SHORT COMMUNICATION

Electrochemical measurements of mass transfer coefficients in a cell simulating tooth canals

J. NANZER, S. LANGLOIS, F. COEURET

Laboratoire de Génie des Procédés, CNRS Ecole Nationale Supérieure de Chimie de Rennes, Avenue du Général Leclerc, 35700 Rennes Beaulieu, France

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1. Introduction

Up to the present the electrochemical method for the determination of mass transfer coefficients between a liquid and a solid has been applied to many geometrical configurations, either with a view to designing electrochemical reactors or in order to solve heat transfer problems through the analogy between mass and heat transfer or for the study of local velocity gradients at walls [1, 2].

An application of this method was made in small size cells simulating the root canal and the associated secondary canals of a tooth (Fig. 1a). These secondary canals appear as ramifications of the main canal, and doubt exists concerning their irrigation, and thus their disinfection, by the disinfecting solution introduced by the dentist in the main canal during treatment.

At the present time, the vibration of a file introduced in the main canal is used, together with a flow-through irrigation of this canal, to debride, clean and disinfect the root canal system. Depending on the type of the commercial equipment used, the vibrations of the file (which is mounted at the extremity of a suitable insert in which the vibrations are produced) are sonic or ultrasonic, while the irrigating solution flows, under pressure, into the root main canal along the file (see Fig. 1b and 2). The use of ultrasonic vibrations is discussed in [3].

The idea of the research described here was to simulate the root canals as in Fig. 1b: the main canal is a straight cylindrical hole the ramifications of which are the secondary canals and the apical canal or apex. The secondary canals may be inclined or not as shown in Fig. 1b. The electrochemical method was applied in order to ascertain the value of the mass transfer coefficient between the liquid introduced into the main canal and electrodes located within the secondary canals; the values of the mass transfer coefficient, $\bar{k}_d$, are representative of the intensity of the convection within the secondary canals.

In initial exploratory experiments made in our laboratory [4], the lateral canals were simulated by short nickel capillaries (500 μm inner diameter) but the resulting analog cell model was then considered too complex for further work.

2. Experimental details

Figure 2 shows the experimental apparatus. The file was mounted at the extremity of the insert which was connected to a vibration generator (sound or ultrasound generator); the vibrations were produced in the insert and transmitted to the file. This part of the apparatus was exactly the same as that used by the odontologist. The insert was fixed on a support which could be moved vertically thus allowing the vertical position of the file to be changed with precision. The electrolyte (which replaced the irrigating solution) was introduced into the usual irrigation flow circuit from a reservoir maintained at 20° C under nitrogen pressure. By changing this pressure, the flow rate of electrolyte, Q_m, was varied. As in odontological use, the liquid flowed down along the file. The electrolyte was a mixture of $Fe(CN)_6K_3$ (0.005 M) and $Fe(CN)_6K_4$ (0.05 M) in NaOH (0.5 M). The ferricyanide concentration was measured by amperometric titration. The density and the kinematic viscosity of the electrolyte at 20° C were respectively 1057 kg m^{-3} and 1.24×10^{-6} m^2 s^{-1}.

The root was simulated by a small cell made of plexiglass, the detail of which is given in Fig. 3. The main canal was 17 mm long, with a diameter of 1 mm. The secondary canals also had a diameter of 1 mm: three of them were horizontal (and contain electrodes 1L, 2L and 3L) and spaced 5 mm between centres and three others were inclined at 45° (and contain electrodes 1R, 2R and 3R) but with their openings at the same level as those of the horizontal canals. The apical canal (or apex) which was at the lower extremity of the main canal contained electrode Ax. While electrodes 1R and 3R were just at the boundary of the main canals, electrode 2R was recessed 0.25 mm from this boundary.

The cathodes (electrodes L, R and Ax) were the polished cross-sectional areas of 1 mm diameter nickel wires. The lateral surface of the wires was previously isolated by coating with a thin layer of Bowen epoxy resin used in odontology. The electrodes were positioned, by use of a microscope, in the canals and fixed by polymerization of the resin. Depending on the canal, the electrode was positioned at the boundary of the main canal (electrodes L) or at a small distance from it (electrodes R), i.e. at the bottom of a small cavity. Further experiments will be made with deeper cavities [5] but at the present state of the research, the location of electrodes very near to the main canal was considered as sufficient. The anode was a nickel tube of diameter 1.5 mm, 10 mm long, located at the top of the main canal.

The electrolyte introduced into the root canal along

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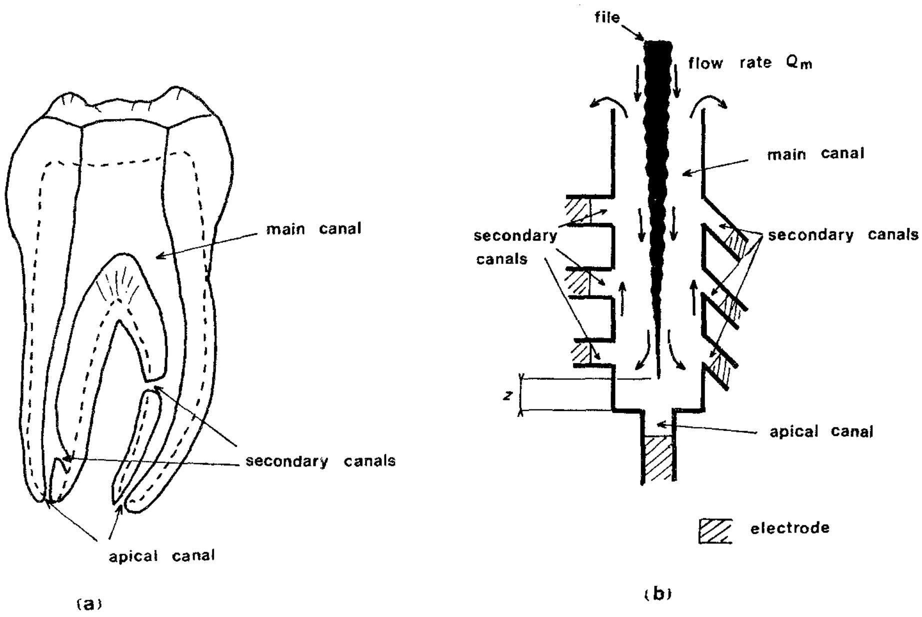

Fig. 1. Schematic views of the section of a root showing the canals (a) and of a cell model of the root canals (b).

the file was discharged from the cell by overflow, and its flow rate was measured by weighing. The values adopted for Q_m in the experiments were $Q_m = 2.9 \times 10^{-4}$ kg s^{-1} (ultrasonic vibrations) and $Q_m = 1.6 \times 10^{-4}$ kg s^{-1} (sonic vibrations).

The electrical circuit was a three-electrode potentiostatic circuit using a Tacussel PRGE polarograph. The electrode L situated near the selected cathode was used as the reference electrode. The current–potential polarization curves of the cathodes were recorded. Two generator-insert systems were used in their respective commercial form: one delivered ultrasonic vibrations (at a frequency of about 25 kHz and variable power increasing from P_1 to P_3), the other delivered sonic vibrations (at a frequency varying between 1.5 kHz and 3.0 kHz; four frequencies $F_1 < F_2 < F_3 < F_4$ were selected for the experiments). Power, frequency and amplitude were not known, as in the case where the equipment is used by an odontologist.

An Endosonic file 25 × 25 mm was used with the ultrasound generator, while two Rispic–Sonic files (15 × 25 mm and 40 × 25 mm) were used with the sound generator. The file was located approximately in the axis of the main canal, its vertical positon z with respect to the lower end of the main canal (Fig. 1b) being measured with precision by visual observation using a cathetometer.

3. Results and discussion

Depending on the experimental conditions (electrode, position of the file, type of vibration, frequency or power, vibration or no vibration), the form of the current–potential curve may be different. As an example Fig. 4 shows, for a file located at $z = 4.4$ mm, three current–potential curves obtained with electrodes 3L, Ax and 3R, respectively.

In the case of Fig. 4a, well-defined limiting current appears when the electrode potential is made progressively more cathodic. The limiting current, I_L, has a high value because the file is vibrating near the electrode. Such a form of curve could also be obtained in situations of free convection [1] but with a very much smaller limiting current and a very much smaller mass transfer coefficient.

In the cases of Figs 4b and 4c, the current–potential curve gives a maximum value and the current stabilizes to I_L values which are 10 to 20 times lower than

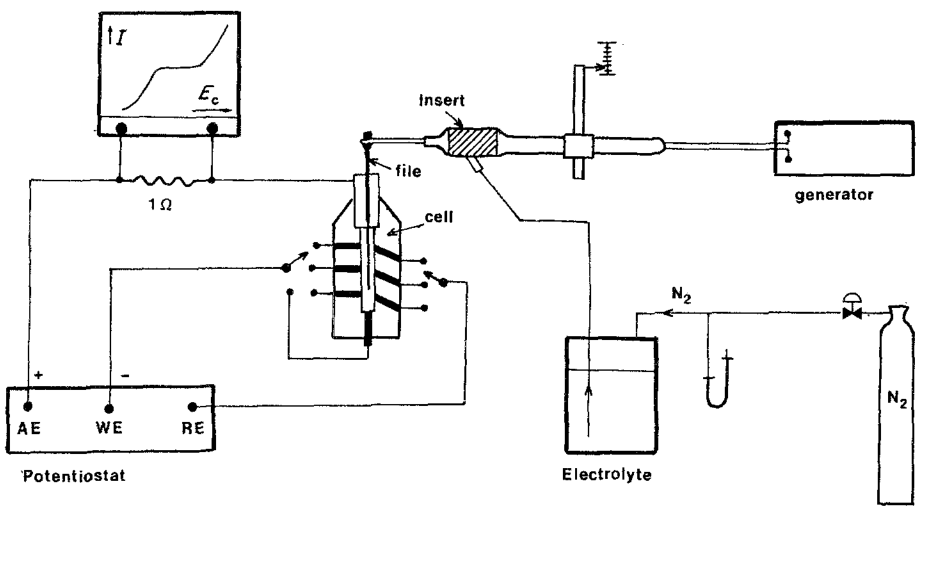

Fig. 2. General diagram of the experimental apparatus.

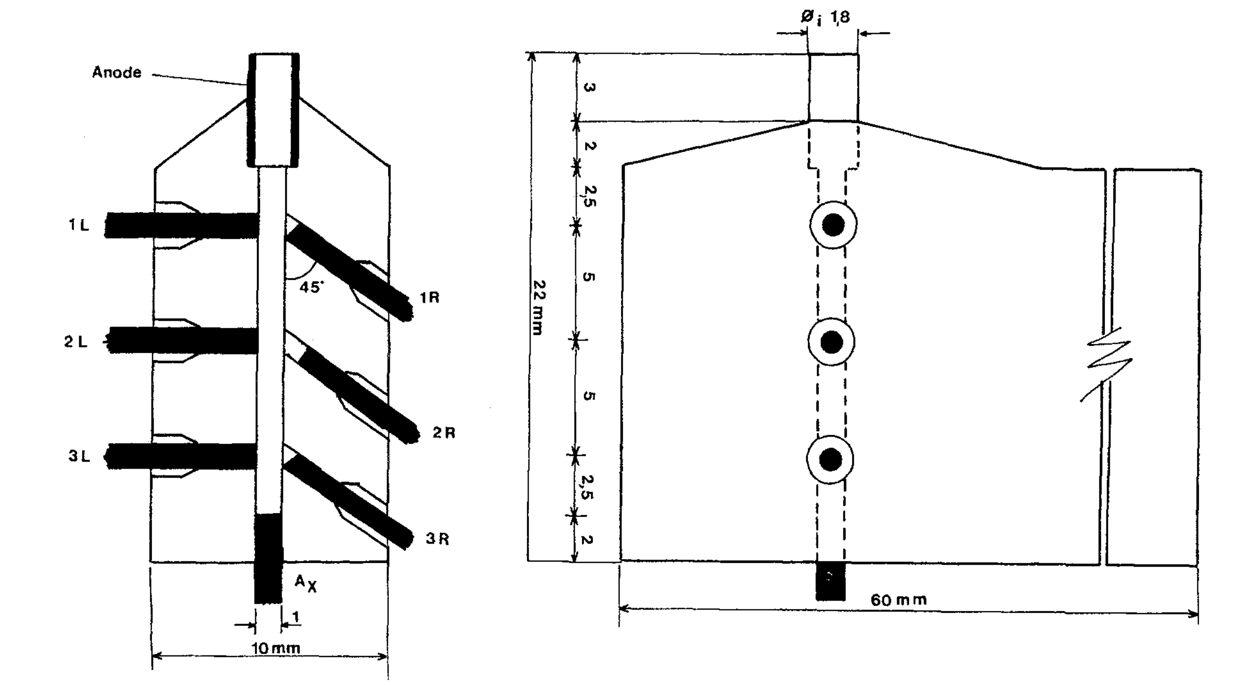

Fig. 3. Cell used in the experiments.

the case of Fig. 4a. It has to be noted that in some experiments with cathodes located in inclined canals, the current did not stabilize in the explored potential range, thus leading to typical 'camel-back' curves [1].

Three categories of experimental mass transfer coefficients are given in Table 1; more data will be presented in [5]. The observation of this table leads to the following comments.

3.1. *Ultrasonic vibrations*

In the experiments with ultrasonic vibrations,

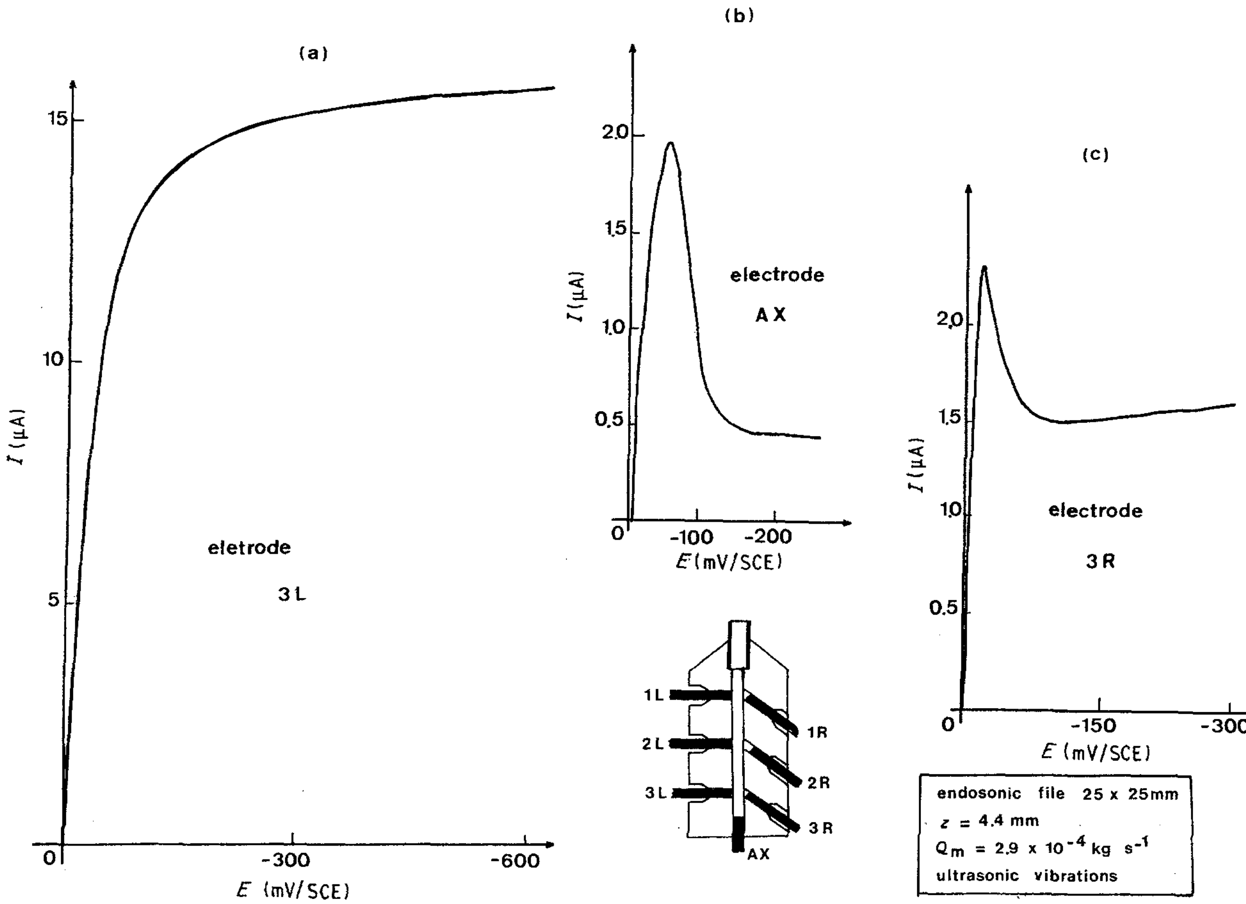

Fig. 4. Typical current-potential curves.

Table 1. Experimental values of the mass transfer coefficients

		Power or frequency	Values of $\bar{k}_d \times 10^5\,m\,s^{-1}$ at the electrodes					
			Ax	3L	1L	3R	2R	1R
Ultrasound generator	Endosonic file 25 × 25 mm	P_1	0.08	5.1	1.0	0.16	0.24	0.85
	$z = 4.4$ mm	P_2	0.16	3.5	1.9	0.21	0.55	1.08
	$Q_m = 2.9 \times 10^{-4}\,kg\,s^{-1}$	P_3	0.18	3.75	6.36	0.63	2.0	8.0
Sound generator	Rispic-Sonic file 15 × 25 mm	F_1	0.71	1.74	0.32	0.13		
	$z = 3.3$ mm	F_2	0.32	1.82	0.34	0.13		
	$Q_m = 1.6 \times 10^{-4}\,kg\,s^{-1}$	F_3	0.37	9.21	5.38	3.14		
		F_4	0.90	12.75	6.0	3.75		
Sound generator	Rispic-Sonic file 40 × 25 mm	F_1	0.45	2.19	–	0.12		
	$z = 3.3$ mm	F_2	0.82	2.64	0.22	0.12		
	$Q_m = 1.6 \times 10^{-4}\,kg\,s^{-1}$	F_3	0.12	2.89	2.20	0.35		
		F_4	0.17	4.33	2.51	0.40		

electrodes 1L and 3L are well irrigated by the electrolyte, while electrode 3R is not well irrigated whatever the power, and electrodes 2R and 1R are only irrigated for power P_3. It clearly follows that there is a different hydrodynamic situation near the electrodes according to whether they are located below or above the file extremity and disposed in horizontal or inclined lateral canals. Except for the highest power P_3, the inclined canals are not well irrigated and the polarogram is similar to Fig. 4b or 4c and $\bar{k}_d$ is about one-tenth of that found when the results indicate forced convection (comparison between 3L and 3R). Also it is evident that the apical electrode Ax is not irrigated whatever the value of the power. The value of $\bar{k}_d$ does not differ significantly from the value measured with only the forced irrigation flow (no vibration) [5]. It may thus be concluded, firstly that the propagation of the ultrasonic waves into lateral canals will be greatly hindered by the inclination of these canals and secondly, that no convection is induced in the vertical direction; the latter conclusion is logical because the file vibrates in the horizontal direction. It will be seen in [5] that for the highest power (P_3), and for $z = 3.3$ mm the influence of the flow rate, Q_m, on the mass transfer coefficient at electrode 3L is small but not negligible; indeed it was observed that:

$$\bar{k}_d = 1.4 \times 10^{-5}(Q_m)^{3.3}$$

where $\bar{k}_d$ is in $m\,s^{-1}$ and Q_m in $kg\,s^{-1}$. Such a result means that the choice of Q_m may be important; also it has to be emphasized that Q_m must allow the hydraulic transport of the solid residues out of the tooth canal.

3.2. *Sonic vibrations*

When the frequency is increased from F_1 to F_4, $\bar{k}_d$ increases continuously for all the electrodes except for electrode Ax. However the values of $\bar{k}_d$ for this electrode are generally higher than with the ultrasound generator (but the files are different in each category of experiment). This means that here the apical region is better irrigated by sonic vibrations than by ultrasonic ones, probably because the amplitudes of the vibrations are greater for the former than for the latter. The convection remains restricted for electrode Ax and also for electrodes 1R and 3R (inclined canals) at low frequencies. The acoustic waves are well propagated horizontally near the extremity of the file and in inclined canals at high frequencies.

Table 1 shows that there are some differences between the results obtained with two different files, but at present state of the research it is not known if they are significant. By increasing the frequency, $\bar{k}_d$ is also improved for file 40 × 25 mm. Only electrode 3L is highly influenced by the vibrations, and the values reached by $\bar{k}_d$ are smaller with file 40 × 25 than with file 15 × 25. No difference between the effects of the two files is evident at low frequencies. Another observation is that for electrode Ax, $\bar{k}_d$ decreases when the frequency increases but perhaps the effect of the amplitude of the vibration is not negligible.

It is clear that the vibration of the file principally improves the regions located near the file extremity; in these regions, it is expected that cavities parallel to the direction of the vibration could be irrigated, but this would have to be established experimentally. However, the fact that the short and wide cavities considered in the present work are not very easily irrigated is not encouraging in this respect. The improvement is smaller in the upper regions, i.e. near the point of attachment of the file (case of electrode 1L). The inclined canals and also the regions located below the file extremity are not well irrigated. This last observation seems to be of interest to the odontologist who seeks to protect the apical canal and to avoid the vibration of the corresponding extremity of the root (apex).

The present work cannot be discussed on the basis of values of power, frequency and amplitude of the vibrations; thus the data obtained depend on the equipment used and also are not easy to extrapolate to similar equipment from the same manufacturer. This undoubtedly restricts the scope of the present work; the fact that the diameter of the lateral canals is too high compared with the real dimensions (about 0.2 mm) also limits its scope.

This is the reason why the present work has to be seen as a demonstration of the usefulness of the electrochemical engineering approach in contributing to the solution of a biomedical engineering problem, rather than a definitive research operation. The problem considered in the present paper deserves further and more complete study.

Acknowledgements

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