the yellow solid with C_2H_5Br gave $CH_3COOC_2H_5$ quantitatively.

(2) Allyl acetate (1.0 mL, 9.3 mmol) was added to a vessel containing $Ni(cod)_2$ (820 mg, 3.0 mmol) and PPh_3 (1.5 g, 6.0 mmol). The mixture was stirred at room temperature for 12 h to obtain a brown precipitate, which was separated by filtration. The brown precipitate was recrystallized from THF–diethyl ether to yield deep red prisms of 1 (900 mg, 71%), mp 125–128 °C dec. Anal. Calcd for $C_{23}H_{23}NiO_2P$: C, 65.6; H, 5.5. Found: C, 65.3; H, 5.6. The same complex was obtained by the reaction of $Ni(ema)(PPh_3)_2$ with allyl acetate at -25 °C (experiment 5).

(3) Reactions of allyl acetate and $Ni(cod)_2$ in the presence of $PEtPh_2$ and P-c-Hx_3 were carried out analogously under conditions given in Table I, and complexes 2 and 3 were isolated. Solvents for the recrystallizations of 2 and 3 were mixtures of allyl acetate and hexane and of allyl acetate and toluene, respectively. 2: mp 54–56 °C. Anal. Calcd for $C_{19}H_{23}NiO_2P$: C, 58.9; H, 6.1. Found: C, 59.5; H, 6.1. 3: mp 75–79 °C. Anal. Calcd for $C_{23}H_{41}NiO_2P$: C, 62.9; H, 9.4. Found: C, 63.4; H, 10.3.

Reaction of Allyl Phenyl Ether (Experiment 8). Allyl phenyl ether (0.80 mL, 5.6 mmol) and THF (2.0 mL) were added to a vessel containing $Ni(cod)_2$ (370 mg, 1.4 mmol) and PPh_3 (390 mg, 1.5 mmol). The mixture was stirred at 30 °C for 4 h to obtain a deep red homogeneous solution. When left standing overnight at -70 °C, the solution gave brownish orange crystals of 4 (500 mg, 81%), which were characterized by comparing its IR and NMR spectra with those of an authentic sample prepared by Bönnemann's method.[12]

Reactions of Diallyl Ether (Experiments 9 and 10). Diallyl ether (0.60 mL, 6.0 mmol) and diethyl ether (0.5 mL) were added to a vessel containing $Ni(cod)_2$ (560 mg, 2.0 mmol) and PPh_3 (530 mg, 2.0 mmol). The mixture was stirred for 12 h at room temperature to obtain a yellow homogeneous solution. When left standing at -5 °C for 2 days the solution gave yellow prisms, which were washed repeatedly with diethyl ether and dried under vacuum to yield 630 mg of 5 (75%), mp 125–127 °C dec. Anal. Calcd for $C_{24}H_{25}NiOP$: C, 68.8; H, 6.0. Found: C, 68.4; H, 6.1.

Diallyl ether (0.50 mL, 5 mmol) and diethyl ether (0.5 mL) were added to a vessel containing $Ni(cod)_2$ (460 mg, 1.7 mmol) and P-c-Hx_3 (790 mg, 2.5 mmol). The mixture was stirred at room temperature for 12 h to obtain a yellow homogeneous solution. When left standing at -25 °C for 2 days the solution gave crystals, which were separated by filtration and recrystallized from diethyl ether to yield white crystals of 6 (490 mg, 66%), mp 174–177 °C dec. Anal. Calcd for $C_{24}H_{43}NiOP$: C, 65.9; H, 9.9. Found: C, 65.2; H, 10.2.

Reactions of Allyl Alkyl Ethers (Experiment 11). Allyl methyl ether (1.0 mL, 13 mmol) and toluene (2.6 mL, 32 mmol) were added (1.0 mL, 13 mmol) to a vessel containing $Ni(cod)_2$ (470 mg, 1.7 mmol) and PPh_3 (900 mg, 3.4 mmol). Stirring the solution for 2 days at room temperature

gave a dark brown solution, from which the solvent was removed by evaporation under vacuum. The remaining yellow solid was characterized as $Ni(cod)(PPh_3)_2$ by its IR spectrum. Reactions of allyl ether and allyl isopropyl ether with the mixture of $Ni(cod)_2$ and PPh_3 proceed similarly, and the occurrence of neither the C–O bond cleavage nor the π-complex formation reaction was observed.

Reactions of Allylic Alcohols (Experiments 12–20). Allyl alcohol (0.40 mL, 5.9 mmol) and THF (2.0 mL) were added into a vessel containing $Ni(cod)_2$ (430 mg, 1.56 mmol) and PPh_3 (984 mg, 3.75 mmol). The mixture was stirred for 2 days at 30 °C to obtain a red solution and an orange precipitate. Evolution of 1.52 mmol of C_3H_6 and formation of 1.44 mmol of H_2O during the reaction were observed (Toepler pump and GLC). After the reaction mixture was cooled to -78 °C, the orange precipitate was separated by filtration, washed with hexane, recrystallized from toluene–hexane, and dried under vacuum to yield 942 mg (1.47 mmol, 93%) of orange crystals, which were identified as $Ni(CH_2=CHCHO)(PPh_3)_2$ by comparing its IR and NMR spectra with those of an authentic sample.[22a,28] The other reactions of allylic alcohols were carried out analogously. $Ni(CH_3CH=CHCHO)(PPh_3)_2$ and Ni-$(C_6H_5CH=CHCHO)(PPh_3)_2$ were characterized by IR and NMR spectroscopies.[22a,28]

Reactions of (η^3-Allyl)nickel Complexes with Nucleophiles. Morpholine (0.30 mL, 2.4 mmol) was added to a vessel containing 110 mg (0.25 mmol) of 3 and the homogeneous solution thus obtained was stirred for 15 h at 15 °C. GLC analysis of the solution indicated formation of 0.18 mmol (72%) of N-allylmorpholine. The reaction of 3 with $HNEt_2$ and reactions of other (η^3-allyl)palladium complexes with morpholine were carried out analogously in near nucleophile at 15–20 °C.

Allylation of Morpholine by Allyl Alcohol. Allyl alcohol (0.5 mL, 7.3 mmol) and morpholine (0.5 mL, 3.9 mmol) were added into a vessel containing 100 mg (0.36 mmol) of $Ni(cod)_2$ and 200 mg (0.76 mmol) of PPh_3. The homogeneous solution was stirred at 15 °C for 15 h to yield 1.2 mmol of N-allylmorpholine.

Spectral Measurement and Analysis. IR spectra were taken on a Hitachi Model 295 spectrometer by using KBr disks under nitrogen. ^1H NMR spectra were recorded on a Japan Electron Optics Laboratory (JEOL) Model JNM-PS-100 spectrometer and ^{13}C- and ^{31}P-NMR spectra on a JEOL Model JNM-PET-PS-100 Fourier transform spectrometer. Microanalysis of C, H, and N was performed by Mr. T. Saito of our laboratory with a Yanagimito CHN Autocorder Type MT-2. The analyses of gaseous and liquid products were carried out with a Shimadzu GC-3BT or GC-6A gas chromatograph.

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Crystal Structures of Repeating Peptides of Elastin. 2. N-(*tert*-Butoxycarbonyl)-L-valyl-L-prolylglycylglycine Benzyl Ester

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Abstract: The crystal structure of Boc-Val-Pro-Gly-Gly-OBzl, one of the repeating peptides in elastin, has been determined by the X-ray method. The peptide crystallizes as an ethyl acetate solvate in the monoclinic space group $C2$ with $a = 36.485$ (5), $b = 9.210$ (2), $c = 10.215$ (1) Å, $\beta = 93.52$ (1)°, and $Z = 4$. The final R index is 0.078 for 3039 reflections with $2\theta \leq 128°$. The basic conformation of the peptide is a type II β turn with Pro-Gly at the corner, as is compatible with the model proposed for Boc-Val-Pro-Gly-Gly-OMe in solution. This folded structure makes a sharp contrast with the extended one of Boc-Val-Pro-Gly-Val-Gly-OH, another repeating pentapeptide in elastin.

Tropoelastin, the precursor protein of elastin, has been shown to contain three kinds of short-range repetitions of amino acid

sequences, a tetrapeptide Val-Pro-Gly-Gly, a pentapeptide Val-Pro-Gly-Val-Gly, and a hexapeptide Val-Ala-Pro-Gly-Val-Gly.[1,2]

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Table I. Crystal Data

chemical formula	$C_{26}H_{38}N_4O_7 \cdot CH_3CO_2C_2H_5$
space group	$C2$
a, Å	36.485 (5)
b, Å	9.210 (2)
c, Å	10.215 (1)
β, deg	93.52 (1)
Z	4
ρ(calcd), g cm^{-3}	1.176
ρ(obsd), g cm^{-3}	1.13
μ(Cu Kα), cm^{-1}	7.28

Studies on these repeating peptides mainly based on NMR have progressed in revealing their conformations.[3-8] The proposed conformational feature common to all three peptide segments and their polymers is a β turn encompassing Pro-Gly. X-ray studies of these peptides can give definite structures in the crystalline state. The crystal structure of the cyclic pentadecapeptide, c-(Val-Pro-Gly-Val-Gly)$_3$, has already been reported,[9] and the peptide molecule has three β turns with each Pro-Gly at the corners.

We also have initiated the X-ray studies of the repeating peptides. In our first report of this series on the structure of the pentapeptide, Boc-Val-Pro-Gly-Val-Gly-OH,[10] it was shown that the peptide takes a rather extended form at the central part of the molecule and adjacent molecules are arranged to form an infinite antiparallel β sheet in the crystalline state.

Several peptides related to the repeating sequences of elastin have been synthesized in our laboratory. Besides the above pentapeptide, only the tetrapeptide Boc-Val-Pro-Gly-Gly-OBzl has been successfully crystallized so far. This peptide is different from Boc-Val-Pro-Gly-Gly-OMe[7] merely in the C terminal, to which a β turn has been proposed on the basis of NMR studies and conformational energy calculations. It is of interest to make a comparison between the structure of Boc-Val-Pro-Gly-Gly-OBzl in the crystalline state and the proposed model for Boc-Val-Pro-Gly-Gly-OMe in solution. This paper gives a precise description of the crystal structure of the title peptide.

Experimental Section

Boc-Val^1-Pro^2-Gly^3-Gly^4-OBzl was prepared by the DCC (N,N'-dicyclohexylcarbodiimide) coupling method. A crystal containing about one ethyl acetate molecule per peptide was obtained from an ethyl acetate/n-hexane solution. Only very tiny crystals were available, and the specimen used for the data collection had the dimension $0.3 \times 0.2 \times 0.02$ mm^3. The unit cell parameters were evaluated from the 2θ values of 12 reflections measured on a Rigaku four-circle diffractometer with graphite monochromatized Cu Kα radiation. The crystallographic data are summarized in Table I. The intensity data with $2\theta \leq 128°$ were collected on the diffractometer by the use of the θ–2θ scan technique. The diffractometer was equipped with a rotating anode X-ray generator which was operated at 50 kV and 60 mA with a fine focus spot. The scan range $\Delta\theta$ was $(0.8 + 0.142 \tan \theta)°$. The intensities of the high-order reflections were so weak that the scane speed and the background counting time were made variable depending on θ; the adopted scheme was 5°/min in θ scan speed and 3 s background countings at each terminal of the scans for $0° < 2\theta \leq 70°$, 2°/min and 7 s for $70° < 2\theta \leq 100°$, 1°/min and 15 s for $100° < 2\theta \leq 115°$, and 0.5°/min and 30 s for $115° < 2\theta < 128°$. The reflections, (20, 0, 0), (040), and (005), monitored as standards were

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Table II. Positional ($\times 10^4$) and Thermal ($\times 10$) Parameters of Nonhydrogen Atoms

atom	x	y	z	B_{eq},^{a} Å^2
C(1)	4493 (2)	3122 (10)	6107 (10)	114 (5)
C(2)	4437 (2)	1048 (9)	4605 (9)	100 (4)
C(3)	4013 (2)	1241 (10)	6430 (10)	120 (6)
C(4)	4228 (1)	2070 (6)	5461 (6)	62 (3)
C(5)	3734 (1)	3819 (6)	4942 (5)	56 (2)
C(6)	3247 (1)	5382 (6)	4024 (4)	53 (2)
C(7)	3348 (2)	6993 (8)	3836 (6)	81 (3)
C(8)	3616 (3)	7487 (10)	4953 (10)	128 (6)
C(9)	3483 (2)	7282 (9)	2534 (8)	108 (5)
C(10)	2941 (1)	4965 (5)	3004 (4)	48 (2)
C(11)	2300 (1)	5029 (5)	2227 (4)	49 (2)
C(12)	1956 (1)	5677 (8)	2807 (5)	70 (3)
C(13)	2065 (2)	5903 (11)	4238 (7)	94 (4)
C(14)	2464 (2)	6225 (9)	4293 (5)	77 (3)
C(15)	2374 (1)	5745 (5)	925 (4)	43 (2)
C(16)	2382 (1)	5426 (6)	−1430 (4)	55 (2)
C(17)	2778 (1)	5554 (7)	−1759 (4)	61 (3)
C(18)	3419 (1)	5243 (6)	−1091 (5)	56 (2)
C(19)	3555 (1)	6783 (6)	−979 (5)	57 (2)
C(20)	4086 (2)	8177 (8)	−1101 (8)	87 (4)
C(21)	4447 (1)	8043 (7)	−1771 (6)	68 (3)
C(22)	4716 (2)	9060 (8)	−1472 (7)	85 (4)
C(23)	5039 (2)	9019 (9)	−2108 (8)	100 (5)
C(24)	5089 (2)	8035 (11)	−3025 (9)	108 (5)
C(25)	4811 (2)	7022 (9)	−3349 (9)	104 (5)
C(26)	4490 (2)	7030 (9)	−2704 (8)	88 (4)
N(1)	3544 (1)	4384 (5)	3906 (4)	59 (2)
N(2)	2596 (1)	5392 (5)	3195 (3)	51 (2)
N(3)	2319 (1)	4899 (4)	−131 (3)	46 (2)
N(4)	3034 (1)	5118 (5)	−860 (4)	51 (2)
O(1)	3982 (1)	2844 (5)	4535 (4)	74 (2)
O(2)	3702 (1)	4132 (7)	6049 (3)	95 (3)
O(3)	3013 (1)	4267 (4)	2019 (3)	57 (2)
O(4)	2464 (1)	7012 (4)	855 (3)	57 (2)
O(5)	2854 (1)	6022 (7)	−2837 (4)	96 (3)
O(6)	3387 (1)	7845 (4)	−763 (4)	73 (2)
O(7)	3913 (1)	6773 (4)	−1150 (4)	70 (2)
C(1S)	3575 (2)	1483 (9)	884 (11)	116 (5)
C(2S)	3951 (3)	1815 (9)	908 (11)	120 (5)
C(3S)	4457 (4)	3600 (24)	721 (22)	236 (17)
C(4S)	4465 (4)	4661 (28)	1427 (18)	223 (15)
O(1S)	4238 (3)	1137 (16)	906 (14)	258 (10)
O(2S)	4016 (1)	3208 (6)	1146 (6)	109 (3)

^{a} Calculated from the anisotropic thermal parameters (deposited).

measured every 50 reflections. During the data collection their intensities decreased by 8%, 3%, and 14% in $|F|$, respectively. This decrease in intensity was so anisotropic that no corrections were made. Although such a large decrease in intensity data is considered intolerable in most cases, no better data set could be obtained since even the above crystal specimen was far larger than any others. Thus a total of 3039 reflections were collected, of which 149 were $F_o = 0$. The intensities were corrected for Lorentz and polarization effects, but not for absorption.

The structure was solved by the direct method with the program MULTAN78.[11] Several trials were made on the basis of different sets of structure factors having different outer limits of 2θ. One of the E maps gave an interpretable outline of the structure of 28 atoms out of 43 non-hydrogen atoms. The successive Fourier calculations revealed the remaining nonhydrogen atoms including an ethyl acetate molecule. The parameters were refined by a block-diagonal least-squares procedure. Taking the difference between the observed and calculated densities or the peak heights in Fourier maps into consideration, the occupany of the solvent molecule seemed not to be stoichiometric; nevertheless, these atoms were assigned the occupancy of unity. Consequently the thermal vibration of the solvent molecule appeared unusually large. The solvent molecule seemed to be partly disordered. A difference Fourier map subsequent to an anisotropic refinement showed the hydrogen positions except for those of the methyl groups and the solvent molecule. Those not located on the map were calculated for their geometrically ideal

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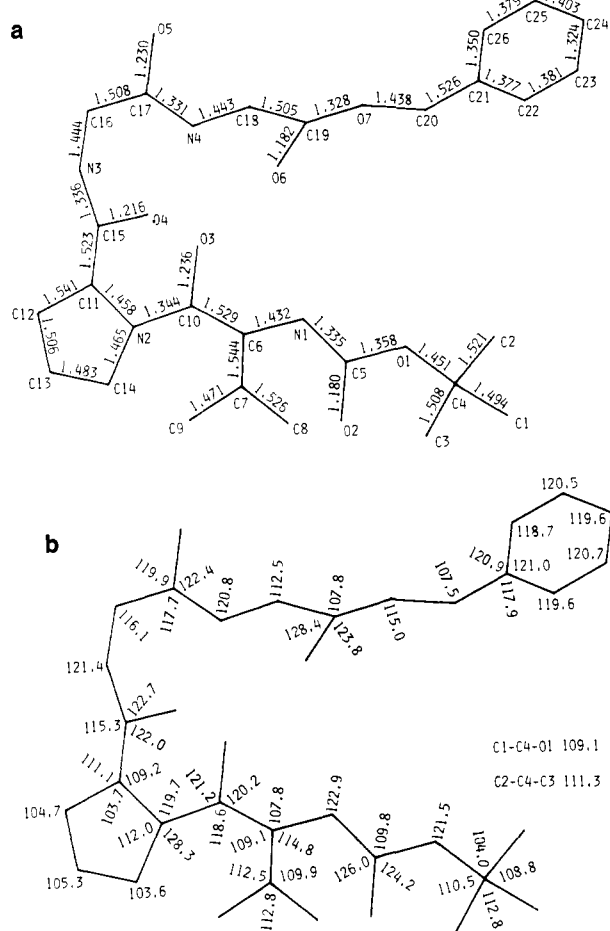
a

Figure 1. (a) Bond lengths (Å). Esd's are 0.006–0.013 Å. (b) Bond angles (deg). Esd's are 0.2–0.9°.
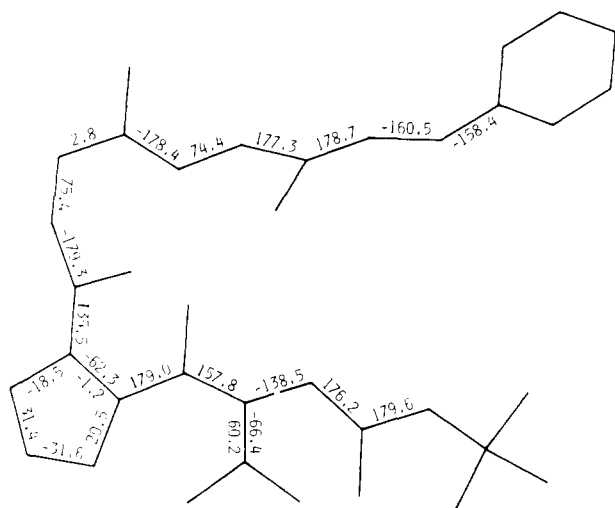
b

Figure 2. Conformational angles (deg). Esd's are 0.3–0.9°.

positions. The hydrogen atoms also were included in the refinement, but their temperature factors were held constant as equal to B_{eq} of their carrier atoms. The hydrogen atoms of the ethyl group of the solvent molecule, however, were not included in the calcn. The final R index was 0.078 for all reflections, and 0.072 for non-zero reflections. The function minimized was $\sum\omega(|F_o| - |F_c|)^2$ with $\omega = [\sigma^2(F) - 0.059|F_o| + 0.004|F_o|^2]^{-1}$ for $F_o \neq 0$, where $\sigma(F)$ is the standard deviation of $|F_o|$ based on the counting statistics, and $\omega = 0.270$ for $F_o = 0$. The atomic scattering factors were taken from "International Tables for X-Ray Crystallography".[12]

(12) "International Tables for X-Ray Crystallography"; Kynoch Press: Birmingham, England, 1974; Vol. IV, pp 72–3.

Table III. Hydrogen Positional Parameters ($\times 10^3$)

| atom	bonded to	x	y	z
H(1)	C(1)	468 (2)	259 (11)	677 (9)
H(2)	C(1)	434 (2)	397 (10)	664 (9)
H(3)	C(1)	463 (3)	368 (10)	537 (9)
H(4)	C(2)	462 (2)	42 (9)	513 (7)
H(5)	C(2)	460 (2)	170 (9)	390 (8)
H(6)	C(2)	424 (2)	41 (9)	416 (8)
H(7)	C(3)	417 (2)	57 (10)	714 (9)
H(8)	C(3)	384 (2)	45 (11)	589 (9)
H(9)	C(3)	385 (2)	202 (12)	696 (8)
H(10)	N(1)	360 (2)	421 (7)	311 (6)
H(11)	C(6)	318 (2)	523 (6)	497 (5)
H(12)	C(7)	309 (2)	789 (8)	377 (6)
H(13)	C(8)	367 (3)	861 (10)	480 (10)
H(14)	C(8)	387 (3)	690 (12)	494 (9)
H(15)	C(8)	350 (3)	731 (12)	594 (10)
H(16)	C(9)	331 (2)	692 (10)	165 (7)
H(17)	C(9)	373 (2)	655 (9)	245 (8)
H(18)	C(9)	358 (2)	837 (9)	246 (8)
H(19)	C(11)	228 (1)	384 (6)	214 (5)
H(20)	C(12)	177 (2)	493 (8)	261 (7)
H(21)	C(12)	190 (2)	673 (7)	242 (6)
H(22)	C(13)	202 (2)	456 (9)	472 (7)
H(23)	C(13)	192 (2)	668 (8)	466 (7)
H(24)	C(14)	250 (2)	739 (8)	415 (6)
H(25)	C(14)	257 (2)	588 (7)	499 (7)
H(26)	N(3)	228 (1)	391 (6)	0 (5)
H(27)	C(16)	228 (1)	642 (7)	−160 (5)
H(28)	C(16)	226 (1)	469 (7)	−202 (5)
H(29)	N(4)	297 (1)	485 (6)	−9 (5)
H(30)	C(18)	348 (1)	486 (7)	−199 (5)
H(31)	C(18)	357 (2)	456 (7)	−49 (6)
H(32)	C(20)	411 (2)	861 (8)	−17 (7)
H(33)	C(20)	390 (2)	892 (8)	−159 (7)
H(34)	C(22)	465 (2)	969 (8)	−66 (7)
H(35)	C(23)	525 (2)	981 (10)	−174 (8)
H(36)	C(24)	536 (2)	791 (10)	−326 (8)
H(37)	C(25)	486 (2)	618 (10)	−414 (8)
H(38)	C(26)	428 (2)	622 (8)	−290 (7)
H(39)	C(1S)	341 (2)	245 (11)	90 (9)
H(40)	C(1S)	353 (2)	89 (9)	176 (9)
H(41)	C(1S)	350 (2)	87 (11)	12 (8)
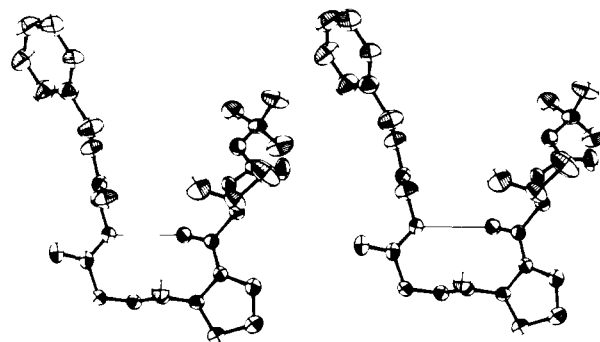
Figure 3. A stereodrawing of the peptide molecule. A thin line shows the intramolecular hydrogen bond. Thermal ellipsoids are drawn at the 30% probability level.

Results and Discussion

The positional and thermal parameters of the non-hydrogen atoms are listed in Table II, and the positional parameters of the hydrogen atoms are in Table III. The bond lengths and angles are shown in Figure 1, together with the numbering scheme of the atoms. These values are in good agreement with those reported previously for the amino acids and peptides.[13] The hydrogen bond parameters are listed in Table IV.

Main Chain Conformation. Type II β Turn. The conformational angles shown in Figure 2 and the stereodrawing by ORTEP II[14] in Figure 3 show that the peptide molecule takes a type II

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Table IV. Hydrogen Bonds and Hydrogen Bond-Like Intermolecular Interactions

donor (D)	hydrogen (H)	acceptor (A)	symmetry equivalent of acceptor	distance, Å		
				D···A	H···A	D-H···A
N(4)	H(29)	O(3)[a]	x,y,z	3.05 (1)	2.23 (6)	160 (5)
N(3)	H(26)	O(4)[b]	$^1/_2 - x, ^1/_2 + y, -z$	2.88 (1)	2.19 (6)	131 (5)
C(14)	H(25)	O(5)[c]	$x,y,1 + z$	3.19 (1)	2.40 (7)	154 (7)
C(18)	H(30)	O(2)[c]	$x,y,-1 + z$	3.32 (1)	2.31 (6)	170 (6)

[a] Intramolecular hydrogen bond.   [b] Intermolecular hydrogen bond.   [c] Hydrogen bond-like intermolecular interaction.

Table V. Conformational Angles and 4→1 Hydrogen Bonds in Type II β Turn

R1 R2	R3	R4		ϕ_2, deg	ψ_2, deg	ϕ_3 deg	ψ_3, deg	N···O distance, Å	ref
Boc- Val-Pro	-Gly	-Gly	-OBzl	−62	136	75	3	3.05	this paper
Pro-Leu	-Gly	-NH₂		−61	128	72		3.04	15
Ibr -Pro	-Ala	-NH	-Ipr[a]	−59	136	66	14	3.05	16
Ibr -Pro-D-Ala	-NH	-Ipr		−62	137	84	3	3.10	16
c-(Val-Pro	-Gly	-Val	-Gly)₃	−53	140	84	−7	3.28	9
c-(Gly-Pro	-Gly-D-Ala	-Pro)		−52	126	74	12	2.87	17
c-(Pro-Gly	-Pro	-Ser-D-Ala)[b]		58	−128	−75	−20	3.04	18
c-(Ser-Ser	-Gly	-Orn	-Orn-Orn)	−57	132	82	−1	2.98	19

[a] Ibr: $(CH_3)_2CHCO-$, Ipr: $-CH(CH_3)_2$.   [b] Type II' β turn.

β turn with Pro²-Gly³ at the corner, the intramolecular 4→1 hydrogen bond being (Val¹)C=O···H-N(Gly⁴). This conformational feature is compatible with the proposed structure for Boc-Val-Pro-Gly-Gly-OMe in solution from a combined analysis of NMR spectra and conformational energy calculations.[7] However, an additional 1→4 hydrogen bond, (Val¹)N-H···O= C(Gly⁴), suggested for Boc-Val-Pro-Gly-Gly-OMe does not exist in the present peptide, which is in a twisted form with the N-terminal part, lower, and the C-terminal part, upper, in Figure 3.

The intramolecular 4→1 hydrogen bond forms a ten-membered ring. The fact that the thermal ellipsoids of the atoms in the ring are, as shown in Figure 3, significantly smaller than those of the remaining atoms indicates a rigidity of the ring.

Although the β-turn structures have been reported for many oligopeptides so far, most of them are a type I, and a type II β turn is not extensively studied especially for the linear peptides. For the linear peptides the present one provides a unique example of the type II β turn. Table V shows the conformational angles (ϕ, ψ) of the second and third residues as well as the hydrogen bond lengths obtained by the X-ray diffraction method in several peptides having the type II β turn. Usually the (ϕ_2, ψ_2) angles are concentrated in a more limited region than the (ϕ_3, ψ_3) angles, as is also the case for the type I β turn.[20] This tendency is partly because the second sites of the β turn structures reported are mostly occupied by the inflexible Pro residue. But at the same time this tendency seems to be one of the general features of the β-turn structures; variation in (ϕ_2, ψ_2) affects the geometry of the 4→1 intramolecular hydrogen bonding more seriously than that in (ϕ_3, ψ_3). This is also evidenced by the conformational energy calculation.[21]

It has been reported that in the type I β turn the NCᵅC' angle of the second residue is significantly larger than the regular tetrahedral angle, while such a widening of the angle has not been found in the type II β turn.[22] The present structure also supports

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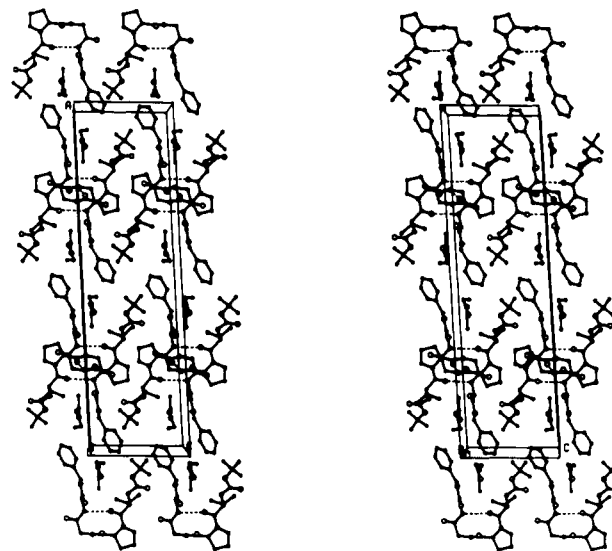
Figure 4. A stereodrawing of the crystal packing viewed down the *b* axis. The hydrogen bonds are shown by thin broken lines.

this tendency, that is, the NCᵅC' angle of Pro², 109.2 (4)°, is close to the regular tetrahedral angle.

Side-Chain Conformations. The Val¹ side chain takes a gauche conformation, although in the conformational energy calculation for Boc-Val-Pro-Gly-Gly-OMe χ¹ of Val¹ was found to prefer 150°,[7] that is, close to the trans conformation. In the present structure the trans conformation causes a repulsion between the Val¹ side chain and the neighboring Pro² side chain if the conformation of the remaining part is fixed as it is. The conformations of the Val¹ side chain and the Val¹-Pro² segment and the presence (or absence) of the intramolecular hydrogen bonds are obviously interdependent elements. In the pentapeptide Boc-Val-Pro-Gly-Val-Gly·OH, which crystallizes in an antiparallel β sheet, both of the Val side chains are in the trans conformation.[10]

The conformation of the pyrrolidine ring of Pro² is Cₛ-Cˠ-exo.[23] Most pyrrolidine rings at the second sites of a type II β turn, of which main chain conformation is the collagen type having large positive χ, are in a Cˠ-exo conformation.

Packing and Hydrogen Bonds. A stereodrawing of the crystal packing viewed down the *b* axis is shown in Figure 4. There is one intermolecular hydrogen bond, (Gly³)N-H···O=C(Pro²),

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which connects the molecules related by a twofold screw axis parallel to the *b* axis. The N–H group of Gly³ points also to the C=O group of Gly⁴, but the distance of N⋯O, 3.37 Å, is too long for hydrogen bonding. One more hydrogen donor available, N–H of Val¹, does not participate in any hydrogen bonds; its closest intermolecular approach is N(1)⋯O(2S), 3.56 Å.

There are two rather short intermolecular C–H⋯O interactions, (Pro²)C⁶–H⋯O=C(Gly³) and (Gly⁴)Cᵅ–H⋯O=C(Boc). Their geometries shown in Table IV are favorable for weak hydrogen bonds. These might be considered as hydrogen bonds.

All the other intermolecular contacts correspond to van der Waals interactions.

Solvent Molecule. The solvent ethyl acetate molecule seems to have an appropriate dimension to the crystal packing, and plays a role of space filling in the crystal. This is well shown by the fact that only an ethyl acetate solution gives a crystal, while neither an ethanol nor an acetone solution could give a crystal.

As shown in Figure 4 the ethyl acetate molecule, however, is very loosely packed in the crystal, and is not involved in any hydrogen bonds. Thus the fugacity of the solvent molecule from the crystal may not be negligible. This may explain first the unusually large temperature factors due to the nonstoichiometric occupancy of the solvent molecule, and second the significant decrease of the diffraction intensities during the X-ray experiment. The loose packing may explain also an evidence of the partially disordered structure of the solvent molecule with the head and tail interchanged at the same site.

Conclusion

The X-ray analysis has established the crystal structure of Boc-Val-Pro-Gly-Gly-OBzl, showing that the basic conformation of this peptide is a type II β turn with Pro²-Gly³ at the corner. This feature is the same as that suggested for Boc-Val-Pro-Gly-Gly-OMe⁷ and the high polymer of the tetrapeptide²⁴ from NMR and conformational energy calculations. Thus for this tetrapeptide unit of elastin, the β turn structure has been shown to be a favorable conformation in crystal as well as in solution. On the other hand we previously reported that the pentapeptide, Boc-Val-Pro-Gly-Val-Gly-OH, is not in a β turn conformation but in an extended form, making an antiparallel β sheet structure.¹⁰ It is worth noting that the molecular conformation is thoroughly changed by an insertion of a Val residue. Thus for the pentapeptide unit, a β turn structure does not seem to be a preferred conformation at least in the crystalline state. At the present stage of the structural studies of the repeating peptides in elastin, both of the β sheet and β turn conformations are said to play important parts in the structure and the function of elastin.

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A Study of the Synthesis and Properties of [2₅](1,2,3,4,5)Cyclophane¹

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Abstract: As part of an overall program investigating the behavior of π-electron systems forced into close proximity, a synthesis of [2₅](1,2,3,4,5)cyclophane (**11**) has been accomplished in six steps, as shown in Scheme I, with an overall yield of 31%. The key to the successful synthesis was the formation of four bridges in a single step, via *o*-xylylene-type intermediates, during gas-phase pyrolysis of 1,2-bis[(1,2:4,5)dicyclobutaphenyl]ethane (**10**). X-ray crystallographic analysis of [2₅](1,2,3,4,5)cyclophane (**11**) shows the mean interdeck distance between benzene rings to be 270 pm. From photoelectron spectral studies the first ionization energy of **11** is found to be 7.67 eV. [2₅](1,2,3,4,5)Cyclophane is thermally stable, showing no evidence of bridge cleavage even on heating at 350 °C. Electrophilic substitution, bromination and Rieche formylation occur readily with **11** and in high yield. Chloromethylation of **11** is anomalous, though, giving 4-formyl-13-methyl[2₅](1,2,3,4,5)cyclophane (**16**). Conversion of **16** to the corresponding tosylhydrazone **18**, followed by treatment with base and irradiation, gives superphane (**19**) in 80% yield, providing a useful alternate synthesis for this important member of the [2ₙ]cyclophane series. Both dicyanoacetylene and perfluoro-2-butyne undergo normal Diels–Alder additions with [2₅](1,2,3,4,5)cyclophane to give the corresponding barrellene adducts **20** and **21**. Treatment of [2₅](1,2,3,4,5)cyclophane (**11**) with bis (η⁶-*p*-cymene)dichlorodi-μ-chloro-diruthenium(II), or bis(η⁶-hexamethylbenzene)dichlorodi-μ-chloro-diruthenium(II), readily gives the corresponding ruthenium complexes **22** and **23**, whereas irradiation of a solution of **11** and (η⁶-*p*-xylene)(η⁵-cyclopentadienyl)iron(II) hexafluorophosphate gives the corresponding iron complex (**24**).

The discovery that the gas-phase dimerization of benzocyclobutenes can be employed to synthesize multibridged cyclophanes² led to a rapid elaboration of all of the remaining, previously unknown, symmetrical [2ₙ]cyclophanes.³ The properties of these molecules are of particular interest because of the insight they provide regarding the effect of forcing two benzene π-electron clouds together face to face at very short distances. In the previous paper of this series, we described the synthesis and properties of [2₆](1,2,3,4,5,6)cyclophane (**19**, superphane), the ultimate in multibridging of a [2ₙ]cyclophane.⁴ In the present paper we describe a synthesis and some of the properties of [2₅]-(1,2,3,4,5)cyclophane (**11**), the penultimate member of the series.

As an extension of our approach to utilize the dimerization of benzocyclobutene units to provide multibridged cyclophanes, the

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