Title page

Metabolism and excretion of rivaroxaban – an oral, direct Factor Xa inhibitor – in rats, dogs and humans

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Running title page

Running title: Metabolism of rivaroxaban in vivo (33/60 characters)

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Abbreviations:
AUC, area under the concentration–time curve; AUC\textsubscript{norm}, AUC normalized to rivaroxaban dose and body weight; AUC\textsubscript{0–tn}, AUC from 0 to the terminal time point; BDC, bile duct-cannulated; C\textsubscript{max}, maximum plasma concentration; C\textsubscript{max, norm}, C\textsubscript{max} normalized to rivaroxaban dose and body weight; ESI, electrospray ionization; FXa, Factor Xa; HPLC, high-performance liquid chromatography; i.v., intravenous; LC, liquid chromatography; LOQ, limit of quantification; LSC, liquid scintillation counting; MS, mass spectrometry; PK, pharmacokinetic; p.o., per oral
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Abstract

Rivaroxaban is a novel, oral, direct Factor Xa inhibitor for the prevention and treatment of thromboembolic disorders. The objective of this study was to investigate the in vivo metabolism and excretion of rivaroxaban in rats, dogs and humans. Single doses of [14C]rivaroxaban (3 mg/kg and 1 mg/kg) were administered to rats (orally/intravenously) and dogs (orally), respectively. A single oral dose of [14C]rivaroxaban (10 mg) was administered to healthy human males (N=4). Plasma and excreta were collected and profiled for radioactivity. Recovery of total radioactivity was high and ≥92% in all species. Unchanged rivaroxaban was the major compound in plasma at all time points investigated, across all species. No major or pharmacologically active circulating metabolites were detected. Rivaroxaban and its metabolites were rapidly excreted; urinary excretion of radioactivity was 25% and 52%, and faecal excretion was 67% and 43% of the dose in rats and dogs, respectively. In humans, 66% of the dose was excreted renally (36% unchanged drug) and 28% in the faeces. Radioactivity profiles in excreta were similar across species. Three metabolic pathways were identified: oxidative degradation of the morpholinone moiety (major pathway), and hydrolysis of the central amide bond and of the lactam amide bond in the morpholinone ring (minor pathways). M-1, the main metabolite in excreta of all species, was eliminated via both renal and faecal/biliary routes. In total, 82% to 89% of the dose administered was assigned to unchanged rivaroxaban and its metabolites in the excreta of rats, dogs and humans.
Introduction

Rivaroxaban is a novel, oral, direct FXa inhibitor in advanced clinical development for the prevention and treatment of thromboembolic disorders. Recently, it has received approval in Canada and the European Union for use in the prevention of venous thromboembolism (VTE) in patients undergoing elective total hip or knee replacement surgery. Rivaroxaban is not only a potent and selective inhibitor of free FXa (Ki 0.4 nM), but also of prothrombinase activity and fibrin-associated FXa activity (Depasse et al., 2005; Perzborn et al., 2005). *In vitro*, rivaroxaban was shown to inhibit thrombin generation and prolong clotting times (Gerotziafas et al., 2005; Perzborn et al., 2005) and, *in vivo*, it had potent antithrombotic effects in a variety of animal venous and arterial thrombosis models (Biemond et al., 2007; Perzborn et al., 2005).

Pharmacokinetic (PK) studies of rivaroxaban in rats and dogs have been reported previously (Weinz et al., 2005). These studies demonstrated that rivaroxaban was absorbed rapidly after oral dosing (absolute bioavailability 57–66% and 60–86% in rats and dogs, respectively), had a favourable PK profile with dose proportional increase in area under the concentration–time curve (AUC), and was rapidly excreted via renal and faecal/biliary routes. Rivaroxaban has also been shown to demonstrate dose-proportional pharmacokinetics and predictable pharmacodynamics in single- (up to 80 mg) and multiple-dose studies in healthy subjects and patients with no evidence of accumulation (Kubitza et al., 2005a; Kubitza et al., 2005b). In addition, rivaroxaban showed high oral bioavailability with a rapid absorption, and was safe and well tolerated. The present studies were conducted to characterize the metabolism and mass balance of rivaroxaban *in vivo*, in rats, dogs and humans.

Methods

Reference compounds and chemicals

[14C]Rivaroxaban ([14C]BAY 59-7939) (5-chloro-N-(((S)-2-oxo-3-[4-(3-oxo-4-morpholinyl)phenyl]-1,3-oxazolidin-5-yl)methyl)-2-thiophene-[14C]carboxamide) (Fig. 1), with a specific activity of 2.69 MBq/mg, an enantiomeric purity >99% enantiomeric excess, and an ultraviolet (UV) and radiochemical purity >99%, was synthesized by the Isotope Chemistry Laboratory of Bayer HealthCare AG (Wuppertal, Germany) (Pleiss et al., 2006). Unlabelled rivaroxaban (BAY 59-7939) (Roehrig et al., 2005),
dose vehicle for human studies, the internal standard (5-chloro-N-[(3,5-dimethyl-4-(3-oxomorpholin-4-yl)phenyl]-2-oxo-1,3-oxazolidin-5-yl)methyl) thiophene-2-carboxamide) and the metabolites M-4 (Pleiss et al., 2006), racemic M-1, M-2, M-7, M-9, the HCl-salt of M-15, M-16, M-17 and M-18 were synthesized at Bayer HealthCare AG (Wuppertal, Germany) and Bayer Schering Pharma AG (Berlin, Germany). M-13 (chlorothiophene carboxylic acid) was purchased from Sigma-Aldrich (Steinheim, Germany). Other reagents and solvents were obtained from commercial sources and were of analytical grade or higher purity.

Rat and dog studies
All procedures were conducted in accordance with the German Animal Protection Act (Deutsches Tierschutzgesetz). Male Wistar rats were purchased from Harlan Winkelmann, Germany. Female Beagle dogs were obtained from Marshall Farms USA (North Rose, New York, NY) or Harlan Winkelmann, Germany. Animal experiments, from which plasma, urine, bile and faeces specimen were collected for drug metabolism investigations, have been previously described in detail (Weinz et al., 2005).

Human study
Study design
A single-centre, non-randomized, open-label, non-placebo-controlled study was conducted in four healthy male subjects, aged 30–54 years, with a body mass index of 20–27 kg/m². Subjects were excluded from the study if they had any known coagulation disorders (e.g. von Willebrand’s disease and haemophilias), conditions associated with an increased risk of bleeding (e.g. periodontitis, haemorrhoids, acute gastroenteritis and acute peptic ulcer), or known sensitivity to common causes of bleeding. Subjects were also excluded from the study if they had received a radiolabelled substance, or been exposed to significant radiation, within the previous 12 months (e.g. serial X-rays, computed tomography scan, barium meal). The study took place at Inveresk Clinical Research, Riccarton, Edinburgh, UK. It was conducted in accordance with the Declaration of Helsinki and the International Conference on Harmonisation (ICH)/WHO Good Clinical Practice standards (ICH-GCP) Guidelines and with the approval of the Independent Ethics Review Committee of Inveresk Clinical Research and the Department of Health (UK) Administration of Radioactive
Substances Advisory Committee (ARSAC). All subjects provided written, informed consent. Subjects entered the clinic 1 day before drug administration and were discharged 7 days after drug administration. Subjects fasted overnight before administration of study drug and received their next meal 4 hours post-dose.

**Dosage form and administration**

Subjects received a single, oral dose of a solution of approximately 10 mg rivaroxaban, containing [14C]rivaroxaban plus unlabelled rivaroxaban with a mean radioactive dose of 47.5 µCi (1.76 MBq). The solution was administered with 240 mL of tap water. Doses were given orally, because this is the route of administration in the clinical setting. The actual radioactive dose received by each subject was determined with reference to the dose concentration, the weight of the dose administered, and the specific activity of [14C]rivaroxaban in the formulated dose.

**Specimen collection and preparation**

Blood samples (approximately 10 mL) were collected in heparinized vials at pre-specified time points (Table 1) from an in situ venous cannula or by venipuncture. Samples were centrifuged at 3000 rpm for 10 min at approximately 4°C to obtain plasma, which was stored at approximately –20°C until analysis. Urine was collected over pre-specified time intervals (Table 1), weighed and stored at –20°C until analysis. Faeces were collected daily (Table 1), weighed and homogenized after dilution with an amount of water corresponding to their weight.

**Measurement of radioactivity**

Total radioactivity in liquid samples (plasma, urine and bile [BDC rats only]) from all species was determined by liquid scintillation counting (LSC) using a Tri-Carb® 2500A liquid scintillation spectrometer (Canberra Packard Instruments Comp., Groningen, The Netherlands). Samples were made up to 1 mL with distilled water, if necessary, and prepared for radioanalysis by the addition of Ultima Gold™ scintillation cocktail. Solid samples (faeces) were homogenized, lyophilized, homogenized again, and combusted using the Canberra Packard System 387 (Oxidizer TRI-CARB 307 and Robot System 80). The formed 14CO₂ was trapped in Carbo-Sorb® and topped up with scintillation cocktail (Permafluor® E⁺) before radioanalysis.
Metabolite profiling
Metabolite patterns in plasma, urine and faeces from all species, and in bile from BDC rats, were determined using high-performance liquid chromatography (HPLC) with on-line radioactivity detection (Ramona® 5; Raytest GmbH, Straubenhardt, Germany) or off-line radioactivity detection by LSC (Wallac 1450 Microbeta™ Plus; Freiburg, Germany) (reference to companion in vitro paper). Plasma samples (1 mL or 2 mL for human samples with a radioactivity concentration <1000 dpm/mL) were precipitated by adding acetonitrile (2 mL or 4 mL), followed by centrifugation. The supernatant was removed and the residue washed with a further 1 mL acetonitrile. Urine samples were either analyzed by HPLC directly, without pre-treatment (for those samples containing high amounts of radioactivity), or extracted using Waters Oasis® cartridges (Waters GmBH, Eschborn, Germany) before HPLC analysis. For urine extraction, a 3-mL urine sample was diluted with 1 mL water and added to a preconditioned Waters Oasis® cartridge (2 mL methanol followed by 2 mL water). Each cartridge was washed with 3.5 mL water and the extracts eluted with 1.5 mL acetonitrile. Faeces were extracted by adding approximately 2 mL acetonitrile to approximately 1 mL faeces suspension. After vortexing and centrifugation, the supernatant was removed and the residue washed with 1–2 mL acetonitrile (depending on the sample weight). For plasma, urine and faeces samples, extracts were combined for each time interval, concentrated by evaporation, and an aliquot was removed for HPLC analysis. Bile samples from BDC rats were directly analyzed by HPLC.

Rivaroxaban and its metabolites were separated on a Nucleosil® 100-5 C8 HD column (125 mm × 2 mm; Macherey & Nagel, Düren, Germany) with a guard column (8 mm × 3 mm). For better separation and assignment of closely eluting metabolites M-2, M-3 and M-8/M-9, a Nucleosil® 100-5 CN column with a guard column (70 mm × 2 mm) was used. Separation of M-8/M-9 could not be achieved and these metabolites were thus balanced together.

Metabolite identification and quantitation
Metabolites were identified by chromatographic characteristics and liquid chromatography/mass spectrometry (LC/MS) analysis. In addition some metabolites of rivaroxaban were isolated by preparative HPLC from in vivo samples (rat urine,
bile and faeces, and human urine); following purification, the structure was confirmed by proton nuclear magnetic resonance (\(^1\)H NMR) spectroscopy. The metabolic fate of the unlabelled (S)-oxamine moiety of rivaroxaban was investigated using LC-MS/MS analysis on an API 3000 mass spectrometer. A HPLC chromatography was established with an Agilent ZorbaxR SB-C18 column (30 mm × 2.1 mm), and 10 mM ammonium formate (pH 4) and acetonitrile as mobile phases. Metabolite M-4 was analyzed in electrospray ionization (ESI) negative mode; all other metabolites were analyzed in ESI positive mode, with an internal standard used in previous studies (Weinz et al., 2005). Appropriate and selective MS/MS transitions were evaluated for all analytes. The lower limit of quantitation (LLOQ) of the method ranged from 5 to 50 ng/mL for all analytes and the linear range was up to at least 1000 ng/mL. For calibration purposes, control human plasma and urine samples were spiked with different concentrations of all analytes in a range of 1–1000 ng/mL. Acetonitrile containing the internal standard was added to precipitate proteins in all plasma samples. For chromatographic reasons the supernatants were diluted with water and then analyzed using LC-MS/MS. Details of metabolite structure elucidation and in vitro studies will be reported under separate cover (reference to companion in vitro paper).

**Pharmacokinetic analysis**

Mean plasma concentration versus time data for total radioactivity, unchanged rivaroxaban and metabolite M-1 were analyzed non-compartmentally (Yamaoka et al., 1978) using software developed inhouse (KINCALC, version 2.50.02, 2001).

**Results**

**Pharmacokinetic evaluation**

**Humans**

Rivaroxaban was well tolerated and no serious adverse event was observed during the course of the study. Extraction recovery of radioactivity in plasma, urine and faeces was in most cases >90% and absolute LLOQ was about 5 ng drug equivalent. The plasma concentration–time profiles of total radioactivity and unchanged rivaroxaban following oral administration of [\(^{14}\)C]rivaroxaban to healthy human subjects are shown in Fig. 2. Total radioactivity and unchanged rivaroxaban reached \(C_{\text{max}}\) 30 min post-dose and both were eliminated rapidly and with a parallel time
course from plasma; at time points later than 24 hours after drug administration the concentrations were below the LLOQ. The AUC of unchanged rivaroxaban accounted for approximately 89% of the AUC of total radioactivity in plasma, and the PK parameters for unchanged rivaroxaban were very similar to those reported for the 10 mg dose in the single-dose escalation study (Kubitza et al. 2005a).

Rats and dogs
The plasma concentration–time profiles of total radioactivity and unchanged rivaroxaban and PK parameters following oral administration of [14C]rivaroxaban to rats and dogs are published elsewhere (Weinz et al. 2005).

Excretion of radioactivity in urine and bile/faeces
Humans
The recovery of total radioactivity in excreta (urine and faeces) 7 days post-dose accounted for 94% of the dose administered (Table 2, Fig. 3). Radioactivity was excreted predominantly in urine, with an average of 66% of the administered radioactive dose being excreted after 7 days, while approximately 28% were excreted in the faeces (Table 2, Fig. 3). A large proportion of the dose (mean 68%) was recovered in urine and faeces already within the first 24 hours.

Rats and dogs
In the p.o. studies in rats and dogs, the recovery of total radioactivity in excreta 7 days post-dose accounted for about 92% and 97% of the dose, respectively (Table 2) (Weinz et al. 2005). In the i.v. study in bile duct-cannulated (BDC) rats, recovery was about 92% after 1 day. Excretion of radioactivity in rats mainly occurred via the biliary/faecal route, with 61–67% of dose after oral or i.v. administration of [14C]rivaroxaban. Following i.v. administration to BDC rats, about 48% were excreted via the biliary and about 13% via the extrabiliary route (Table 2). Renal excretion accounted for 25–30% in rats. In dogs, both excretion pathways were of similar importance, with about 52% renal and 43% faecal excretion (Table 2).

Metabolite profiles in plasma
Humans
Unchanged rivaroxaban was identified as the main compound in human plasma at all
time points investigated after oral administration of 10 mg [¹⁴C]rivaroxaban, accounting for 89% of the AUC₀–tn of total radioactivity in all four subjects (Fig. 4). A few minor metabolites were detected; among these were M-1, M-4, M-5, M-7 and M-8/M-9. The most prominent metabolite (M-1) accounted for only 3% of the AUC₀–tn of total radioactivity on average. The elucidation of the structure of these metabolites is published elsewhere (reference to companion in vitro paper). More than 95% of the total radioactivity in plasma could be attributed to unchanged rivaroxaban and known metabolites of rivaroxaban.

The amide hydrolysis of [¹⁴C]rivaroxaban, leading to M-13 and subsequently to M-4, was of special interest, because the radioactive ¹⁴C label is located on the carbonyl moiety adjacent to the chlorothiophene moiety. Therefore, only M-4, and not the unlabelled part of the compound, is considered in ¹⁴C-mass balance studies of rivaroxaban. The mechanism of cleavage and the metabolic fate of the unlabelled part of the molecule has been elucidated in vitro (reference to companion in vitro paper). In order to investigate the importance of these unlabelled metabolites in man in vivo, human plasma samples were analyzed using a sensitive HPLC-MS/MS assay for the quantitation of M-15, M-16, M-17 and M-18, against M-4 (reference to companion in vitro article). None of the unlabelled metabolites was detected in human plasma samples and only trace amounts of M-4 were found. Overall, no major circulating metabolite of rivaroxaban was found in human plasma.

**Rats and dogs**

Unchanged rivaroxaban was identified as the main compound in rat and dog plasma at all time points investigated after oral administration of [¹⁴C]rivaroxaban (Fig. 4). The AUC of unchanged rivaroxaban accounted for 83% and 71% of the AUC of total radioactivity in rats and dogs, respectively. Few minor metabolites were detected in plasma; of these, the most prominent metabolite, M-1, accounted for only 6% and 5% of the AUC of total radioactivity in rat and dog plasma, respectively. A few minor metabolites were observed in both species, among which M-2 and M-8/M-9 were identified in rat plasma and M-2, M-6 and M-7 in dog plasma. Total radioactivity, unchanged rivaroxaban, and metabolite M-1 were eliminated rapidly following oral administration. Similarly to humans, no major circulating metabolite was found in the plasma of rats and dogs.
Metabolite profiles in urine and bile/faeces

Humans
Following oral administration of \([^{14}C]\text{rivaroxaban}\) to healthy human subjects, metabolite M-1 was identified as the main metabolite in excreta. M-1 was eliminated via renal and faecal/biliary routes, in total accounting for 22% of the dose. Metabolites M-4 and M-7 were found in almost equal amounts of 7–8% of the dose (Tables 3 and 4; Fig. 5). M-4 was eliminated exclusively via the renal route (Table 3), whereas M-7 was eliminated via renal and faecal routes. Few other minor metabolites were observed in excreta. Metabolic profiles in urine and faeces were qualitatively similar between the different sampling intervals. However, unchanged rivaroxaban was the major component in urine, accounting for 36% of the total dose; about 7% of the dose was excreted faecally. In total, about 43% of the dose was excreted as unchanged drug in humans. Overall, 89% of the radioactive dose administered could be assigned to unchanged rivaroxaban and known metabolites of rivaroxaban in human excreta. Similarly to human plasma, human urine fractions were analyzed using a sensitive HPLC-MS/MS assay for the quantification of the unlabelled metabolites M-15, M-16, M-17 and M-18, against M-4 (reference to companion \textit{in vitro} article). Only metabolites M-15, M-17 and M-18 were found and quantified in human urine. A mass balance of these unlabelled metabolites against the radiolabelled counterpart M-4 was established, for which M-4 was quantified either by radioanalysis or by specific LC-MS/MS analysis. The LC-MS/MS quantification of M-4 was in the range of 93-112%, compared with the data quantified using radioactivity (Table 5). Furthermore, the mass balance of the unlabelled metabolites M-15, M-17 and M-18 against the labelled counterpart M-4 in human urine samples was in the range of 81-113% (Table 5). These \textit{in vivo} data confirmed the proposed \textit{in vitro} pathway of a hydrolytic cleavage of rivaroxaban and provided strong evidence that metabolites M-4 and M-15/M-17/M-18 represent the endpoints of this metabolic pathway.

Rats and dogs
Two major metabolites, M-1 and M-4, and few minor metabolites were observed in excreta following i.v. administration of \([^{14}C]\text{rivaroxaban}\) to BDC rats and after oral administration to dogs (Tables 3 and 4). M-1 was identified as the main metabolite in rats and dogs and was eliminated via the renal and faecal/biliary routes (Tables 3
and 4). As in humans, M-4 was excreted exclusively via the renal route (Table 3). Metabolic patterns in excreta were qualitatively similar across different sampling intervals in both species.

In urine, unchanged rivaroxaban and known metabolites of rivaroxaban accounted for approximately 25% and 30% of the administered radioactive dose in intact and BDC rats, respectively, and for 44% of the dose in dogs (0–5 days post-dose). M-1 was the major metabolite in rat urine, 12% of the dose, and M-4 was the major metabolite in dog urine, 16% of the dose (Table 3).

Extensive metabolism of rivaroxaban was observed in the excreta of BDC rats following i.v. administration (Tables 3 and 4). Unchanged rivaroxaban accounted for only 11% of the administered radioactive dose but M-1 for about 62%. Metabolite M-1 was the only metabolite detected in bile, representing 44% of the dose (Table 3). Overall, 87% and 82% of the administered radioactive dose could be assigned to unchanged rivaroxaban and known metabolites of rivaroxaban in rats and dogs, respectively.

Discussion

The studies summarized in this paper focus on the metabolism and excretion of radiolabelled rivaroxaban ([14C]rivaroxaban) after administration of single i.v. and oral doses to rats and after administration of a single oral dose to dogs and humans. Unchanged rivaroxaban accounted for the majority of total radioactivity in human plasma after oral administration of 10 mg [14C]rivaroxaban, reflecting a minimal presence of metabolites. Accordingly, the plasma concentration–time curve for unchanged rivaroxaban was very similar to that of total radioactivity, showing that the pharmacological effects of rivaroxaban are solely due to unchanged drug.

Rivaroxaban was absorbed rapidly after oral administration to humans (tmax 30 min) and subsequently eliminated rapidly from plasma to give concentrations below the LLOQ at time points later than 24 hours after drug administration. This suggests that the pharmacodynamic effects of rivaroxaban in humans would be initiated rapidly after oral administration, and would cease rapidly after treatment was terminated (Kubitza et al., 2005b; Kubitza et al., 2005a). Unchanged rivaroxaban was also identified as the main compound in the plasma of rats and dogs. In all three species, no major radiolabelled circulating metabolite was detected in plasma, and the most prominent of the minor metabolites, M-1, accounted for only a very small proportion
of total radioactivity in plasma (about 3–6% across all species).

In addition, none of the unlabelled metabolites M-15, M-16, M-17 and M-18, derived from the hydrolysis of the amide bond at the chlorothiophene moiety, was detected in human plasma.

The PK characteristics of rivaroxaban, derived from this mass balance study, were consistent with the findings of previous phase I studies investigating single and multiple doses of rivaroxaban in healthy human subjects (Kubitza et al., 2005b; Kubitza et al., 2005a).

[14C]Rivaroxaban-associated radioactivity was excreted rapidly in humans. Excretion occurred predominantly via the renal route (66%) and, to a lesser extent, via faecal/biliary routes (28%), with 36% of rivaroxaban excreted unchanged in the urine, and 7% excreted unchanged in faeces. Rapid, dual-mode excretion of rivaroxaban was also observed in rats and dogs, although the contribution of each excretion route to the total excretion of radioactivity differed from that in humans. In dogs, renal and faecal/biliary pathways were of approximately similar importance; in rats, excretion occurred mainly via the faecal/biliary routes. The recovery of approximately 13% of radioactivity in faeces following i.v. administration to BDC rats indicates that [14C]rivaroxaban-associated radioactivity undergoes extrabiliary excretion to a certain extent.

The administered radioactive doses were almost completely recovered (94%) in the excreta of humans 7 days after administration. Similarly, the recovery of radioactivity in excreta 24 hours after i.v. administration to BDC rats, 48 hours after i.v. or oral administration to intact rats, and 7 days after oral administration to dogs, accounted for the majority of the administered radioactive dose (92% and 97%, respectively). The metabolic pathways of rivaroxaban in humans were similar to those in rats and dogs, and to those observed in the in vitro metabolism studies using liver microsomes and hepatocytes from different species, including man (reference to companion in vitro paper).

A high mass balance of known metabolites was achieved in the in vivo metabolism studies. The majority of the administered radioactive dose could be assigned to rivaroxaban and all known metabolites of rivaroxaban in rat, dog and human excreta after intravenous or oral administration of [14C]rivaroxaban. M-1 was identified as the major metabolite in human excreta, and was eliminated via renal and faecal/biliary
routes. Metabolites M-2, M-4 and M-7 were identified as less prevalent metabolites. M-4 was excreted exclusively via the renal route, whereas M-2 and M-7 were excreted through both the renal and the faecal/biliary pathways. The urinary and faecal/biliary metabolite profiles in rats and dogs were qualitatively similar to those in humans, although M-4 was the major metabolite in urine of dogs (rather than M-1), and M-7 was found in dogs but not in rats.

Structural studies revealed that the metabolite M-1 was produced through oxidative degradation of the morpholinone moiety of rivaroxaban (forming M-2), followed by oxidative cleavage of the ring (reference to in vitro paper). In addition, the minor metabolites M-5 and M-6 are also products of the oxidative degradation of the morpholinone ring. Metabolite M-4 was produced by hydrolysis of the amide bond of rivaroxaban, with subsequent conjugation of the 5-chloro-2-thiophene-carboxylic acid (M-13) with glycine. Metabolite M-7 results from the hydrolytic cleavage of the lactam amide bond in the morpholinone moiety. It can be concluded that the metabolism of rivaroxaban occurs via two major pathways: oxidative degradation of the morpholinone moiety and hydrolysis of the different amide bonds.

In man, rivaroxaban is eliminated via three pathways: approximately 43% of the dose is excreted as unchanged drug via urine (36%) and faeces (7%, representing non-absorbed or extrabiliarily excreted material); approximately 14% of the dose (M-4 and M-7) is eliminated via hydrolytic cleavage of the two different amide bonds; and approximately 32% of the dose is eliminated via oxidative pathways. The proposed scheme for the metabolism of rivaroxaban – based on structures of all known metabolites and metabolite profiles – is depicted in Fig. 6. The renal excretion of one-third (36%) of the dose as unchanged drug suggests the involvement of transport proteins. In vitro studies showed rivaroxaban to be a substrate for P-glycoprotein (P-gp) and breast cancer resistance protein (Bcrp). Details of these studies will be published elsewhere (manuscript in preparation).

In summary, the present study demonstrated high species similarity in the metabolism of rivaroxaban in humans, rats and dogs, with almost all administered dose assigned to known structures. Comparison of the in vivo data presented here with the in vitro data published in a companion paper (reference to companion in vitro paper) indicates a very good in vitro/in vivo correlation. Reactive metabolites were
not found in either *in vitro* or *in vivo* studies.

Following rapid absorption, rivaroxaban is metabolized via different types of biotransformation reactions, and the drug and metabolites are rapidly eliminated via renal and biliary/faecal routes. No major circulating active metabolites were observed. In humans, a dual mode of elimination was observed, with almost half of the dose excreted as unchanged drug (in the urine and faeces) and the other half excreted after metabolic biotransformation.

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Footnotes
This study was supported by Bayer HealthCare AG
Legends for figures

Figure 1. Chemical structure of $[^{14}C]$rivaroxaban.

Figure 2. Plasma concentration–time profiles of total radioactivity and unchanged rivaroxaban after a single oral administration of $[^{14}C]$rivaroxaban 10 mg to healthy human subjects (N=4). Data are presented as geometric means ±SD (semi-logarithmic scale).

Figure 3. Cumulative excretion of radioactivity (percentage of administered dose) in urine and faeces after a single oral dose of $[^{14}C]$rivaroxaban to healthy human subjects (N=4). Data are presented as arithmetic means ±SD.

Figure 4. Radioactivity profile of plasma 1 hour after oral administration of $[^{14}C]$rivaroxaban to (A) a male Wistar rat, (B) a female Beagle dog, and (C) a healthy human male.

Figure 5. Radioactivity profile of (A) human urine fraction (0–4 hours) and (B) human faecal extract (2–3 days) after oral administration of $[^{14}C]$rivaroxaban to one subject.

Figure 6. Proposed metabolic pathways of rivaroxaban in vivo in rats, dogs and humans.
### Tables

**Table 1.** Summary of [\(^{14}\)C]rivaroxaban doses, routes of administration and timing of biological sample collection in rats, dogs and humans

<table>
<thead>
<tr>
<th>Species</th>
<th>Route</th>
<th>Single dose</th>
<th>Number</th>
<th>Matrix</th>
<th>Sampling time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat</td>
<td>p.o.(^a)</td>
<td>3 mg/kg (2.69 MBq/mg)</td>
<td>3 per time point</td>
<td>Plasma &amp; Urine &amp; Faeces</td>
<td>1, 2, 4, 8; 0–8, 8–24, daily until 168 hours; Daily until 168 hours</td>
</tr>
<tr>
<td></td>
<td>i.v.(^b)</td>
<td>3 mg/kg (2.69 MBq/mg)</td>
<td>5</td>
<td>Urine &amp; Bile &amp; Faeces</td>
<td>0–4, 4–8, 8–24; 0–24</td>
</tr>
<tr>
<td>Dog</td>
<td>p.o.</td>
<td>1 mg/kg (2.69 MBq/mg)</td>
<td>3</td>
<td>Plasma &amp; Urine &amp; Faeces</td>
<td>0.25, 0.5, 1, 2, 4, 8, 10; Daily until 168 hours</td>
</tr>
<tr>
<td>Human</td>
<td>p.o.</td>
<td>10 mg (1.76 MBq)(^c)</td>
<td>4</td>
<td>Plasma &amp; Urine &amp; Faeces</td>
<td>0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 2.5, 3, 4, 6, 8, 12, 15, 24; 0–4, 4–8, 8–12, 12–24, daily until 168 hours; Daily until 168 hours</td>
</tr>
</tbody>
</table>

\(^a\)Intact rats  
\(^b\)Bile duct-cannulated rats  
\(^c\)Mean actual dose received by human subjects
Table 2. Excretion of total radioactivity after single administration of $[^{14}\text{C}]$rivaroxaban to rats, dogs and humans

<table>
<thead>
<tr>
<th>Species</th>
<th>Route</th>
<th>Sample collection time (days)</th>
<th>Radioactivity (% of dose)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Urine</td>
</tr>
<tr>
<td>Rat p.o.</td>
<td>7</td>
<td></td>
<td>24.7</td>
</tr>
<tr>
<td>Rat i.v.</td>
<td>1</td>
<td></td>
<td>30.3</td>
</tr>
<tr>
<td>Dog p.o.</td>
<td>7</td>
<td>52.2</td>
<td>42.8</td>
</tr>
<tr>
<td>Human p.o.</td>
<td>7</td>
<td>65.7</td>
<td>28.0</td>
</tr>
</tbody>
</table>

i.v., intravenous; p.o., oral

$^a$Intact rats

$^b$Bile duct-cannulated rats

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### Table 3. Metabolite balances in urine, bile and faeces (selected metabolites) following administration of [14C]rivaroxaban to rats, dogs and humans in time interval analyzed

<table>
<thead>
<tr>
<th>Sample</th>
<th>Species</th>
<th>Time (days)</th>
<th>Route</th>
<th>% of dose in time interval</th>
<th>Radioactivity (% of dose)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rivaroxaban</td>
<td>M-1</td>
</tr>
<tr>
<td>Urine</td>
<td>Rat</td>
<td>0–2</td>
<td>p.o.</td>
<td>23.5</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Rat</td>
<td>0–1</td>
<td>i.v.</td>
<td>30.3</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>Dog</td>
<td>0–5</td>
<td>p.o.</td>
<td>52.0</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>Human</td>
<td>0–2</td>
<td>p.o.</td>
<td>65.4</td>
<td>36.2</td>
</tr>
<tr>
<td>Bile</td>
<td>Rat</td>
<td>0–1</td>
<td>i.v.</td>
<td>48.4</td>
<td>–</td>
</tr>
<tr>
<td>Faeces</td>
<td>Rat</td>
<td>0–1</td>
<td>i.v.</td>
<td>12.9</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Dog</td>
<td>0–5</td>
<td>p.o.</td>
<td>42.5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Human</td>
<td>0–4</td>
<td>p.o.</td>
<td>26.4</td>
<td>7.3</td>
</tr>
</tbody>
</table>

i.v., intravenous; p.o., oral

*aIntact rats; b bile duct-cannulated rats

*Unchanged rivaroxaban and known metabolites
Table 4. Summarized metabolite balances in excreta (selected metabolites) following administration of [\(^{14}\)C]rivaroxaban to rats, dogs and humans

<table>
<thead>
<tr>
<th>Species</th>
<th>Route</th>
<th>Radioactivity (% of dose)</th>
<th>Rivaroxaban</th>
<th>M-1</th>
<th>M-2</th>
<th>M-4</th>
<th>M-5</th>
<th>M-6</th>
<th>M-7</th>
<th>M-8/M-9</th>
<th>Total*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat</td>
<td>i.v.*</td>
<td>11.0</td>
<td>61.8</td>
<td>5.9</td>
<td>5.4</td>
<td>1.9</td>
<td>&lt;0.1</td>
<td>–</td>
<td>1.0</td>
<td>87.1</td>
<td></td>
</tr>
<tr>
<td>Dog</td>
<td>p.o.</td>
<td>9.0</td>
<td>34.7</td>
<td>10.6</td>
<td>15.7</td>
<td>2.7</td>
<td>2.6</td>
<td>3.8</td>
<td>2.6</td>
<td>81.7</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>p.o.</td>
<td>43.5</td>
<td>22.0</td>
<td>1.8</td>
<td>7.6</td>
<td>2.5</td>
<td>1.2</td>
<td>6.6</td>
<td>3.7</td>
<td>88.9</td>
<td></td>
</tr>
</tbody>
</table>

i.v., intravenous; p.o., oral

*Bile duct-cannulated rats

*Unchanged rivaroxaban and known metabolites
**Table 5.** Summarized data for the mass balance calculation in urine of the sum of unlabelled metabolites M-15, M-17 and M-18 against counterpart M-4 in healthy volunteers after administration of 10 mg $[^{14}C]$rivaroxaban

<table>
<thead>
<tr>
<th>Volunteer No</th>
<th>M-15 (µmol)</th>
<th>M-17 (µmol)</th>
<th>M-18 (µmol)</th>
<th>Total M-15, M-17 and M-18 (µmol)</th>
<th>M-4 (µmol)</th>
<th>Total M-15, M-17and M-18 vs M-4 (µmol)</th>
<th>LC-MS (%)</th>
<th>Radiodetection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>001M</td>
<td>0.14</td>
<td>0.26</td>
<td>1.22</td>
<td>1.62</td>
<td>2.01</td>
<td>1.79</td>
<td>81</td>
<td>91</td>
</tr>
<tr>
<td>002M</td>
<td>0.22</td>
<td>0.29</td>
<td>0.81</td>
<td>1.32</td>
<td>1.29</td>
<td>1.30</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>003M</td>
<td>0.19</td>
<td>0.47</td>
<td>1.80</td>
<td>2.46</td>
<td>2.18</td>
<td>2.34</td>
<td>113</td>
<td>105</td>
</tr>
<tr>
<td>004M</td>
<td>0.21</td>
<td>0.24</td>
<td>1.05</td>
<td>1.51</td>
<td>1.65</td>
<td>1.47</td>
<td>91</td>
<td>103</td>
</tr>
</tbody>
</table>
*indicates position of $^{14}$C-label
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