From studies of biochemical mechanism to novel biological mediators: prostaglandin endoperoxides, thromboxanes, and leukotrienes

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Introduction

Following the completion of the structural work on the prostaglandins with Sune Bergström and co-workers (for reviews, see refs. 1-3) I was very fortunate in being able to spend a year in the Chemistry Department at Harvard University, Cambridge, Massachusetts. During this stay I had the opportunity to study both theoretical and synthetic organic chemistry. The year in Cambridge had a profound effect on my future research. At this time Konrad Bloch, E. J. Corey, Frank Westheimer, Robert B. Woodward, and several other prominent scientists were among the faculty members of the department and it was indeed a stimulating place for a young M.D. interested in chemistry. I was working in E. J. Corey's laboratory and we have continued to collaborate in several areas since then.

In 1964 it was established that there was a biogenetic relationship between the polyunsaturated fatty acids and prostaglandins (4,5). This finding was of considerable biological interest and since the mechanisms of the reactions involved were unknown, I decided to study this problem in the laboratory I had established at that time.

Mechanism of Biosynthesis of Prostaglandins

The conversion of 8,11,14-eicosatrienoic acid into prostaglandin E\textsubscript{1} (PGE\textsubscript{1}) involves introduction of two hydroxyl groups and one keto group. Incubation of 8,11,14-eicosatrienoic acid in an atmosphere of \textsuperscript{18}O\textsubscript{2} showed that the oxygen atoms of the hydroxyl groups were derived from oxygen gas whereas the keto oxygen did not contain any \textsuperscript{18}O (6,7). That this was due to exchange between the keto oxygen of the water was shown in later experiments (8). In these studies the keto group was reduced immediately with borohydride and the resulting trihydroxy acid derivative was shown to contain three atoms of \textsuperscript{18}O. These experiments were extended by carrying out the reaction in a mixture of \textsuperscript{18}O\textsubscript{2} (8). The reduced product was converted into the trimethoxy derivative and the side chain carrying a hydroxyl group was cleaved off by oxidation with permanganate periodate. The resulting dicarboxylic acid ester contained the two oxygens that were introduced...
into the five-membered ring during the biosynthesis. Analysis of this molecule by mass spectrometry showed that it contained either two atoms of $^{18}$O or two atoms of $^{16}$O in the ring and that molecules with one atom of $^{18}$O and one of $^{16}$O in the ring were virtually absent. The experiment demonstrated that the oxygen atom of the hydroxyl group at C-11 and of the keto group at C-9 originated in the same molecule of oxygen (Fig. 1).

It was also shown that the hydrogens at C-8, C-11, and C-12 are retained in their original positions during the conversion of 8,11,14-eicosatrienoic acid into PGE$_1$, which is in agreement with the mechanism proposed (see below). Experiments with hypothetical intermediates, namely, 15-hydroperoxy-8,11,13-eicosatrienoic acid and 15-hydroxy-8,11,13-eicosatrienoic acid indicated that the initial reaction consisted of the introduction of the oxygens in the ring (9,10). However, two different mechanisms for the incorporation of the oxygen molecule seemed possible (9-11). In one of the pathways leading from 8,11,14-eicosatrienoic acid to the proposed intermediate, the oxygen is added across carbon atoms C-9 and C-11 with concomitant formation of the new carbon-carbon bond between C-8 and C-12. The other pathway involves a lipoxygenase-like reaction with
formation of 11-peroxy-8,12,14-eicosatrienoic acid as the initial step. In both of the pathways leading to the cyclic peroxide intermediate one hydrogen at C-13 is removed. In the latter pathway the hydrogen at C-13 is most likely removed as the initial step whereas the removal of this hydrogen occurs later in the first pathway. It was thus conceivable that removal of the hydrogen was the rate-determining step and that substitution of tritium for hydrogen in the precursor would give a kinetic isotope effect. The resulting enrichment should appear in the precursor acid in the second pathway whereas the first pathway should produce enrichment of tritium in an oxygenated intermediate. Precursor acids, which were sterospecifically labeled with tritium at C-13 and labeled with $^{14}$C at C-3, were therefore synthesized (10).

The conversion of the doubly labeled acids into PGE$_1$ was catalyzed by a vesicular gland preparation and the $^3$H/$^{14}$C ratios of the precursor, product, and the precursor remaining after the reaction were determined. It was found that 13D-$^3$H-$^3$H-3-$^{14}$C-8,11,14-eicosatrienoic acid retained the tritium label during the conversion to PGE$_1$. The 13L-$^3$H-$^3$H-3-$^{14}$C-8,11,14-eicosatrienoic acid, however, was transformed into PGE$_1$ with essentially complete loss of tritium. The precursor isolated after 75% conversion was significantly enriched (284% retention) with respect to tritium. Thus, the initial step in the transformation of 8,11,14-eicosatrienoic acid into prostaglandin is the stereospecific elimination of the 13L-hydrogen. This reaction is followed by introduction of oxygen at C-11 in a lipoxygenase-like reaction to give 11-peroxy-8,12,13-eicosatrienoic acid (10,12). It is of interest in this context that soybean lipoxygenase removes the same hydrogen both specifically ($\omega$8) and stereospecifically (L) (9).

However, the plant lipoxygenase introduces the oxygen molecule in $\omega$6 position whereas the lipoxygenase, which is a component of the prostaglandin synthetase, introduces the oxygen in $\omega$10 position (9). The 11-peroxy-8,12,13-eicosatrienoic acid visualized to be formed in the initial oxygenation is subsequently transformed into an endoperoxide (8) by a concerted reaction involving addition of oxygen at C-15, isomerization of the $\Delta^{13}$ double bond, formation of the new carbon-carbon bond between C-8 and C-12, and attack by the oxygen radical at C-9. This is shown in Fig. 1. Indirect evidence indicates a free-radical mechanism (13,14). The endoperoxide is transformed into PGE$_1$ by removal of hydrogen at C-9 or into PGF$_{10}$ by a reductive cleavage of the peroxide.

When washed microsomes were used as enzyme source, eicosatrienoic acid gave rise to other products (15-17). These cannot act as precursors in the biosynthesis of prostaglandins; however, their structures and the fate of $^3$H in labeled precursors during their formation provided additional evidence for the proposed scheme of the transformation. The monohydroxy acid fraction from an incubation with eicosatrienoic acid was shown to consist of 11-hydroxy-8,12,14-eicosatrienoic acid, 15-hydroxy-8,11,13-eicosatrienoic acid, and 12-hydroxy-8($\text{trans}$),10($\text{trans}$)-heptadecadienoic acid. The mechanism of formation of the C$_{17}$ acid was studied by using 3-$^{14}$C-eicosatrienoic acid, which also contained tritium label at C-9, C-10, or C-11 (16). These experiments showed that the conversion resulted in loss of the tritium label in these three positions. Furthermore, malonaldehyde was
identified by condensation with L-arginine to give δ-N-2-(pyrimidinyl)-L-ornithine or with urea to form 2-hydroxypyrimidine. The derivative of malonaldehyde contained the 3H label from the 9-3H and 11-3H labeled precursor whereas 3H originally in position C-10 was lost by enolization of the malonaldehyde.

It was further found that a compound with chromatographic properties similar to those of PGE$_1$ and which was transformed into PGF$_{1α}$ by borohydride reduction was formed from eicosatrienoic acid (17). The structure of the new product was found to be 9α,15-dihydroxy-11-ketoprost-13-enoic acid (11-dehydro-PGF$_{1α}$) (18). In the conversion of 9-3H,3-14C- and 11-3H,2-14C-8,11,14-eicosatrienoic acid to 11-dehydro-PGF$_{1α}$, the latter precursor lost the 3H label, whereas the 9-3H label was retained. These experiments on the structures of the various products from eicosatrienoic acid and the fate of 3H labels in their formation provided strong evidence for the existence of the endoperoxide intermediate.

Isolation and Characterization of Prostaglandin Endoperoxides

Subsequently it was possible to detect and isolate an endoperoxide from short-time incubations of arachidonic acid with the microsomal fraction of homogenates of sheep vesicular glands (19). The incubation mixtures were treated with stannous chloride in ethanol in order to reduce endoperoxide into PGF$_{2α}$. This was followed by sodium borodeuteride reduction and determination of the resulting PGF$_2$ species by multiple-ion analysis. This method made it possible to assay PGE$_2$ as well as 11-dehydro-PGF$_{2α}$ and PGF$_{2α}$. It was of particular interest that a peak of PGF$_{2α}$ appeared in the initial phase of the incubation period. No metabolic transformation of PGF compounds had been observed in preparations of sheep vesicular gland, and thus it was unlikely that the PGF$_{2α}$ peak could be ascribed to enzymatic formation of PGF$_{2α}$ followed by rapid metabolic degradation. Furthermore when the SnCl$_2$ and sodium borodeuteride reduction was omitted, the peak of PGF$_{2α}$ disappeared, indicating that PGF$_{2α}$ was formed by chemical reduction of an oxygenated derivative present in the initial phase of the incubation. That an oxygenated intermediate was formed and temporally accumulated was also suggested by the finding that the rate of PGE$_2$ formation was slower than the rate of oxygenation of the precursor acid.

Additional support for the existence of an oxygenated intermediate that was convertible into PGF$_{2α}$ by SnCl$_2$ reduction came from experiments in which reduced glutathione or p-mercuribenzoate was added to the microsomal suspension. The former agent increased the rate of PGE$_2$ formation and suppressed the peak of PGF$_{2α}$, whereas the latter agent decreased the rate of PGE$_2$ formation with a simultaneous increase in the height and duration of the PGF$_{2α}$ peak. The oxygenated intermediate detected by these experiments was also isolated. On thin-layer radiochromatographic analysis of the product (methyl esters) isolated after a 30-s incubation of labelled arachidonic acid with microsomes in the presence of p-mercuribenzoate a new radioactive derivative appeared. This derivative was identified as the methyl ester of the earlier postulated endoperoxide. In an extension of these studies the endoperoxide described above was obtained as the
free acid; in addition, an endoperoxide carrying a hydroperoxy group at C-15 was isolated (20,21). We suggested the trivial names PGG₂ for the less polar endoperoxide (15-hydroperoxy-9α,11α-peroxidoprost-5,13-dienoic acid) and PGH₂ for the more polar endoperoxide (15-hydroxy-9α,11α-peroxidoprost-5,13-dienoic acid). The structure of PGG₂ was established by three separate experiments. Treatment of PGG₂ with mild reducing agents such as SnCl₂ and triphenylphosphine gave PGF₂α as the major product. This showed the presence of a peroxide bridge between C-9 and C-11 but did not discriminate between a hydroxy and a hydroperoxy group at C-15 since the agents used would reduce the latter group into the former. In a second experiment, PGG₂ was treated with lead tetracetate in benzene followed by triphenylphosphine. In this case 15-keto-PGF₂α was the major product. Lead tetracetate causes dehydration of hydroperoxides into ketones, and therefore, formation of a 15-ketoprostaglandin from PGG₂ by this treatment strongly indicated the presence of a hydroperoxy group at C-15. The isomerization of PGG₂ into 15-hydroperoxy-PGE₂ in aqueous medium gave independent evidence for a peroxide group at C-15 (Fig. 1).

Two reactions are involved in the conversion of PGG₂ into PGE₂, i.e., reduction of the hydroperoxy group at C-15 into a hydroxy group (peroxidase) and isomerization of the endoperoxide structure into a 3-hydroxyketone (endoperoxide isomerase) (Fig. 1). The endoperoxide isomerase was found to be almost entirely associated with microsomal fraction. The enzymic activity was stimulated by reduced glutathione.

The endoperoxides were quite unstable ($t_{1/2} = 5$ min); however, if they were stored under anhydrous conditions in acetone they could be kept for several weeks. When their biological activity was tested on in vitro preparations it was found that the effects of the endoperoxides on gastrointestinal smooth muscle were comparable to those of PGE₂ and PGF₂α. On the other hand, the effects on vascular (rabbit aorta) and airway (guinea pig trachea) smooth muscle were considerably greater than those of PGE₂ and PGF₂α respectively (22). Both endoperoxides were potent contractors of the isolated human umbilical artery (23). Administration of PGG₂ and PGH₂ intravenously to guinea pigs (22) produced an increase in insufflation pressure, which was more marked than that caused by corresponding doses of PGF₂α. The cardiovascular effects of the endoperoxides showed a complex pattern. The blood-pressure response was triphasic, i.e., a transient fall consistently followed by a shortlasting rise and then by a sustained reduction. These studies on vascular and airway smooth muscle demonstrated that the endoperoxides had effects that could not be attributed to conversion into the stable prostaglandins.

Additional studies in our laboratory showed that the two endoperoxides also had unique effects on platelets. Thus PGG₂ and PGH₂ induced rapid and irreversible aggregation of human platelets (19,20,24).

**Discovery of Unstable Aggregating Factor and Thromboxanes**

The biological effects of the pure endoperoxides were of particular interest in relation to other studies which demonstrated that arachidonic acid caused aggregation when added to human platelets (23,26),
and labile aggregating material (LASS) was formed from this acid when it was incubated with preparations of sheep vesicular glands (27-29). Furthermore, the potency of the endoperoxides in causing contractions of the isolated rabbit aorta was of particular interest in relation to the so-called rabbit-aorta-contracting substance (RCS) (30). RCS was reported to be formed in guinea pig lung during anaphylaxis and was later suggested to be due to the endoperoxide intermediate in prostaglandin biosynthesis (31). We found that material with similar biological properties was formed after addition of arachidonic acid to human platelets. However, the RCS from guinea pig lung and platelets was found to consist of one major component with a $t_{1/2}$ of about 30 s and minor component of PGG$_2$ and/or PGF$_2$ with $t_{1/2}$ of 4-5 min (32). The short-lived major component of RCS could be generated by addition of arachidonic acid to platelets.

We therefore incubated 1-14C-arachidonic acid with suspensions of washed human platelets in order to obtain structural information about RCS. Three major metabolites were isolated (33). One of them was found to be 12L-hydroxy-5,8,10,14-eicosatetraenoic acid (12-HETE) (Fig. 2). The corresponding hydroperoxide (HPETE) could be isolated after incubation of arachidonic acid with sonicated platelets. Formation of 12-HETE from arachidonic acid was also reported to occur in bovine platelets (34). A more polar metabolite was identified as 12L-hydroxy-5,8,10-heptadecatrienoic acid (HHT) whereas a third component was found to be the hemiacetal derivative of 8(1-hydroxy-3-oxopropyl)-9-12L-didhydroxy-5,10-heptadecadienoic acid.

![Fig. 2. Transformation of arachidonic acid in human platelets.](image-url)
Fig. 3. Maximum aggregation induced by 0.1 ml of suspensions of washed platelets incubated for different times with 120 ng of arachidonic acid (●). The content of PGG$_2$/H$_2$ in these samples is also given (○). The platelet suspension in the aggregometer tube was preincubated for 2 min with 1.4 x 10$^5$ M indomethacin.

(thromboxane B$_2$, PHD). "1-1$^4$C"-PGG$_2$ added to suspensions of human platelets was rapidly converted into HHT and thromboxane B$_2$.

All of the identified metabolites of arachidonic acid were stable compounds and could therefore not be identical to the very unstable (t$_{1/2}$ = 30 s) RCS. Additional biological work with the platelets involving characterization of the material formed from arachidonic acid was therefore carried out. When arachidonic acid was incubated with washed platelets and an aliquot of the incubate was transferred to a suspension of platelets preincubated with indomethacin, aggregation took place. This was not due to PGG$_2$ or PGH$_2$ since the amounts found were only about one per cent of those required to explain the response. A more detailed analysis of the appearance of the aggregating factor and the endoperoxides showed that the amount of endoperoxides was highest in the very early phase of the incubation period, whereas the aggregating factor had a maximum later (35) (Fig. 3). Experiments using filtrates of incubates prepared as described above showed that the aggregating factor was very unstable. When the log dose (arbitrary units) was plotted against time of incubation at 37°C, a linear relationship was obtained. The half-life of the aggregating factor was 33-46 s. A factor with similar properties was also generated from the endoperoxide, PGG$_2$. In addition to inducing irreversible aggregation, the unstable factor also caused release of serotonin from platelets.

Further work involving $^{18}$O$_2$ experiments suggested that thromboxane B$_2$ was formed from PGG$_2$ by rearrangement and subsequent incorporation of one molecule of H$_2$O (33). It was therefore conceivable that if the rearranged intermediate had an appreciable lifetime it should be trapped in the presence of nucleophilic reagents (36). This was found to be the case. Addition of 25 vol. of methanol to washed platelets incubated with arachidonic acid for 30 s gave two derivatives that were less polar than thromboxane B$_2$. The
mass-spectral data indicated that the two compounds obtained by addition of methanol were epimers of thromboxane B₂ methylated at the hemiacetal hydroxyl group (Fig. 4). The two epimers also appeared when methanol was added to platelets incubated with PGG₂ for 30 s. Addition of ethanol to platelets incubated with arachidonic acid for 30 s similarly gave rise to epimers of thromboxane B₂ ethylated at the hemiacetal hydroxyl group. Finally, addition of 5 vol. of 5 M sodium azide to platelets incubated with arachidonic acid gave an azido alcohol, i.e., a derivative of thromboxane B₂ in which the hemiacetal hydroxyl group was replaced by an azido group. The trapping experiments showed the existence of a very unstable intermediate in the conversion of PGG₂ into thromboxane B₂.

In order to determine the half-life of the intermediate, the platelet suspension was incubated with ¹⁻¹⁴C⁻⁻arachidonic acid for 45 s and the reaction was stopped by filtration. The clear, essentially platelet-free filtrate was kept at 37°C, and aliquots were removed after different times and immediately added to 25 ml of methanol containing tritium-labelled mono-O-methylthromboxane B₂. A linear relationship between the logarithms of the ¹⁴C/³H ratios of the purified methyl ester of mono-O-methylthromboxane B₂ and the times of incubation was obtained. The half-life thus obtained was 32 ± 2 (S.D.) s.

Fig. 4 shows the proposed structure of the unstable intermediate. The acetal carbon atom binding two oxygens should be susceptible to attack by nucleophiles, e.g., H₂O (giving thromboxane B₂) as well as

Fig. 4. Scheme of transformations of PGH₂ into thromboxane derivatives.
CH$_3$OH, C$_2$H$_5$OH, and N$_3^-$ (giving derivatives of thromboxane B$_2$ described above). Addition of CH$_3$O$_2$H to platelets incubated with arachidonic acid led to formation of mono-O-methylthromboxane B$_2$ lacking carbon-bound $^2$H. This finding excluded an alternative structure of the unstable intermediate, i.e., an unsaturated oxane ((I) in Fig. 4). Furthermore, the $t_1/2$ of thromboxane A$_2$ seemed to exclude a carbonium ion structure ((II) in Fig. 4), which in aqueous medium should be considerably less stable.

The available evidence indicated that the aggregating factor and RCS were due to the same compound. Thus, they were both derived from arachidonic acid or PGG$_2$, their formation from arachidonic acid was blocked by indomethacin, and their half-lives were similar. It was proposed that this material is identical with the unstable intermediate detected chemically in platelets (Fig. 4) because of similar properties.

The new oxane derivatives were named thromboxanes because of their structure and origin. Thromboxane A$_2$ is the highly unstable bicyclic compound, and thromboxane B$_2$ is the stable derivative provisionally named PHD. The subscript indicates the number of double bonds, as in the prostaglandin nomenclature. The structure of thromboxane B$_2$ has been confirmed by synthesis (37-40).

Thromboxane A$_2$ has been shown to possess a variety of strong biological effects. The best-known of these are induction of platelet aggregation and the release reaction (36,40) as well as strong constricting effects on vascular smooth muscle. The first vessel to be studied in this respect was the rabbit aorta (30,32); later, similar contractile responses were observed in other vessels as well, such as coronary arteries (42-46), the mesenteric and celiac arteries (47,48), the umbilical artery (23), and others.

These dual effects of TXA$_2$, induction of vasoconstriction and platelet aggregation, both come into operation after a vessel has been injured. They indicate that TXA$_2$ probably plays a role in normal hemostasis in vivo as well as in pathological conditions with an increased tendency to vasospasm and/or thrombosis. Several reviews have been written on the biological effects and possible roles of thromboxanes in vivo (e.g., refs. 41,50). Thromboxane A$_2$ has also potent contractile effects on airways, demonstrable both in vitro and in vivo (51).

Following the isolation of the endoperoxides and the discovery of thromboxane A$_2$ it was found that arterial tissue converts the endoperoxide into a product with opposite effects (52). Structural work demonstrated that it was an enol ether derivative (53). This vasodilator and antiaggregating compound was named PGI$_2$, or prostacyclin. Thromboxane A$_2$ and prostacyclin probably form a hemostatic mechanism for control of the tonus of blood vessels and the aggregation of platelets in vivo. These platelet and vessel-wall reactions, which are of considerable interest in antithrombotic therapy, are summarized in Fig. 5. The main focus is now on the development of specific thromboxane synthetase inhibitors for this purpose. For a recent review see reference 54.

**Discovery of the Leukotrienes**

The role of prostaglandins in inflammation was brought into focus with the discovery by Vane and collaborators that non-steroidal
anti-inflammatory drugs like aspirin inhibit the enzyme (cyclooxygenase) responsible for conversion of arachidonic acid into prostaglandins and thromboxanes (55). Anti-inflammatory steroids also inhibit the formation of prostaglandins; however, the mechanism of action is different. The steroids inhibit the formation of prostaglandins by blocking the release of arachidonic acid from the phospholipids. Since aspirin-like drugs and steroids have different anti-inflammatory effects it seemed conceivable to us that some of these differences might be due to formation of additional pro-inflammatory derivatives of arachidonic acid. Studies of the transformation of arachidonic acid in leukocytes, which were carried out to test this hypothesis, have recently resulted in the recognition of a novel group of compounds, the leukotrienes. These compounds seem to be of importance in both immediate hypersensitivity reactions and inflammation.

When arachidonic acid was incubated with polymorphonuclear leukocytes it was found that the major metabolite was a new lipoxygenase product, viz. 5(S)-hydroxy-6,8,11,14-eicosatetraenoic acid (5-HETE) (56). Additional studies also demonstrated the formation of 5(S),12(R)-dihydroxy-6,8,10,14-eicosatetraenoic acid (major product) (leukotriene B₄, cf. below), two additional 5(S),12-dihydroxy-6,8,10-trans,14-cis-eicosatetraenoic acids, epimeric at C-12, and two isomeric 5,6-dihydroxy-7,9,11,14-eicosatetraenoic acids (Fig. 6) (57,58).

Stereochemical studies, demonstrating formation of two acids with all trans conjugated trienes and epimeric at C-12 and one major isomer (12R) with different configuration of the triene raised the question of the mechanism of formation (58). With isotopic oxygen it was demonstrated that the oxygen of the alcohol group at C-5 originated in molecular oxygen, whereas the oxygen of the alcohol
group at C-12 was derived from water (Fig. 6) (59). These observations led us to develop the hypothesis that leukocytes generated an unstable intermediate which would undergo nucleophilic attack by water, alcohols, and other nucleophiles. Leukocytes were therefore incubated for 30 s with arachidonic acid followed by addition of 10 vol. of methanol, 10 vol. of ethanol, or 0.2 vol. of N HCl. Trapping with methanol (or ethanol) yielded two new less polar compounds, which were present in equal amounts and which had ultraviolet spectra identical to those of compounds I and II (Fig. 6). Infrared spectrometry indicated that the conjugated trienes had all-trans geometry. Mass spectrometric analyses of the two compounds showed that they were isomeric and carried hydroxyl groups at C-5 and methoxy groups at C-12. The alcohol groups at C-5 had (S) configuration and it was obvious that the compounds were the C-12 epimers of 5(S)-hydroxy-12-methoxy-6,8,10,14(E.E.E.Z)eicosatetraenoic acid (Fig. 6).

These experiments demonstrated that leukocytes generated a metabolite of arachidonic acid, which can undergo a facile nucleophilic reaction with alcohols. Analysis of samples obtained from trapping experiments performed under different conditions always showed
inverse relationships between the amount of compounds I and II and their 12-O-alkyl derivatives. This result suggested that compounds I and II and the 12-O-alkyl derivatives were formed nonenzymatically from the same intermediate.

The stability of the intermediate was determined by incubating leukocytes with arachidonic acid for 45 s followed by addition of 1 vol. of acetone in order to inactivate the enzyme. After different time intervals aliquots of the mixture were transferred to flasks containing 15 vol. of methanol. Analysis by chromatography showed that the $t_{1/2}$ of the intermediate, measured as the 12-O-methyl derivative, was 3-4 min. Concomitantly with the decrease in the concentration of the intermediate the concentrations of compounds I, II, IV, and V increased whereas the concentrations of compounds III and 5-hydroxy-6,8,11,14-eicosatetraenoic acid remained constant. These data suggested that the epimeric 5,6- and 1,12-dihydroxy acids (compounds I, II, IV, and V) are formed by nonenzymatic hydrolysis of a common unstable intermediate, whereas compound III is generated by enzymatic hydrolysis of the same intermediate (Fig. 6). Similar experiments performed at acid and alkaline pH showed that the intermediate was acid-labile and considerably more stable under alkaline conditions. It was also found that the two 5,6-dihydroxy derivatives (IV and V) were formed non-enzymatically from the same intermediate as the enzymatic product, 5S,12R-dihydroxy-eicosatetraenoic acid, and that $^{18}$O from molecular oxygen was exclusively retained at C-5 of these derivatives whereas $^{18}$O from water was introduced at C-6 or C-12. On the basis of the experimental data described above, the structure 5,6-oxido-7,9,11,14-eicosatetraenoic acid (leukotriene A$_4$, LTA$_4$) (Fig. 6) was proposed for the intermediate (59).

The formation of compounds I-V from the epoxide intermediate is shown in Fig. 6. With the exception of compound III these are formed by chemical hydrolysis of the epoxide through a mechanism involving a carbonium ion. This derivative added hydroxyl anion preferentially at C-6 and C-12 to yield four isomeric products which contain the stable conjugated triene structure. The formation of compound III is enzymatic since it is not racemic at C-12 and since it is only formed by non-denatured cell preparations.

The structure, 5,6-oxido-7,9,11,14-eicosatetraenoic acid (leukotriene A$_4$, cf. below) (59) proposed for the intermediate has subsequently been confirmed by chemical synthesis and the stereochemistry has been elucidated (60). The 5S,12R-dihydroxy acid formed enzymatically was earlier shown to contain one cis and two trans double bonds in the conjugated triene. The location of the cis double bond (A$^5$ position) was recently established by synthetic methods (61). The allylic epoxide intermediate can exist in free form since it has been isolated from human polymorphonuclear leukocytes (62). The suggested mechanism for the biosynthesis of the epoxide from arachidonic acid (Fig. 6) involves initial formation of 5-hydroperoxy-6,8,11,14-eicosatetraenoic acid (5-HPETE). The epoxide is formed from 5-HPETE and subsequent abstraction of the pro-R hydrogen at C-10, and elimination of hydroxyl anion from the hydroperoxy group (63). The dehydration reaction has been found to be catalyzed by a soluble enzyme, which was recently isolated from leukocytes (64).
Slow-Reacting Substance of Anaphylaxis (SRS-A)

The occurrence of a smooth-muscle-stimulating factor (SRS) appearing in the perfusate of guinea pig lung treated with cobra venom was described in 1938 (65). The factor was shown to be released also by immunological challenge (66). Biological studies of SRS suggested that it might be an important mediator of anaphylactic and other immediate hypersensitivity reactions (67, 68). Characterization of SRS indicated that it was a polar lipid with UV-absorption and that it might contain sulfur (69-71). Studies with labelled arachidonic acid suggested that this acid might be incorporated into SRS (72, 73).

Studies in our laboratory showed that treatment of human neutrophils with the ionophore A23187 resulted in stimulation of the synthesis of the 5,12-dihydroxy acid (LTB₄) described above (58). On the basis of the stimulatory effect of the inophore on both SRS production (74) and LTB₄ formation, the UV-absorbance data, and other considerations, we developed the hypothesis that there was a biogenetic relationship between the unstable allylic epoxide intermediate in neutrophils and SRS generated in a variety of systems.

For production of relatively large amounts of SRS we found that murine mastocytoma cells (CXBGABMCT-1) stimulated with the calcium ionophore A23187 were more suitable than previously described systems (75). The SRS was purified by high-pressure liquid chromatography. The purified material showed an absorbance maximum at 280 nm and gave a typical contraction of guinea pig ileum, which was reversed by FPL-55712 (75). The ultraviolet characteristics resembled those of the dihydroxy acids; however, the maximum was shifted 10 nm to higher wavelength. This was in agreement with a sulfur substituent α to a conjugated triene. Labelled arachidonic acid and cysteine were incorporated into the product.

Degradation of SRS by Raney nickel desulfurization gave 5-hydroxyarachidic acid, indicating that the arachidonic acid derivative and cysteine were linked by a thioether bond (Fig. 7). This finding also supported the hypothesis that there was a biogenetic relationship between the 5-lipoxygenase pathway in leukocytes and SRS. The positions of the double bonds in SRS were determined by reductive ozonolysis. The isolation of 1-hexanol among the products indicated that the Δ¹⁴ double bond of arachidonic acid had been retained. The approach used for locating the conjugated triene was based on previous studies in our laboratory that had shown that arachidonic acid and related fatty acids containing two methylene interrupted double bonds at the ω6 and ω9 positions are oxygenated to give derivatives with isomerization of the ω6 double bond to ω7. Incubation of the isolated SRS with lipoxygenase resulted in isomerization of the Δ¹⁴ double bond into conjugation with the conjugated triene (forming a tetraene) since there was a bathochromic shift of 30 nm. This finding indicated that SRS contained a Δ¹¹-cis double bond and additional double bonds at Δ7 and Δ9. The structural work at this stage showed that SRS was a derivative of 5-hydroxy-7,9,11,14-eicosatetraenoic acid with a cysteine-containing substituent in thioether linkage at C-6. Derivatization of cysteine was suggested by the failure to isolate alanine after desulfurization. The cysteine-containing substituent was
Therefore referred to as RSH in the reports of this work (75-77). Further studies involving amino acid analyses of acid-hydrolyzed SRD demonstrated that in addition to cysteine, one mol of glycine and one mol of glutamic acid were present per mol of SRS. End-group (dansyl method and hydrozinolysis) and sequence analyses (dansyl-Edman procedure) of the peptide showed that it was γ-glutamylcysteinylglycine (glutathione). The structure of the SRS from murine mastocytoma cells was therefore 5-hydroxy-6-S-glutathionyl-7,9,11,14-eicosatetraenoic acid, leukotriene (LT)C₄ (cf. below) (Fig. 7) (78). The structure was confirmed by comparison with synthetic material. This represented the first structure determination of an SRS-A (78). The preparation and some properties of corresponding cysteinylglycine derivative (LTD₄) and cysteinylderviative (LTE₄) were also reported at the same time (78). These compounds were later isolated from natural sources (see below). The proposed stereochemistry for LTC₄ was confirmed and unambiguously assigned by total synthesis including preparation of stereoisomers of LTC₄ (79). The synthetic work was carried out by E.J. Corey and co-workers. LTC₄ is thus 5(S)-hydroxy, 6(R)-S-glutathionyl-7,9trans-11,14-cis-eicosatetraenoic acid.

Later studies using a different cell type, the RBL-I cells, demonstrated that the major-slow reacting substance was LTD₄ (5(S)-hydroxy,6(R)-S-cysteinylglycine-7,9-trans-11,14-cis-eicosatetraenoic acid) (80).

Following the structure determination of SRS from mastocytoma cells (75,78) and synthetic preparation of LTC₄, LTD₄, and LTE₄ (78), all of these cysteine-containing leukotrienes (Fig. 8) have been found in a variety of biological systems using comparison with synthetic material or partial characterization by chemical or physical methods for identification (Table 1). STS-A is thus a mixture of leukotrienes
containing cysteine, i.e. the parent compound LTC\textsubscript{4} and the metabolites LTD\textsubscript{4} and LTE\textsubscript{4}.

Transformation of LTA\textsubscript{4} into LTC\textsubscript{4} by enzymatic addition of glutathione has been demonstrated in both mastocytoma cells and human leukocytes pretreated with the inhibitor of arachidonic acid metabolism, BW755 (81). These studies confirm the originally proposed pathway for biosynthesis of SRS, i.e. formation of LTA\textsubscript{4} from arachidonic acid via 5-HPETE followed by addition of glutathione to LTA\textsubscript{4} with opening of the epoxide at the allylic position C-6 to give LTC\textsubscript{4} (75).

The biological significance of the biosynthetic pathways described and the cumbersome systematic names of the compounds involved suggested the introduction of a trivial name for these entities (76). The term 'leukotriene' was chosen because the compounds were discovered in leukocytes and the common structural feature is a
Table 1. Identification of leukotrienes from different sources

<table>
<thead>
<tr>
<th>Source</th>
<th>LTA₄</th>
<th>LTB₄</th>
<th>LTC₄</th>
<th>LTD₄</th>
<th>LTE₄</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rabbit peritoneal leukocytes</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td>57,59</td>
</tr>
<tr>
<td>Human peripheral leukocytes</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td>86,119,120</td>
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<tr>
<td>Mouse mastocytoma cells</td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td>75,77,121</td>
</tr>
<tr>
<td>Rat basophilic leukemia cells</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>80,122,123</td>
</tr>
<tr>
<td>Rat peritoneal cells</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td>124,125,126</td>
</tr>
<tr>
<td>Rat leukocytes</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td>127,128</td>
</tr>
<tr>
<td>Rat macrophages</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td>129</td>
</tr>
<tr>
<td>Mouse macrophages</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>130</td>
</tr>
<tr>
<td>Human lung</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>131</td>
</tr>
<tr>
<td>Guinea-pig lung</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>132</td>
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<td>Cat paws</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>133</td>
</tr>
</tbody>
</table>

conjugated triene. Various members of the group have been designated alphabetically: leukotrienes A are 5,6-oxido-7,9-trans-11-cis; leukotriene B, 5(S),12(R)-dihydroxy-6-cis-5,19-trans; leukotrienes C, 5(S)-hydroxy-6(R)-γ-glutamyl-cysteinylglycyl-7,9-trans-11-cis; and leukotrienes E, 5(S)-hydroxy-6(R)-5-cysteinyll-7,9-trans-11-cis-eicosapolyenoic acids. Since precursor acids containing the Δ⁵ double-bond system (i.e. 5,8,11-eicosatrienoic acid, arachidonic acid, and 5,8,11,14,17-eicosapentaenoic acid) can be converted to leukotrienes containing 3-5 double bonds, a subscript denoting this number is used (82). Leukotriene A₄ is thus the epoxy derivative of arachidonic acid which can be further transformed to leukotrienes B₄, C₄, and E₄.

Leukotriene C₄ is metabolized to leukotriene D₄ by enzymatic elimination of glutamic acid by γ-glutamyl transpeptidase (80). The remaining peptide bond in leukotriene D₄ is hydrolyzed by a renal dipeptidase to give leukotriene E₄ (83). It has recently been found that LTE₄ can also function as acceptor of γ-glutamic acid forming a γ-glutamylcysteinyll derivative, named LTF₄ (84,85) (Fig. 8).

In addition to the 5-lipoxygenase, leukocyte preparations contain enzymes catalyzing introduction of oxygen at C-12 and C-15 (86). Recently, evidence has been obtained for leukotriene formation after initial oxygenation at either of these positions (87-91).

Biological Effects of the Leukotrienes

Studies with pure leukotrienes have provided detailed information about the effects of this group of compounds in different biological systems. The leukotrienes containing cysteine (LTC₄, D₄, and E₄) are
potent bronchoconstrictors in several species including humans and they seem to have specific effects on the peripheral airways (92-99). They also show potent vasoconstrictor activity and have negative ionotropic effects on the cardiac contractions (100).

In recent studies using bronchi from atopic patients sensitive to birch pollen (101) the relative importance of the leukotrienes as mediators of anaphylaxis has been demonstrated. Treatment of the preparation with a histamine antagonist, mepyramine, and cyclooxygenase inhibitor, indomethacin, did not reduce the response to the specific allergen. However, benoxaprofen and a prostacycline derivative (U-60257), both of which block leukotriene formation (102,103) inhibited the anaphylactic contraction in bronchi from asthmatics induced by birch pollen. Incubation of the atopic lung tissue with antigen resulted in a release of LTC\(_4\), LTD\(_4\), and LTE\(_4\), which could be inhibited by the prostacyclin derivative U-60257 (101). These studies indicate that the leukotrienes containing cysteine (LTC\(_4\), LTD\(_4\), and LTE\(_4\)) are major mediators of airway anaphylaxis, the finding that inhibition of leukotriene formation blocks ascaris-induced asthma in monkeys also indicates that leukotriene antagonists or inhibitors of their formation could be of therapeutic value in the treatment of bronchial asthma (102).

When injected intradermally into guinea pigs LTC\(_4\) and LTD\(_4\) cause extravasation of Evans blue (92,96,98). More recent studies involving intravital microscopy of the cheek pouch of the hamster (Mesocricetus auratus) have demonstrated specific effects of these leukotrienes on the permeability of the post-capillary venules (104). According to dose-response curves, LTC\(_4\) and LTD\(_4\) both induced a significant increase of vascular permeability at much lower concentrations than histamine. Leukotriene C\(_4\) was approximately 5000 times more potent than histamine in this respect. The cysteinyl-containing leukotrienes seem to increase the vascular permeability by a direct action on the vessel wall, since it occurs rapidly and does not require release of histamine or prostaglandins or the participation of polymorphonuclear leukocytes. Leukotriene B\(_4\) also causes extravasation of plasma, although at higher concentrations. The reaction occurs with some latency and requires adhering leukocytes. Administration of a vasodilator together with leukotrienes potentiates the increase in plasma leakage caused by a submaximal dose of leukotrienes, as has been reported in the guinea pig for PGE\(_2\) and LTD\(_4\) (105) and in the guinea pig, rabbit and rat for PGE\(_2\) and LTBo (106,107).

When LTB\(_4\) was administered to the hamster cheek pouch in the same close-range as LTC\(_4\) it caused a dramatic increase in the adhesion of leukocytes to the endothelium in small venules (104). Increased adherence of human leukocytes caused by LTB\(_4\) has also been demonstrated in vitro using a column of nylon fibers (108). During superfusion with LTB\(_4\) (6-10 min) the number of interstitial white cells increased. This finding is consistent with the chemotactic stimulant property of LTB\(_4\). This effect of LTB\(_4\) has been demonstrated in vitro using either the Boyden chamber technique or migration under agarose (109-112). In vivo this effect has been monitored by determining white-cell accumulation in the peritoneal cavity of guinea pigs following intraperitoneal injection of LTB\(_4\) (113). The studies described above indicate that LTB\(_4\) might be a mediator in
Fig. 9. Formation of prostaglandins, thromboxanes, and leukotrienes.

the migration of leukocytes from the blood to areas of inflammation. Recent work has also demonstrated that LTB₄ activates neutrophils. Addition of nanomolar concentrations of LTB₄ to the cells results in rapid aggregation, degranulation, superoxide generation, and mobilization of membrane-associated calcium (114-116).

Studies on the mechanism of action of anti-inflammatory steroids indicate that they inhibit the release of the precursor acid, arachidonic acid, whereas cyclo-oxygenase inhibitors such as aspirin block the transformation of this acid into prostaglandins and thromboxanes (Fig. 9). The steroid-induced inhibition of arachidonic acid release, proposed to be due to formation of peptide inhibitors of phospholipase A₂, prevent formation of not only prostaglandins and thromboxanes but also leukotrienes and other oxygenated derivatives (117-118). Some of the therapeutic effects of steroids which are not shared by aspirin-type drugs might therefore be due to inhibition of leukotriene formation. The recent increased knowledge about the transformation of arachidonic acid and the biological effects of the metabolites seem to provide new possibilities to develop novel and more specific therapeutic agents.

Acknowledgement

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NOVEL BIOLOGICAL MEDIATORS 809

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