Summary and conclusions

New in vitro models and methodologies are presented in this thesis that measure, image and compare the cleaning efficiency of several irrigation methods and solutions. Numerous experiments were conducted that have led to a better understanding of the mechanisms of action and optimization of cleaning efficiency of root canal irrigation. This will help to improve current endodontic practice aiming for a more predictable outcome.

In chapter II different experiments were presented using a standardized bovine root canal model. The ability of this model to quantify the chemical efficiency (reaction rate) between sodium hypochlorite (NaOCl) and the dentinal wall during root canal irrigation was assessed and controlled. A dimensional characterization of the model allowed further comparison with a human size tooth and differences in sizes were accounted for. The following was concluded:

- Concentration, activation and activation method, refreshment and exposure time enhanced the chemical efficiency of NaOCl when in contact with dentin, whereas pH did not.
- Concentration was the most influential factor on the chemical efficiency of NaOCl. This effect could not be compensated for by a combination of ultrasonic activation, multiple refreshments and extended exposure time.
- The intermittent flush protocol, which combines multiple activation/refreshment cycles, increased the reaction rate of NaOCl by 28% in comparison to similar conditions without refreshment. The total amount of chlorine consumed during each activation/refreshment cycle decreases significantly, with no significant change after the third cycle.
- Activation is a strong enhancer of the reaction rate of NaOCl. Its effect was not limited to the activation period but extended to the rest interval of 3 min after activation, whereas the consumption of available chlorine increased significantly. This effect seemed to be more pronounced after irrigant activation by laser.
- The temperature rise of irrigant during ultrasonic activation (3.9ºC and 9.9ºC after 20 and 60 s, respectively) was not sufficient to alter the reaction rate. Therefore, it can be concluded that the increase in chemical effect by ultrasonic activation of the irrigant is due to convection phenomena such as microstreaming (improved mixing of irrigant resulting in refreshment of active molecules at the contact surface) and cavitation.
- Changes in pH, which affects the free available chlorine form (HOCl/OCl⁻), did not affect the reaction rate of 2% NaOCl with dentin, therefore the reported differences in the tissue dissolution capacity and/or antimicrobial efficacy can be better explained by chemical differences in the predominant chlorine form at pH5 (HOCl) and pH12 (OCl⁻) than by the amount of molecules involved in the reaction.

In chapter III new insights on the evolution of pH and temperature of irrigants during root canal therapy were presented. Clinically representative models were proposed and characterized. The importance of respecting a clinically realistic volume of irrigant to surface area in in vitro models was highlighted and discussed. A numerical model simulating the thermodynamics of root canal irrigation was introduced and validated for endodontic research. The following was concluded:
pH

• Reduction of the pH of NaOCl with prechloric acid was suggested in the endodontic literature. Compared to the classic method (hydrochloric acid), used in chapter II, it allows the stabilization of the solution at higher concentrations for longer times. 3% NaOCl solutions with a pH 5 were chemically stable for 1 hour.

• Exposure time to dentin and concentration of a NaOCl solution significantly influence the pH of NaOCl. However, the observed buffer effect of dentin was too limited to change the form of free chlorine available (HOCl/OCl⁻) in both pH 12 and pH 5 NaOCl solutions. Therefore, the biological effect (antimicrobial/tissue dissolution capacity) of the irrigant is not expected to change inside the root canal.

• Agitation of irrigant and pre-conditioning of dentin with EDTA did not alter the pH. These conditions were selected to represent the final stages of the root canal treatment, when the bulk of pulp tissue has been removed. At this point, alkalinization or further acidification of the NaOCl solutions, as suggested in literature, does not seem to be necessary.

Temperature

• Irrigation of the root canal with irrigant pre-heated to 60°C and 45°C resulted in temperatures higher than 21°C throughout the root canal. However, this effect was only present during irrigant delivery, independent of the irrigation duration.

• The cooling rate of syringes at chair side was determined. Irrigant preheated to 60°C can maintain a temperature higher than 45°C inside the root canal and therefore enhance the chemical activity of NaOCl the irrigant during delivery for 2.5 minutes.

• A numerical model to simulate the thermodynamic behaviour of the irrigant inside the tooth and its surroundings agreed well with the experiments and also suggested that certain in vitro models may lead to different outcomes than in vivo conditions.

• The use of pre-heated irrigant increases the temperature at the external surface of the root. The maximum temperature measured was 39.2°C observed in the middle third of the root.

In Chapter IV a combination of sensitive analytical sonochemical techniques with powerful imaging tools, gave new detailed insights into the cleaning mechanisms of irrigant activation techniques, such as the occurrence and location of transient cavitation (growing and implosion of bubbles) around sonic or ultrasonic activated endodontic instruments. The main conclusions are:

• In Ultrasonic Activated Irrigation, cavitation is correlated with ultrasonic power occurring in combination with the lowest and clinically significant power settings. Long-exposure photography showed evidence of cavitation both in straight and curved canals, at the entrance of lateral canals and isthmi, and also up to 2 mm beyond the tip of the file.

• The amount of cavitation is dependent on the instrument design, tip size and taper but also on the type of irrigant and on the confinement of the canal to be treated.

• There was no cavitation in Sonic Activated Irrigation. The results are explained by the reduced velocity of the liquid around the tip (1.4 m/s), which is well below the cavitation threshold of 15 m/s.
In Chapter V two different in vitro models have been used in order to evaluate the cleaning efficacy of ultrasonic activated irrigation. By cutting a groove in the root canal wall, dentin debris removal could be evaluated and the effect of refreshment (intermittent flush protocol) and type of irrigant on the cleaning efficiency of Ultrasonic Activated irrigation (at that time named Passive Ultrasonic Irrigation) be studied. A novel hydrogel model was introduced and characterized. This is the first model which enables us to study the effect of the mechanical and chemical aspect of different irrigation protocols in removing biofilm-like viscoelastic materials situated in lateral canals and isthmi. The main conclusions were:

**Groove Model**

- Ultrasonic activation of the irrigant combined with the intermittent flush method produces a cumulative effect over 3 refreshment/activation cycles.
- Sodium hypochlorite as an irrigant is significantly more effective than carbonated water, which is significantly more effective than distilled water, in removing dentin debris from the root canal during ultrasonic activation.
- All studied and aforementioned solutions presented similar fluidic properties.

**Hydrogel Model**

- The hydrogel developed in this study displayed viscoelastic behaviour with material properties similar to those reported for natural biofilms.
- The removal of the hydrogel from a lateral canal or isthmus of the root canal resulted from convection and was characterised by an initial rapid and unstable removal, followed by slower, constant viscous removal (isthmus) or the detaching of pieces of hydrogel (lateral canal).
- More hydrogel was removed from the lateral canal using UAI when using water as irrigant than with NaOCl, because of the formation of bubbles that inhibited further removal.
- The chemical dissolution of the hydrogel by NaOCl took place at a much lower rate than that detected in the presence of activation. No hydrogel was removed from lateral canals or isthmi with water and without activation.

The models and methodologies described in this thesis serve as promising tool for future research on the cleaning efficiency of root canal irrigation and irrigant activation. The results reported in thesis may contribute to the scientific and clinical awareness of the mechanical and chemical aspects of irrigation, which altogether may lead to a better clinical outcome.