

## Structures of Molecules at the Atomic Level: Caffeine and Related Compounds

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**Recent researches have shown that the lengths of the chemical bonds, whether completely or partially covalent or ionic, are sums of the radii of the adjacent atoms and/or ions. An investigation of the bond length data for the molecular components of nucleic acids, showed (for the first time) that all were effectively the sums of the covalent radii of the adjacent atoms. This work shows that the bond lengths in caffeine and related molecules are likewise sums of the covalent radii of C, N, O, and H. This has enabled arriving at the atomic structures of these molecules, also for the first time.**

Key Words: additivity of covalent and or ionic radii, atomic structure of DNA, bond lengths, complete covalency in biological molecules, golden ratio based ionic radii.

### INTRODUCTION

It was shown in recent years (Heyrovská 2005, 2006, 2009) that bond lengths of completely or partially covalent or ionic bonds are sums of the radii of the adjacent atoms and or ions. The atomic radii are the covalent radii (Pauling 1960) or the bonding atomic radii (www.prenhall.com)  $d(A)$  defined as,

$$d(A) = d(AA)/2 \quad (1)$$

where  $d(AA)$  is the interatomic distance. The ionic radii are the Golden sections of  $d(AA)$ , based on the Golden ratio  $\phi$ , (Heyrovská 2005, 2006). The Golden ratio ( $\phi = 1.618$ ), also known as The Divine ratio, appears in the geometry of a variety of Nature's creations, as described e.g. in (www.goldennumber.net). It is the ratio  $a/b$  of a larger segment (a) to a smaller segment (b) of a line which are such that  $a/b = (a + b)/a$ . From the latter, one obtains the Golden quadratic equation,  $a/b = (a/b)^2 - 1$  whose positive root is  $(a/b) = (1 + 5^{1/2})/2 = \phi (= 1.618..)$ . The segments  $a = c/\phi$  and  $b = c/\phi^2$  are called the Golden sections of the

line of length  $c = a + b$ . Note that  $(1/\phi) + (1/\phi^2) = 1$ . A simple way of visualizing  $\phi$  is that it is equal to the ratio of the diagonal to a side in a regular pentagon.

It was shown (for the first time) that, in fact, the Golden ratio arises right in the core of the atom (Heyrovská 2005) as follows: the ground state Bohr radius for H ( $a_B = 0.53 \text{ \AA}$ ) is related to the ionization potential,  $I_H = (e/2\kappa a_B)$ , which in turn is the sum (or the absolute difference in potentials) of  $I_p (= e/2\kappa a_p)$  and  $I_e (= -e/2\kappa a_e)$  of  $p^+$  and  $e^-$ , respectively, where  $\kappa = 4\pi\epsilon$  is the electrical permittivity. From these one obtains,

$$a_B = a_p + a_e; \quad 1/a_B = (1/a_p) - (1/a_e) \quad (2a,b)$$

$$(a_e/a_p)^2 - (a_e/a_p) - 1 = 0 \text{ (Golden quadratic, on combining Eqs. 2a,b)} \quad (3a)$$

$$(a_e/a_p) = \phi = (1 + 5^{1/2})/2 = 1.618... \text{ (positive root)} \quad (3b)$$

where  $a_p = (a_B/\phi^2)$  and  $a_e = (a_B/\phi)$  are the Golden sections of  $a_B$ .

A square with  $a_B$  as a side has two protons and two electrons at opposite corners. The diagonal of this square

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gives (Heyrovská 2005) the covalent bond length,  $d(\text{HH}) = 0.74 \text{ \AA}$  of the  $\text{H}_2$  molecule (Pauling 1960). The covalent radius  $d(\text{H}) = d(\text{HH})/2 = 0.37 \text{ \AA}$ . Since  $a_b$  has two Golden sections, one gets the following relations:

$$d(\text{HH}) = 2d(\text{H}) = 2^{1/2}a_b = 2^{1/2}(a_c + a_p) = d(\text{H}^-) + d(\text{H}^+) \quad (4a)$$

$$d(\text{H}^-) = d(\text{HH})/\varphi^2 \text{ and } d(\text{H}^+) = d(\text{HH})/\varphi \quad (4b,c)$$

where  $d(\text{H}^-) = 2^{1/2}a_c = 0.46 \text{ \AA}$  and  $d(\text{H}^+) = 2^{1/2}a_p = 0.28 \text{ \AA}$  are the anionic and cationic radii of H, respectively, and are the Golden sections of  $d(\text{HH})$ . Note also that  $2^{1/2}d(\text{H}) = a_b$  is the diagonal of a square with  $d(\text{H})$  as a side.  $\text{H}^-$  and  $\text{H}^+$  are (Heyrovská 2005) the ionic forms in the resonance structures suggested by Pauling (1960) for the  $\text{H}_2$  molecule.

A survey of the literature shows that  $d(\text{H}^+) = 0.74/\varphi^2 = 0.28 \text{ \AA}$  is actually the empirical radius for hydrogen suggested by Pauling (1960) for explaining the partially ionic bonds in hydrogen halides ( $\text{HX}$ ), where X has the covalent radius. It can be seen therefore that the partial ionic character of the  $\text{HX}$  bond is (Heyrovská 2005) due to  $d(\text{H}^+)$ .

It was found (Heyrovská 2005) that on subtracting  $d(\text{H}^+) = 0.28 \text{ \AA}$ , from the known (Pauling 1960) bond lengths  $d(\text{HX})$  of hydrogen halides and  $d(\text{MH})$  of alkali metal hydrides, where  $\text{X} = \text{F}, \dots, \text{I}$  and  $\text{M} = \text{Li}, \dots, \text{Cs}$ , one obtains  $d(\text{X}^-)$  and  $d(\text{M}^+)$ , respectively, as shown in Eqs. 5a,b.  $d(\text{X}^-)$  is found to be half the covalent bond distance  $d(\text{XX})$  and  $d(\text{M}^+)$  is a Golden section of the metal lattice distance,  $d(\text{MM})$  as shown:

$$d(\text{HX}) - d(\text{H}^+) = d(\text{XX})/2 = d(\text{X}^-); \text{ (for HX)} \quad (5a)$$

$$d(\text{MH}) - d(\text{H}^+) = d(\text{MM})/\varphi^2 = d(\text{M}^+); \text{ (for MH)} \quad (5b)$$

On subtracting the values of  $d(\text{M}^+)$  obtained from Eq. 5b from the known (Pauling 1960) interionic distances  $d(\text{MX})$  in alkali halides, one obtains  $d(\text{X}^-)$ , which is a Golden section of  $d(\text{XX})$  as shown (Heyrovská 2005):

$$d(\text{MX}) - d(\text{M}^+) = d(\text{XX})/\varphi = d(\text{X}^-); \text{ (for MX)} \quad (5c)$$

These show that the covalent atomic radii and Golden ratio based ionic radii are additive, and that like  $d(\text{HH})$ ,

both  $d(\text{MM})$  and  $d(\text{XX})$  have two Golden sections which are the anionic and cationic radii of each of M and X.

For covalent bonds such as CH, NH, OH, etc., (Heyrovská 2005, 2006, 2009, Pauling 1960), the bond length  $d(\text{AB})$  is the sum of covalent radii  $d(\text{A}) = d(\text{AA})/2$  and  $d(\text{B}) = d(\text{BB})/2$  as given by,

$$d(\text{AB}) = d(\text{A}) + d(\text{B}) \quad (6)$$

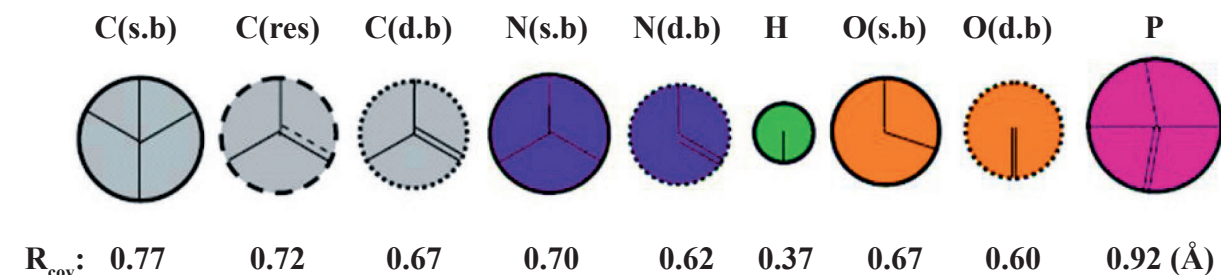
Thus, many bond lengths were shown (Heyrovská 2005) to be sums of the covalent and or ionic radii of the two atoms and or ions constituting the bonds, whether partially or fully covalent or ionic. The additivity of atomic and or ionic radii was found to hold even in aqueous electrolyte solutions (Heyrovská 2006a). Also, the lengths of hydrogen bonds (Heyrovská 2006b) in many inorganic and biochemical groups including in the Watson-Crick base pairs in DNA (and RNA) were shown to be sums of the radii of the H donor and H acceptor atoms or ions, the covalent radius of H and of the transient proton.

### Completely covalent bonds in DNA and RNA

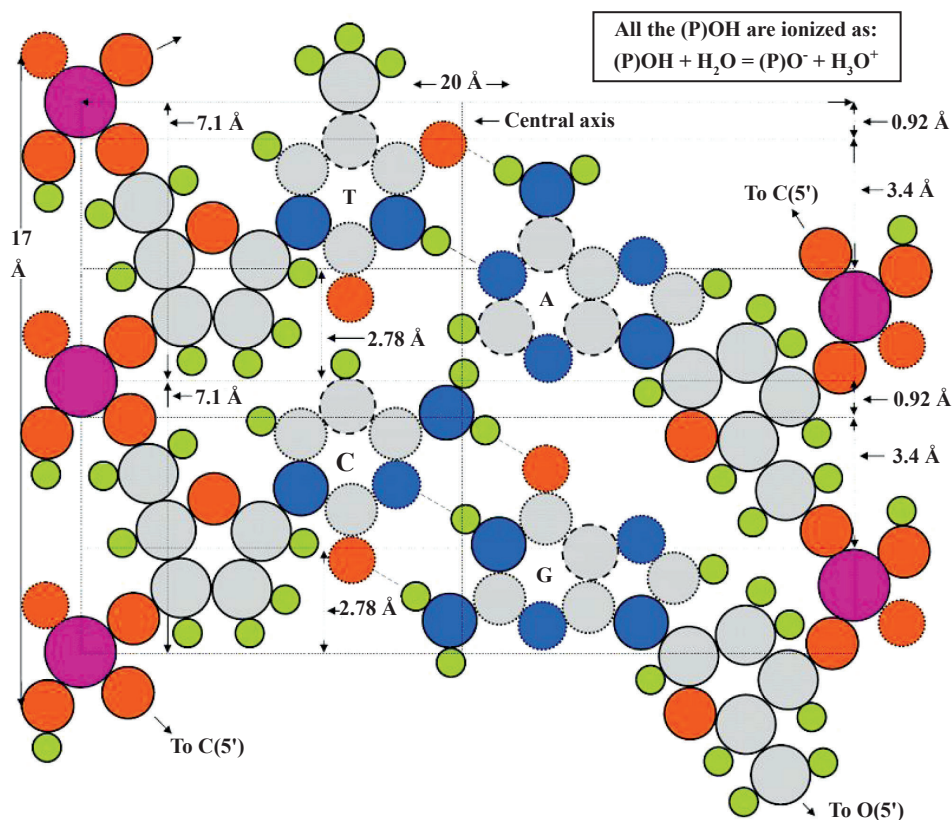
On investigating the bond length data for biological molecules like the molecular components of DNA and RNA, it was found that all the skeletal bond lengths are sums of the appropriate covalent radii of the adjacent atoms, C, N, O, H, and P (Heyrovská 2008). These covalent radii are shown in Figure 1 and they explain the 34 : 20  $\text{\AA}$  section of the DNA (or RNA) helix on the atomic scale (for the first time) as shown in Figure 2. The details can be found in (Heyrovská 2008).

### Completely covalent bonds in caffeine and related molecules

Proceeding next to another set of important biological molecules, namely, caffeine (Zajac et al. 2003), its liver metabolites and xanthine (en.wikipedia.org), it is shown here (for the first time) that the atomic radii in Fig. 1 also explain all the bond lengths.



**Figure 1.** Covalent radii (Pauling 1960) of the atoms: C, N, H, O and P which account (Heyrovská 2008) for all the bond lengths in DNA and RNA. Subscripts: s.b: single bond (C: as in diamond), res.: resonance bond (C: as in graphite and benzene), d.b: double bond.



**Figure 2.** Atomic structures of the molecules in DNA nucleotides (Heyrovská 2008), with bond lengths as sums of the covalent radii (see Fig. 1) of the adjacent atoms. In the 17 Å section, there are 5P atoms (this is half the 34 : 20 Å section per turn of the helix with ten P atoms and each P atom is 10 Å from the central axis (Franklin and Gosling 1953). RNA has U and ribose in place of T and deoxyribose respectively. The lengths of the hydrogen bonds between T & A and C & G are explained (Heyrovská 2006) as sums of the donor and acceptor atoms/ions and of H and the transient proton.

**Table 1.** Average bond lengths ( $\pm 0.03$  Å) (1: Ucin et al. 2007, 2: Egawa et al. 2006, 3: Gunasekaran et al. 2005) and the corresponding sums of atomic covalent radii, R(sum). See Fig. 1 for the radii of the atoms in the atomic structures in Fig. 4, which also shows the numbering of the atoms.

| 1                                 | 2                 | 3         | 4         | 5       | 6         | 7       | 8         | 9       | 10      | 11       | 12      |
|-----------------------------------|-------------------|-----------|-----------|---------|-----------|---------|-----------|---------|---------|----------|---------|
| ←-----#Average bond lengths-----→ |                   |           |           |         |           |         |           |         |         |          |         |
| Bonds                             | \$R(\text{sum})\$ | Caf.      | Theobr.   | Xan.    | Xan.      | Caf.    | Caf.      | Xan.    | Caf.    | Theophy. | Theobr. |
|                                   |                   | 1 : theor | 1 : theor | 1 : exp | 1 : theor | 2 : exp | 2 : theor | 3 : exp | 3 : exp | 3 : exp  | 3 : exp |
| $C_{db} - O_{db}$                 | 1.27              | 1.21      | 1.21      | 1.23    | 1.21      | 1.21    | 1.23      | 1.22    | 1.23    | 1.21     | 1.21    |
| $C_{db} - N_{db}$                 | 1.29              | 1.34      | 1.34      | 1.35    | 1.34      | 1.33    | 1.35      | 1.32    | 1.33    | 1.32     | 1.32    |
| $C_{db} - N_{sb}$                 | 1.37              | 1.38      | 1.38      | 1.37    | 1.37      | 1.38    | 1.38      | 1.35    | 1.37    | 1.36     | 1.36    |
| $C_{res} - C_{db}$                | 1.39              | 1.40      | 1.40      | 1.39    | 1.40      | 1.40    | 1.40      | 1.42    | 1.38    | 1.39     | 1.41    |
| $C_{res} - N_{sb}$                | 1.42              | 1.39      | 1.38      | 1.38    | 1.38      | 1.38    | 1.38      | 1.34    | 1.41    | 1.34     | 1.34    |
| $C_{sb} - N_{sb}$                 | 1.47              | 1.46      | 1.46      |         | 1.46      | 1.46    | 1.46      |         | 1.48    | 1.47     | 1.47    |
| $C_{db} - H$                      | 1.04              | 1.08      | 1.08      |         | 1.08      | 1.09    | 1.08      | 0.98    | 1.15    | 0.98     | 0.98    |
| $N_{sb} - H$                      | 1.07              |           | 1.00      |         | 1.00      |         |           | 0.98    |         | 0.98     | 0.98    |
| $C_{sb} - H$                      | 1.14              | 1.08      | 1.09      |         |           | 1.09    | 1.09      |         |         |          |         |

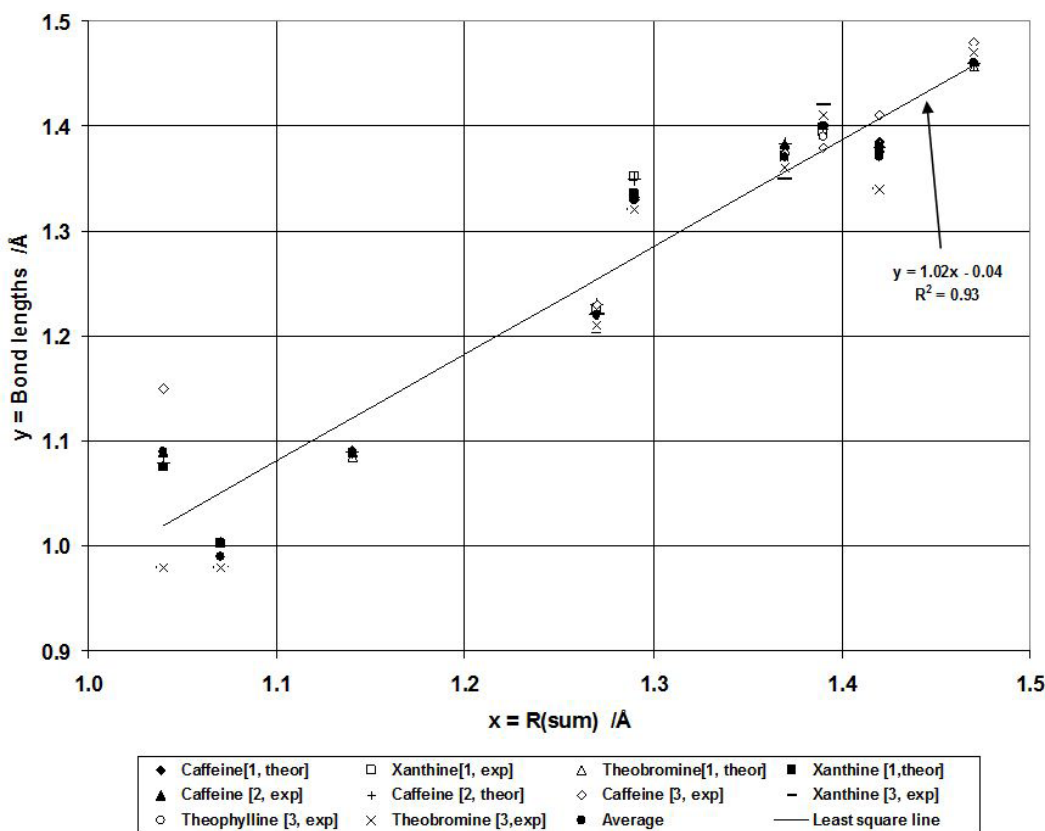
#Abbreviations: Caf.: Caffeine, Theobr.: Theobromine, Theophy.: Theophylline, Xan.: Xanthine.

‡Covalent radii (Å): N(1) = N(3) = N(7) = Ns.b. = 0.70; N(9) = Nd.b. = 0.62; C(2) = C(4) = C(6) = C(8) = Cd.b. = 0.67; C(5) = Cres = 0.72; C(1) = C(3) = C(7) = Cs.b. = 0.77; O(2) = O(6) = Od.b. = 0.60; all H = 0.37.

In Table 1 are assembled the average bond lengths ( $\pm 0.03 \text{ \AA}$ ) in the literature (Ucun et al. 2007; Egawa et al. 2006; Gunasekaran et al. 2005), which include both experimental and theoretical values (see cols. 3-12). The corresponding sums of atomic covalent radii,  $R(\text{sum})$  using the data in Figure 1 are given in column 2. Table 2

shows a comparison of the radii sum  $R(\text{sum})$  (see col. 3) with the corresponding overall average of the bond lengths (see col. 4) in cols. 3-12 of Table 1.

A graph of the average bond lengths from the literature (data in Tables 1 and 2) versus  $R(\text{sum})$  is shown in Figure 3. The average values fall on a least square straight line



**Figure 3.** Graph of the average bond lengths in caffeine and related molecules (Ucun et al. 2007; Egawa et al. 2006; Gunasekaran et al. 2005) (data in Tabs. 1 and 2) versus the sum of the covalent radii,  $R(\text{sum})$ . Note that  $R(\text{sum})_{\text{calc}}$ . in Tab. 2 (using the slope and intercept of the least square line) agree well ( $\pm 0.02 \text{ \AA}$ ) with  $R(\text{sum})$ .

**Table 2.** Comparison of the sum of atomic radii  $R(\text{sum})$  with the overall average of the bond lengths (1: Ucun et al. 2007; 2: Egawa et al. 2006, 3: Gunasekaran et al. 2005) in Tab. 1. See Fig. 4 for the numbering and Fig. 1 for the type (col. 2) of the atoms. Note that  $R(\text{sum})_{\text{calc}}$ . (l.sq.line in Fig. 2) in col. 5 reproduces  $R(\text{sum})$  ( $\pm 0.02 \text{ \AA}$ ) in col. 3.

| 1   | 2                                   | 3               | 4             | 5  |
|---|-------------------------------------|-----------------|---------------|--|
| Bonds of the same length                  | Bonds                               | $R(\text{sum})$ | Average (1-3) | $R(\text{sum})_{\text{calc.}}$ : l.sq.line |
| C2 - O2 = C6 - O6 =                       | C <sub>d,b</sub> - O <sub>d,b</sub> | 1.27            | 1.22          | 1.26                                       |
| C4 - N9 = N9 - C8 =                       | C <sub>d,b</sub> - N <sub>d,b</sub> | 1.29            | 1.33          | 1.28                                       |
| C2 - N1 = N1 - C6 = C2 - N3 = N3 - C4 =   | C <sub>d,b</sub> - N <sub>s,b</sub> | 1.37            | 1.37          | 1.36                                       |
| C4 - C5 = C5 - C6 =                       | C <sub>res</sub> - C <sub>d,b</sub> | 1.39            | 1.40          | 1.38                                       |
| C5 - N7 =                                 | C <sub>res</sub> - N <sub>s,b</sub> | 1.42            | 1.37          | 1.41                                       |
| N1 - C1 = N3 - C3 = N7 - C7 =             | C <sub>s,b</sub> - N <sub>s,b</sub> | 1.47            | 1.46          | 1.46                                       |
| C8 - H8 =                                 | C <sub>d,b</sub> - H                | 1.04            | 1.09          | 1.02                                       |
| N1 - H1 = N3 - H3 = N7 - H7 =             | N <sub>s,b</sub> - H                | 1.07            | 0.99          | 1.05                                       |
| C1 - H1, H1', H1'' = C3 - H3, H3', H3'' = |                                     |                 |               |  |
| C7 - H7, H7', H7'' =                      | C <sub>s,b</sub> - H                | 1.14            | 1.09          | 1.12                                       |



(Atomic structures of caffeine and its liver metabolites)

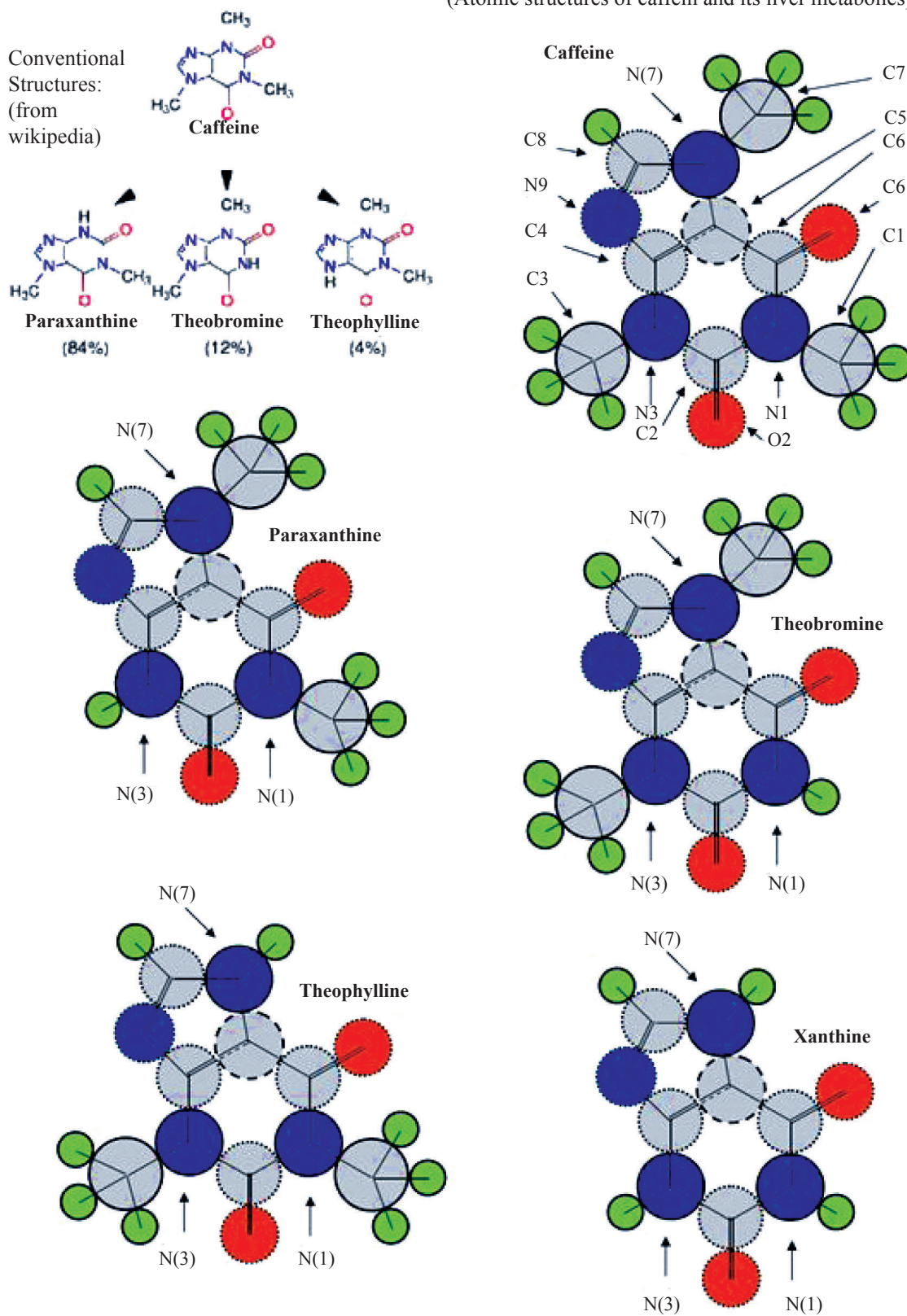


Figure 4. "Atomic structures" of caffeine and related molecules with bond lengths as sums of the covalent radii of the adjacent atoms. Left top: conventional molecular structures (see: en.wikipedia.org and Cazeneuve et al).

with slope = 1.02 and intercept, -0.04. It can be seen that the values of R(sum),calc. in the last column in Table 2 (using the slope and intercept of the least square line) agree well with R(sum) in col. 3. Thus all the bond lengths in caffeine and the related molecules are sums of the appropriate covalent radii of the adjacent atoms. This is similar to the finding for the molecular components of DNA and RNA (Heyrovska 2008), see section 2 above.

This result has thus enabled the conventional molecular structures (en.wikipedia.org) (see Figure 4, left top) of these compounds to be converted here into the “atomic structures” as shown in Figure 4, with all bond lengths as sums of the atomic covalent radii.

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