dimesone mixture argon saturated ethanol was added and the liquid phase was separated from the powder after 30 min. The monomer liquid was separated from the aqueous phase after

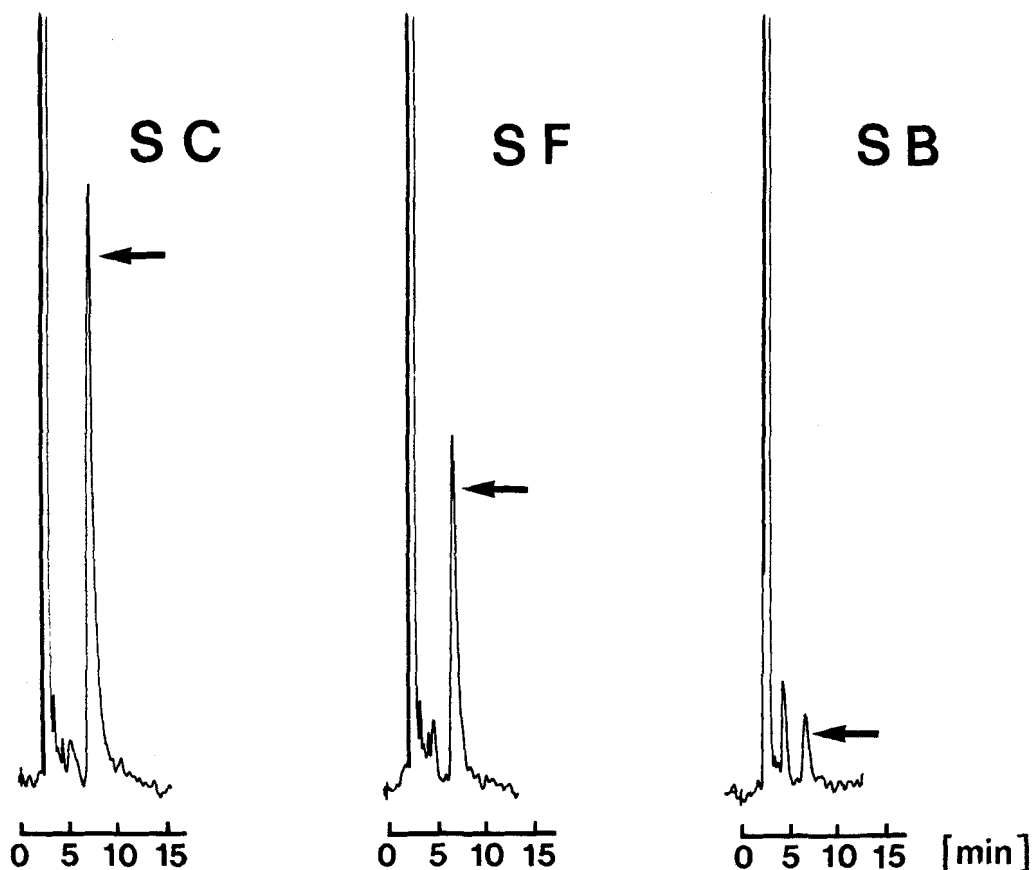


Fig. 3. Typical HPLC-chromatograms with the peak of the formaldehyde-dimedone reaction product indicated with an arrow. To the left and in the center chromatograms representing formaldehyde released from an auto-polymerized dough and pour type denture base polymer respectively. To the right a chromatogram representing formaldehyde released from a heat-polymerized denture base polymer.

72 hours and 30 ml argon saturated ethanol added to the aqueous phase. The water-ethanol solutions were then analyzed by means of HPLC.

Analysis of monomer composition

The monomer liquids were diluted in methanol and the content of methyl methacrylate and cross-linking agents determined by quantitative, reversed phase HPLC, supported by combined gas chromatography mass spectrometry (990 Gas Chromatograph, Perkin-Elmer

Corp., Norwalk, CT 06856, USA, Hitachi Perkin-Elmer RMU-6L Mass Spectrometer, Hitachi Ltd., Tokyo, Japan).

Determination of oxygen in the monomer liquids

The monomer liquids used in this investigation were analyzed for the content of dissolved oxygen by means of an oxygen analyzer (Fieldlab Oxygen Analyzer, Beckman Instruments, Inc., Fullerton, CA 92634, USA). The results were expressed as parts per million (ppm) weight by weight.

Formation and degradation of oxygen-methyl methacrylate copolymer

Methyl methacrylate monomer was washed free from inhibitor, dried and purified by vacuum distillation (14). The oxygen-methyl methacrylate copolymer was prepared by bubbling pure oxygen through the monomer liquid (25 g) at 37°C in the presence of an initiator for four weeks. The procedure of Mayo & Miller (14) was used, except that the reaction temperature was 37°C instead of 50°C. After four weeks the reaction mixture was analyzed by HPLC with respect to the content of unreacted methyl methacrylate monomer, methyl pyruvate and formaldehyde. Formaldehyde formed during the oxidation processes was also collected as dry paraformaldehyde in the condenser of the reactor, and in the exit trap it was determined as the formaldehyde-dimedone product. For quantitative determination the dry paraformaldehyde was weighed, and the formaldehyde-dimedone product was determined quantitatively by HPLC.

The concentration of the oxygen-methyl methacrylate copolymer from the reaction mixture was obtained by vacuum distillation at room temperature. The residue was dissolved in methanol and the polymeric peroxide separated on cooling (1). After repeated dissolving and precipitation, the product was isolated as a colorless mass at -20°C. At room temperature the oxygen-methyl methacrylate copolymer was a high-viscous oil.

A portion (approx. 100 mg) of the oxygen-methyl methacrylate copolymer was treated under inert conditions with the aqueous dimedone solution of 37°C for 72 hours in the same manner as the denture base specimens. The separated aqueous solution mixed with ethanol was analyzed by means of HPLC for the quantitative determination of formaldehyde. With argon saturated water without dimedone the same procedure was used to determine the quantity of released

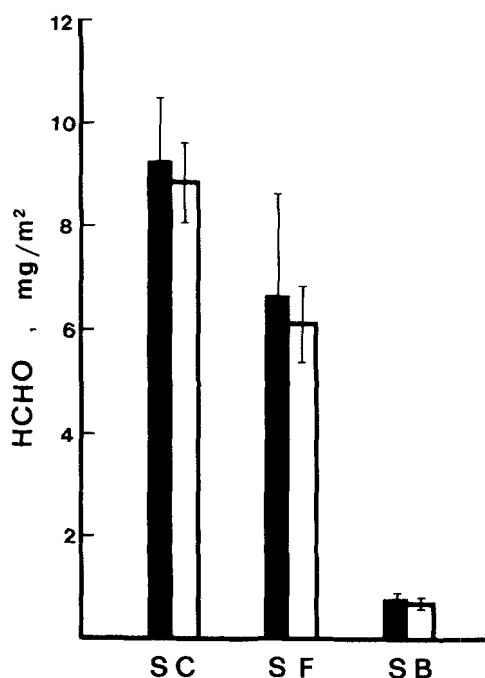


Fig. 4. Release of formaldehyde from denture base polymers, with relatively low contents of the cross-linking agent ethylene glycol dimethacrylate in the monomer liquids, during 72 hours at 37°C in water. SC; auto-polymerized dough type, SF; auto-polymerized pour type, and SB; heat-polymerized denture base polymer. Solid bars in air-saturated water and open bars in argon-saturated water.

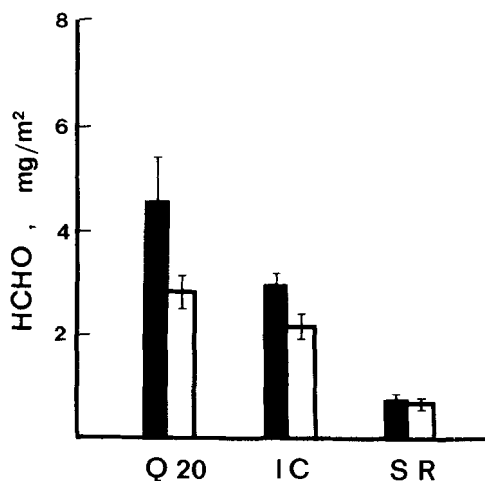


Fig. 5. Release of formaldehyde from denture base polymers, with relatively high contents of the cross-linking agent ethylene glycol dimethacrylate in the monomer liquids, during 72 hours at 37°C in water. Q20; auto-polymerized dough type, IC; auto-polymerized pour type, and SR; heat-polymerized denture base polymer. Solid bars in air-saturated water and open bars in argon-saturated water.

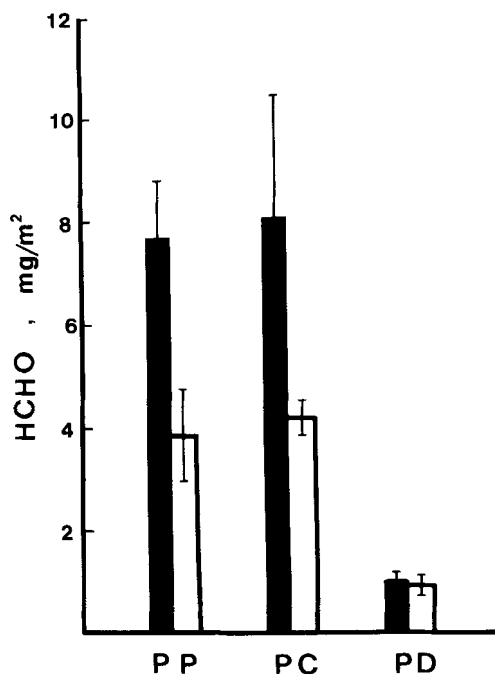


Fig. 6. Release of formaldehyde from denture base polymers, with the cross-linking agent 1.4-butanediol dimethacrylate, during 72 hours at 37°C in water. PP; auto-polymerized dough type, PC; auto-polymerized pour type, and PD; heat-polymerized denture base polymer. Solid bars in air-saturated water and open bars in argon-saturated water.

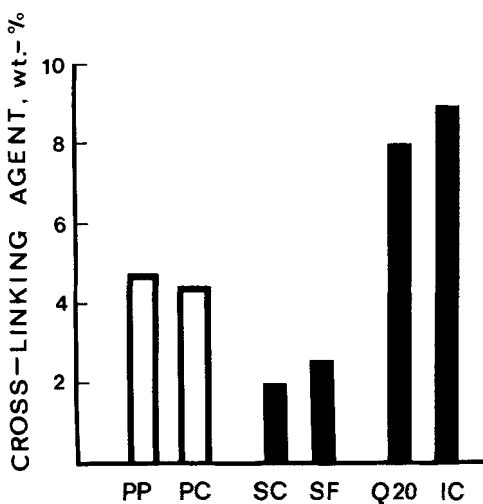


Fig. 7. Content of the cross-linking agent 1.4-butanediol dimethacrylate (open bars) and ethylene glycol dimethacrylate (solid bars) in the monomer liquids of auto-polymerized dough and pour type denture base polymers.

methyl methacrylate monomer from the oxygen-methyl methacrylate copolymer after 72 hours at 37°C.

RESULTS

Release of formaldehyde

The quantities of formaldehyde released during the first 72 hours in water from the surface of the nine investigated denture base polymers are shown in Figs. 4, 5 and 6. It should be noted that all three heat-polymerized materials released relatively small quantities compared with some of the auto-polymerized dough and pour type resins. The quantities of formaldehyde released from the polymer powders are found to be relatively low, and were calculated to be less than 1 mg per m² for all products. The quantities of formaldehyde determined in the monomer liquids used in this investigation were below the detection limit.

Analyses of monomer liquids

The auto-polymerized denture base polymers represent different types with respect to the content of cross-linking agents in the monomer liquids (Fig. 7). 1.4-butanediol dimethacrylate was found as the cross-linking agent in two auto-polymerizing materials. The other monomer liquids represent two categories: one with a low content, and the other with a relatively high content of the cross-linking agent ethylene glycol dimethacrylate.

Oxygen in the monomer liquids

The content of dissolved molecular oxygen in all monomer liquids used in this investigation ranged from 58.5 to 62.5 ppm.

Oxygen-methyl methacrylate copolymer

After four weeks at 37°C the reaction between methyl methacrylate and oxygen gave a mixture of methyl methacrylate monomer, methyl pyruvate, formaldehyde and oxygen-methyl methacrylate

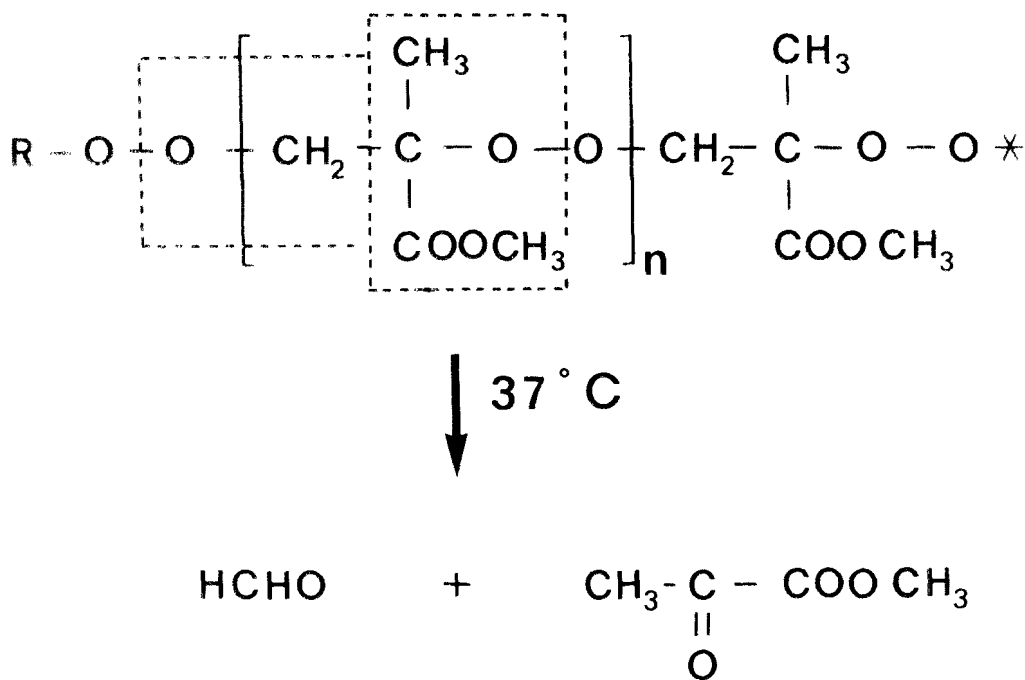


Fig. 8. Decomposition of the oxygen-methyl methacrylate copolymer with formation of the cleavage products formaldehyde and methyl pyruvate.

copolymer. The reaction mixture contained 51 weight-% methyl methacrylate and 13 weight-% methyl pyruvate. Formaldehyde was isolated as paraformaldehyde, 400 mg, from the condenser, and as dissolved formaldehyde in the reaction mixture and in the exit trap, 250 mg. A calculated balance based on the content of methyl methacrylate monomer and methyl pyruvate in the reaction mixture showed that approximately 40% of the methyl methacrylate was converted. Approximately 13% of the monomer was converted to methyl pyruvate and formaldehyde, and approximately 27% to oxygen-methyl methacrylate copolymer.

The weight of the isolated purified oxygen-methyl methacrylate copolymer was 2.5 g, i.e. approximately 30% of the calculated yield. The purified copolymer contained less than 1 mg methyl methacrylate per g copolymer.

Equimolar quantities of formaldehyde and methyl pyruvate should be formed during the reactions (14), i.e. the determined 650 mg formaldehyde represented approximately 65% of the calculated yield.

The degradation of the oxygen-methyl methacrylate copolymer in water at 37°C showed that after 72 hours 3.8 mg (0.13 mmol) formaldehyde and 5.8 mg (0.06 mmol) methyl methacrylate monomer were released per gram copolymer.

DISCUSSION

Dimedone is a specific reagent for aldehydes and gives reaction products with low solubility in water (4). It has previously been reported that heat-cured acrylic denture base polymers contain formaldehyde (24,25). One of the previous

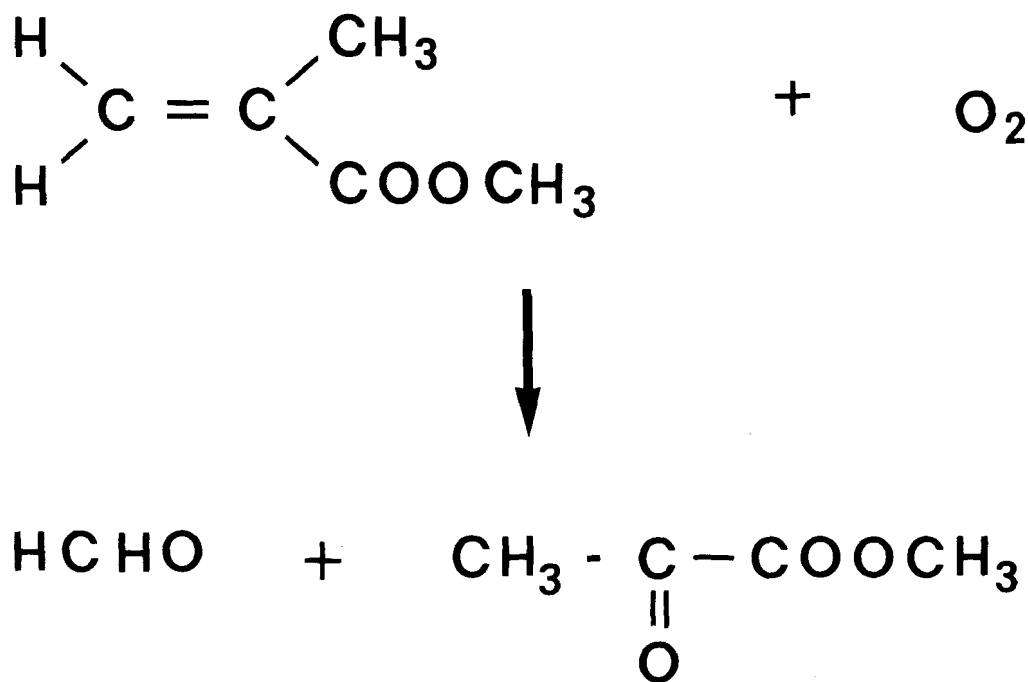


Fig. 9. The oxydation reaction of methyl methacrylate monomer with formation of formaldehyde and methyl pyruvate.

reports is also based on the use of dimedone as reagent. By means of gas chromatography the amounts of formaldehyde were determined by measuring the remaining quantities of dimedone after the reaction had been completed (25). The method used in this investigation is specific for formaldehyde, because the quantity of the dimedone-formaldehyde reaction product is measured. Moreover, the dimedone reaction products of the various aldehydes have different retention times in the applied HPLC-system.

The conversion process of methyl methacrylate monomer to poly(methyl methacrylate) can be divided into three dominant stages (22): The initial stage is the inhibition period during which there is no polymerization. The intermediate stage has a comparatively constant rate of polymerization, and in the main stage, the so-called gel-stage, the conversion in-

creases to very high rates of polymerization.

During the initial stage, the inhibition period, an alternating copolymerization of methyl methacrylate and oxygen has been assumed (19). The length of the inhibition period should be proportional to the initial concentration of oxygen, and an added inhibitor, e.g. p-hydroquinone, should increase the inhibition period (3). Mayo & Miller (14) studied the reactions between methyl methacrylate and oxygen at 50°C. In their study it was concluded that most, if not all of the cleavage products, i.e. formaldehyde and methyl pyruvate, were primary oxydation products, not secondary products from decomposition of oxygen-methyl methacrylate copolymer.

The formation of the cleavage products and oxygen-methyl methacrylate copolymer at 37°C in the present study

confirm these previous investigations. The reaction of oxygen-methyl methacrylate copolymer in water at 37°C indicated that the polymeric peroxide depolymerized with formation of the cleavage products formaldehyde and methyl pyruvate. In addition, the copolymer depolymerized with formation of the monomer methyl methacrylate. The cleavage reaction with formation of formaldehyde and methyl pyruvate from the polymeric peroxide radical and the non-radical termination products can be represented by the simplified reaction scheme shown in Fig. 8. The formation of the cleavage products according to primary oxidation processes can be presented simplified according to Fig. 9. Accordingly, formaldehyde can be formed in different ways in denture base polymers: Some of the formaldehyde can be formed during the inhibition period as a primary oxidation product. Formaldehyde also can be formed as a cleavage product of oxygen-methyl methacrylate copolymer, and some formaldehyde can be formed as an oxydation product of remaining monomeric methyl methacrylate in the polymerized denture base material.

The release of formaldehyde in air saturated water was found to be larger than in argon-saturated water. The differences in quantity represent formaldehyde formed by oxydation of unreacted methacrylate in the polymerized material. The results also demonstrate that the quantity of released formaldehyde is dependent on the processing conditions of the denture base polymer, i.e. the auto-polymerized dough and pour type materials release more formaldehyde than the heat-cured materials. The quantity of released formaldehyde from different heat-cured materials is of the same magnitude. The release of the relatively small quantities of formaldehyde from heat-cured materials is probably due to the fact that the oxygen-methyl methacrylate copolymer

is thermally unstable. At the processing conditions of the heat-cured materials with 30 min in boiling water the polymeric peroxide will to a great extent decompose and the volatile formaldehyde diffuse out of the denture base materials. Prolonged time at high temperatures should further decrease the quantity of releasable formaldehyde.

The auto-polymerized dough and pour type materials released different quantities of formaldehyde from the surfaces. The monomer liquids of the various materials have different formulations with respect to the content of the cross-linking agent, Fig. 7. They have, however, also various powder/liquid ratios, Table 2. The auto-polymerized materials with the highest content of the cross-linking agent ethylene glycol dimethacrylate and with the highest powder/liquid ratio released less formaldehyde than the other auto-polymerized materials. Further studies are necessary to explain the differences in the amounts of released formaldehyde from the auto-polymerized materials.

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