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# AN INSTRUMENT FOR BONE MINERAL MEASUREMENT USING A MICROPROCESSOR AS THE CONTROL AND ARITHMETIC ELEMENT*

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# AN INSTRUMENT FOR BONE MINERAL MEASUREMENT USING A MICROPROCESSOR AS THE CONTROL AND ARITHMETIC ELEMENT*

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## ABSTRACT

We have developed a self-contained instrument for the determination of bone mineral content by photon absorptometry. A high-resolution detection system allows measurements to be made at up to 16 photon energies. Control and arithmetic functions are performed by a microprocessor. Analysis capability and limitations are discussed.

## Introduction

The measurement of bone mineral content and geometrical parameters by photon absorptometry is a well established technique[1]. In this measurement a well collimated, monoenergetic beam of gamma rays of energy between 25 and 75 keV is scanned across an extremity of the patient. Usual practice is to use the forearm although in some cases the heel or even the mandible have been used. The transmitted beam is detected by a radiation detector, and the beam intensity is measured. Most workers in the past have used sodium iodide detectors. There the relatively poor energy resolution limits the species of radioisotope that can be used to generate the monoenergetic beam. We have incorporated a high purity germanium detector into the bone-scanner system and have thus increased the range of suitable isotopes[2].

The transmitted beam intensity is recorded as a function of position in either a one or two dimensional rectilinear pattern. Various parameters may be computed from this data as signatures for bone mineral content and geometrical properties. The transmitted beam intensity may be expressed as:

$$I(x) = I_o e^{-\mu/\rho|_x \rho(x)T} \tag{1}$$

where $I(x)$ is the transmitted beam intensity at coordinate x,

$I_o$ is the primary beam intensity,

$\mu/\rho|_x$ is the average mass absorption coefficient at coordinate x,

$\rho(x)$ is the average density at x, and T is the thickness of the sample.

The quantity in the exponent is the average over the entire transmitted beam path of all the materials intercepted by the beam. The assumption is made that there are only two materials in this path: bone mineral and a tissue equivalent material. (This tissue equivalent medium is usually assumed to be water although more accurate equivalents are available[3].) Furthermore, the total thickness of material through which the beam travels is assumed to be constant. This is achieved by surrounding the extremity to be scanned by tissue equivalent material. Under these conditions, the exponent in Eq. (1) may be decomposed as follows:

$$\mu/\rho|_x \rho(x)T = \mu/\rho|_b \rho_b(x)T_b(x) + \mu/\rho|_t \rho_t(x)T_t(x) \tag{2}$$

where $\mu/\rho|_{b(t)}$ is the mass absorption coefficient for bone mineral (tissue equivalent material).

$T_b(x) + T_t(x) = T,$

$\rho(x)_{b(t)}$ is the density of bone mineral (tissue equivalent material) at x and

$T_{b(t)}(x)$ is the thickness of bone mineral (tissue equivalent material) at x.

It is assumed that the density and mass absorption coefficients of bone mineral and tissue equivalent do not vary as a function of position. If we define bone mineral content, $\sigma_b(x)$, as the number of grams/cm$^2$ of bone mineral at position x, then

$$\sigma_b(x) = \ln \frac{I(o)}{I(x)} \Big/ \left(\mu/\rho|_b - \mu/\rho|_t \frac{\rho_t}{\rho_b}\right) \quad . \tag{3}$$

Bone mineral is usually assumed to be calcium hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) although many other calcium phosphates are also present in lesser quantities[6].

The parameter that is usually calculated to serve as an index of bone mineralization is:

$$\sigma_b = \int dx\, \sigma_b(x) \tag{4}$$

where the integral is taken over a transverse section of the bone. This parameter is referred to as "bone mineral content" and has units of grams/cm.

The analysis of bone mineral content for a single energy photon may be extended to several energies[4]. For

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each added transmission measurement at a new energy, the content of a separate constituent may be measured. In practice there are various experimental difficulties arising from the functional energy dependence of the mass absorption coefficients. Recent evidence indicates that multiple energy transmission is valuable in correcting errors caused by adipose tissue in the transmitted beam[5].

This instrument is designed to be self-contained with data acquisition and analysis capability sufficient to perform multienergy analysis of bone mineral content. All data acquisition and analysis is performed under the control of a digital processor. Digital computation procedures have sufficient speed and accuracy necessary for the relatively complex multienergy analysis. Having made the decision for a digital system, we have selected a commercial microprocessor for implementation[10].

This paper reports the development of this device and presents initial data based on monoenergetic bone mineral analysis. Software development for multienergy analysis is presently continuing.

## Scanning Apparatus

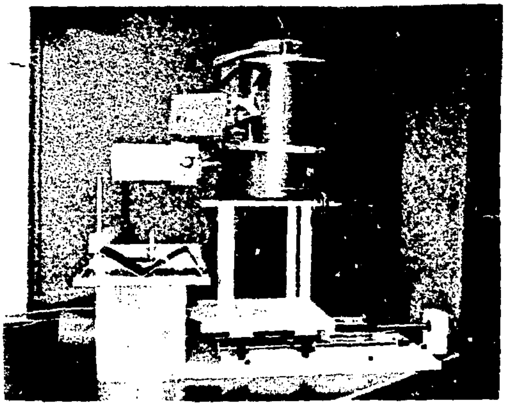

Fig. 1

Linear bone scanning apparatus. The Ge(HP) detector and cryostat are shown along with the linear bearings and forearm immobilization apparatus.

Figure 1 is a photograph of the linear scanning apparatus. The patient's arm is held fixed while the source and detector move together across the patient's forearm. Either the right or left arm may be scanned. The source-detector carriage moves on linear ball bearings to insure accuracy and rigidity. A stepping motor moves the scanning carriage by means of a lead screw. Limit switches detect the start and end of each scan. The distance between the switches is operator variable.

The photon detector is of the grooved high-purity-germanium type, approximately 4 mm in diameter and 3 mm depletion depth, with energy resolution of 530 eV at 60 keV. This type of detector is chosen for several reasons. The excellent energy resolution (compared to NaI) enables photons scattered multiply through small angles to be rejected. Secondly, several isotopes that would otherwise be of use in bone mineral analysis would be rejected because of background from higher energy photon transitions unless a Ge(HP) detector is used. Thirdly, although a high purity germanium detector must be used at liquid nitrogen temperatures, it can be allowed to warm up when not in use.

The source selected for initial setup and tests is $^{170}$Tm. Principle radiations from this source include an 84.25 keV gamma ray, ytterbium K x-rays and bremsstrahlung from a beta transition of approximately 1 MeV. The half-life is 127 days[7,8]. The source is commercially available at approximately $20/Ci[9]. We use a 15 Ci source in this instrument of dimensions 2 x 2 mm. The radiation dose to the forearm during a typical scan is < 5 mR.

The source collimation for the system is provided by a lead collimator with a rectangular opening of 1 mm x 3 mm and 38 mm length. The 3 mm side of the opening is aligned with the bone shaft, thereby averaging over a small section of shaft length. A post-collimator may be placed over the detector to further improve system spatial resolution. The spatial resolution of the system without post-collimation is approximately 1 mm FWHM.

## Electronic Hardware

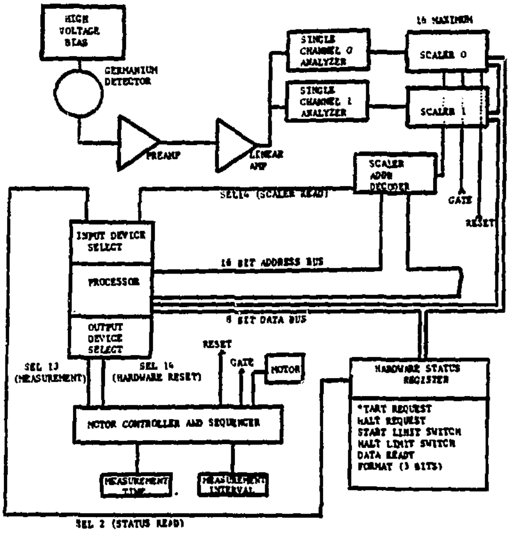

Fig. 2

Electronic block diagram for the present system with two energy capability. Digital hardware allows the number of scalers to be increased to 16.

The electronic hardware is divided into analogue and digital subsystems. The analogue subsystem (Fig. 2) processes the linear signal information using standard "NIM" module equipment. The preamplifier is dc-coupled to the detector. The main amplifier uses gaussian shaping (selectable time constant) with baseline restoration. The output is routed to a single channel analyzer for each energy photon selected for analysis, two of which are now in the system. A digital ratemeter is available for visual diagnostic inspection of the system but is not used in the data collection stream.

The digital subsystem (Fig. 2) contains the hardware for collection of count rate information, scanner control and data analysis. The output of each single channel analyzer is routed to a 16 bit scaler in the digital subsystem. Four scalers are presently implemented. A transmission measurement at a particular coordinate is initiated by the processor under program control (SEL 13). The scanning carriage is indexed by a distance switch selectable on the rear panel. After an adjustable settling time to allow microphonics in the detector to decay, the scalers are gated on for a measurement time of from ½ to 2 seconds, switch selectable on the rear panel. The data-ready bit, which is reset at the sequence start, is set at the end of the measurement.

The processor may interrogate the status of the run at any time by reading the eight bit status register (SEL 2). This register contains start and halt request bits (setable from the front panel), the data ready bit, the start and end limit switches (to define the extent of the scan) and three bits of "format" information used as a parameter in the data analysis.

The processor may reset the hardware under program control (SEL 14). This command resets start and halt request bits, and positions the scanner carriage at the start limit switch.

The processor contains $1024_{10}$ words of eight bit read/write memory for data storage, $256_{10}$ words for calculation and $3584_{10}$ words of programmable/erasable read only memory.

## Measurement and Analysis Software

### Processor Preliminaries

The processor used to implement this instrument has some functional limitations usually not found in minicomputers. Chief among these is the difficulty in directly accessing memory. All storage is accessed using a 14 bit register as an effective address (H, L registers). This register may be incremented or decremented under program control, but data does not carry over from the lower order eight bits to the higher order six bits. Thus memory is effectively divided into pages of $256_{10}$ words each.

Because of this memory access structure, among other reasons, a series of protocols is required to obtain orderly and efficient program structure with machine language programming. The working storage is addressed sequentially as a parameter stack. Registers H, L used as the stack vector, point to the top of the stack, defined in this system to be on one page of $256_{10}$ words. The stack is further divided into common and stack storage areas as shown in Fig. 3.

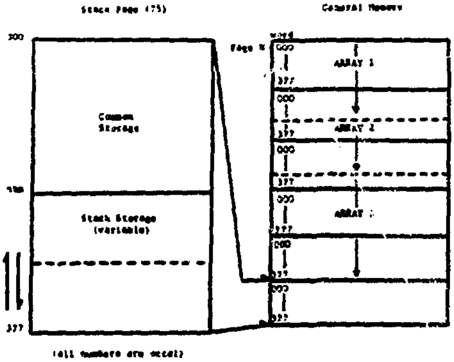

Fig. 3

Memory map showing typical processor storage organization.

Common storage is permanently assigned to the main and subprograms for array vectors, count cells, hardware control words, communication between subroutines and the like. Each subroutine assigns dynamically space for local variables in stack storage.

Data is loaded to and stored from the general registers in the processor by two sets of routines. The common routines access storage relative to location zero on the stack page. The index routines access storage relative to the stack pointer.

The stack page ($256_{10}$ 8 bit words) can accommodate only a limited amount of data. Figure 3 shows a memory map when larger amounts of data need be stored. This added storage is called general memory and is used for data arrays. Associated with each array there should be an array descriptor block in common storage, specifying relevant array parameters at the option of the programmer. An address calculation routine can then be developed to generate a vector to the appropriate datum. Transfers of data to and from the stack and general memory are then made using block transfer routines.

Space is limited for transmission of subroutine arguments through the processor general registers. Multi argument routines therefore transfer information at the top of stack storage relative to the stack pointer. For instance, floating point arithmetic operations are performed between the top one or two arguments with the result replacing them.

With these protocols it becomes possible to program the processor in machine language. The source program is prepared, edited, assembled and linked on a file structured computer (PDP-15 operating DOS). No software development can be carried out using a stand-alone microprocessor system. These devices are to be used as execution computers only.

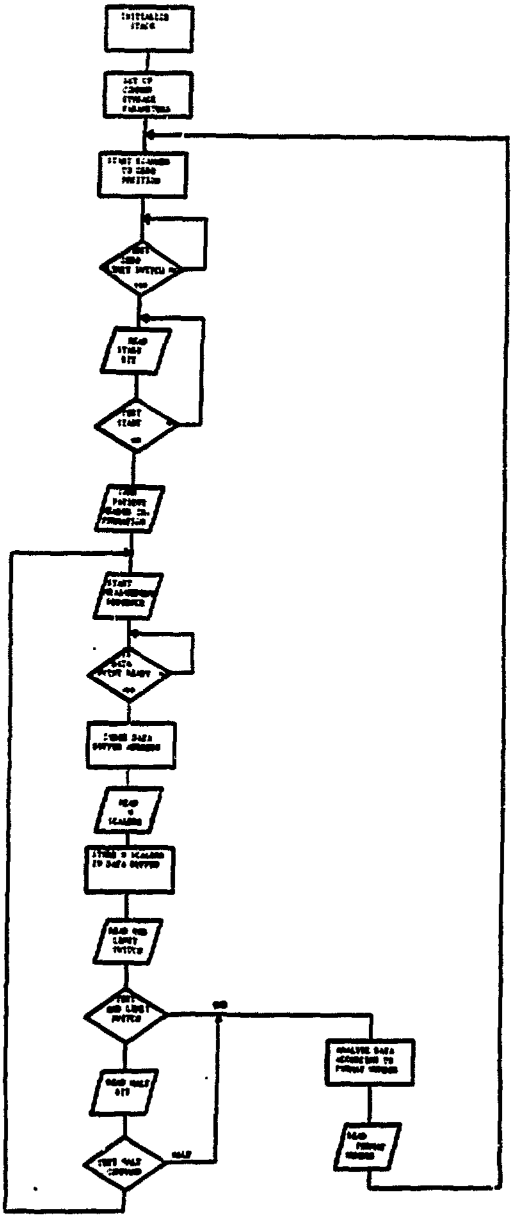

Fig. 4

Measurement sequence flow chart. This simple measurement loop requires no interrupts.

## Measurement Sequence and Data Analysis

The measurement sequence flow chart is shown in Fig. 4. No interrupts are used in this system since all tasks are performed sequentially. All branch control is performed according to bits in the hardware status register. Parallel task execution, including interrupt handling, is considered to be unsuitable for this simple instruction set and limited debugging facility. The system is presently capable of taking data in two energy windows but these are easily expandable to 16 if necessary. Each 16 bit datum is stored in a general memory array containing $1024_{10}$ words. Thus, at two energies per data point, $256_{10}$ coordinate points may be measured in any particular scan. Data analysis is facilitated by a 24-bit floating-point package and exponential-conversion output routine. The logarithm function also uses this package in its calculation. The floating point word is in sign-magnitude representation with a 16 bit mantissa, 1 bit sign and 7 bit exponent.

Data analysis is performed according to the setting of the format switch. There are three analyses presently implemented on the system, which may be selected in combination according to the format switch. Each of these analysis routines is modular and may be removed or inserted in the code with no modifications except to the common storage setup.

The first routine analyzes each bone separately at each energy for bone width, mineral content, and cortical thickness. The edges of the bone are detected by the deviation of the transmitted data from the baseline value. The width is then the difference of these coordinates. The baseline is determined by averaging over ten points at the beginning of each scan. Cortical thickness is determined at the leading edge of each bone by detecting the minimum in the transmitted data and subtracting from this coordinate that at which the data departs from the baseline. This method yields a measure of thickness whose usefulness will be determined in further clinical studies. The bone mineral content is determined according to Eq. (4) where the integral is performed according to the trapezoidal rule, and the limits of integration are the bone edge coordinates widened by approximately ten percent. The baseline value, I(0), is determined as previously described. Although widening the limits of integration degrades statistical accuracy somewhat, it causes the data to be insensitive to the exact position of the patient's arm, thus eliminating a potential source of error. Data are taken with energy 0 set at the ytterbium $K_\alpha$ energy (52 keV) and energy 1 set at the gamma ray energy (84 keV). These are energies not previously used in photon absorptometry. Thus the denominator in Eq. (3) was calculated for water as tissue equivalent and calcium hydroxyapatite as bone mineral using data in Ref.11. This calibration will be tested against known reference standards[12].

The second routine plots the data for each energy, automatically normalizing the baseline on the plot. These plots are typed at 30 characters per second on a page printer. Data for an entire scan can be typed in approximately 5 minutes.

The third routine types the unprocessed data in a format suitable for analysis off-line.

We are presently extending the monoenergetic analysis described above to two energies so that systematic errors in bone mineral determination can be reduced.

## Instrument Operation

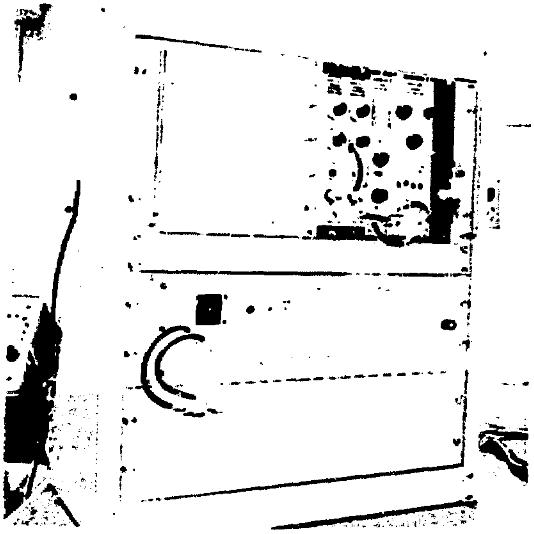

Fig. 5

Front control panel of the bone scanner. The upper NIM bin contains from left to right the detector bias supply, two single channel analyzers, the ratemeter, and the main amplifier. The processor controls are below. Visible are the start and halt buttons and the format switch.

Every effort is made to keep operating procedures simple. Once the analysis routines desired are selected by the format switch and the scan initiated (Fig. 5), the entire data acquisition and analysis is performed automatically without operator intervention. The scan may be aborted at any time by the operator. A 30 char/sec page printer is used for display of results and plots. The keyboard of this device is used only to control the energy to be plotted in the graphic routine.

Daily calibration procedures are not necessary since there are no analogue calculations or instrumental drifts. The analogue pulse processing circuits are known to be stable to 0.1% in the temperature range encountered in the laboratory. Thus the instrument is immune to day-to-day calibration changes.

## Sample Data and Results

Data has been taken in a series of runs on a standard phantom[13]. This phantom consists of a lucite block with two hollow aluminum cylinders simulating the radius and ulna. The radius and wall thickness of the large tube is 1.6 cm and 0.20 cm, and of the small tube is 1.3 cm and 0.10 cm. The equivalent bone mineral content of the tube is given for $^{125}$I and, hence, is inappropriate for this study. Figure 6 shows a scan of this phantom where the data plot is printed out. Twenty such runs were repeated with the phantom in place to check the statistical accuracy of the data. The average value of bone mineral content, cortical thickness and bone width derived from these tests by the instrument analysis routine is shown in Table I for the incident energy equal to 52 keV. The calculated statistical error, based on standard propagation techniques, is also shown. The agreement between these quantities is good.

A sample scan is shown in Fig. 7. The printout of the various analysis parameters is shown at the top of the figure, while the data is below. The scan time for this run is approximately 3 minutes.

We have applied a microprocessor in a small instrument with a certain self-contained, digital, computational requirement. For relatively simple calculations, these devices serve adequately as execution processors. Beyond a certain calculational sophistication, roughly on a par with this problem, they are not recommended due to their limited calculational ability and speed. One must always have a separate, more powerful computer available for source code manipulation, assembly, and linkage. The potential application must be well defined before software development is undertaken since changes are difficult to make without a higher level language. For the multienergy algorithm that is presently being developed, data is collected with this device and analyzed off line with a FORTRAN coded program, thus facilitating changes in the method. When the method is finally determined, the microprocessor will be reprogrammed from monoenergetic analysis.

## Acknowledgements

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### Table I

Phantom Study at 52 keV Incident Energy

| | Bone Mineral | | | Bone Width* | Cortical Thickness* |
|---|---|---|---|---|---|
| | $\sigma_b$ (g/cm) | Measured Fractional Standard Deviation | Calculated Fractional Standard Deviation | (cm) | (cm) |
| Bone 1 | 1.4382 | 0.5% | 0.4% | 1.63 | 0.20 |
| Bone 2 | 0.7386 | 1.2% | 1.0% | 1.32 | 0.15 |

*Measurement did not vary between scans due to coordinate quantization.

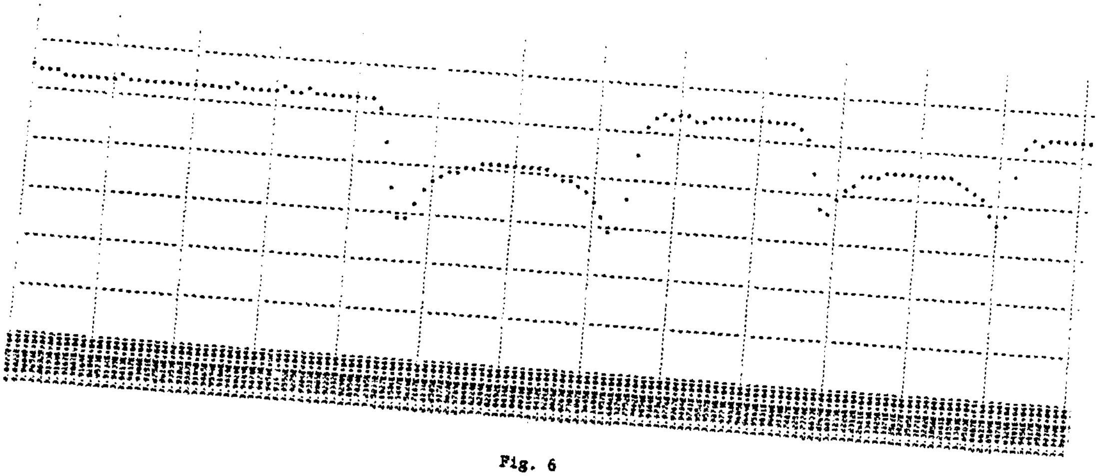


Fig. 6

Typical phantom scan.

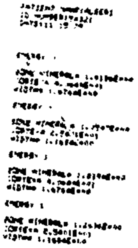
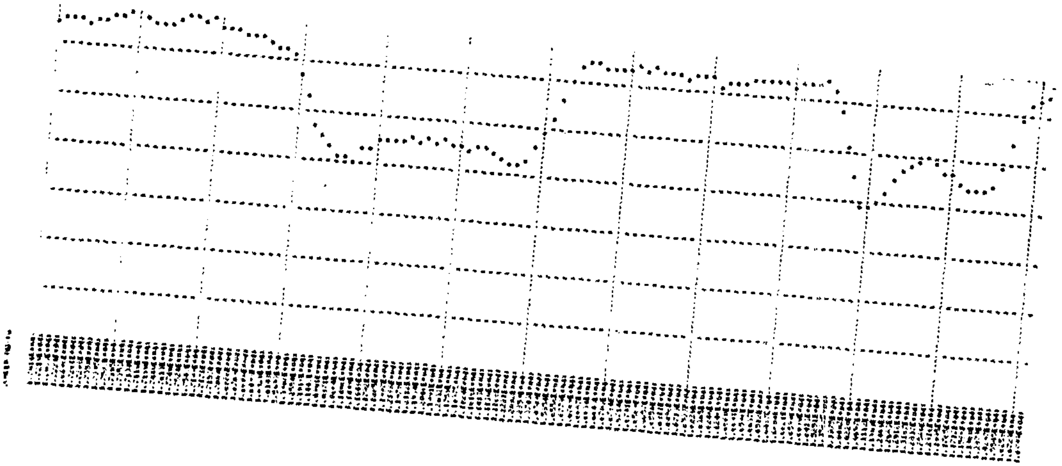


Fig. 7

Scan of one of the authors. The bone mineral analysis is on top and the graphical plot of the data at 52 keV is below.



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