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A NEW INOTROPIC PACEMAKER SYSTEM

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Abstract: A new “inotropic” pacemaker system is introduced for patients unable to increase heart rate in accordance with cardiocirculatory strain. An inotropic pacemaker senses the increase of heart contraction (inotropy) and uses this information to adjust the pacing rate. The fiber optic sensor, the optoelectrical unit and the re-closing of the control-loop are explained. The device is tested successfully in first experiments, both in technical set-ups and in pig hearts. *Copyright © 2002 IFAC*

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1. THE PHYSIOLOGICAL CARDIOVASCULAR CONTROL LOOP

Pacemaker patients suffer from an interruption of signal flow within the cardiovascular control loop. The main elements of physiological short-term control are depicted in Fig. 1: the regulated variable is arterial pressure which is sensed by baroreceptors situated at special sites within the vessel walls of the arterial system. This information is transmitted via electrical impulses (“action potentials”) to neuronal networks in the lower brain stems, i.e. to parts of the autonomic nervous system’s antagonistic components (“sympathetic” and “parasympathetic” networks) in the medulla oblongata. These possess four possibilities of counteracting, via feedback control, disturbances (orthostatic, physical or emotional stress, blood loss etc.) of the system:

1. modification of heart rate (“chronotropy”) by acting on the inherent physiological pacemaker of the heart, the sinus node,
2. modification of atrio-ventricular conduction time within the heart (“dromotropy”),
3. modification of heart contraction and thus stroke volume (“inotropy”),
4. modification of the peripheral vascular resistance by contraction of the smooth muscles within thesmall arteries and arterioles.

The actions 1 - 3 determine cardiac output which, multiplied with total peripheral resistance, yields arterial pressure.

The most frequent indications for the implantation of a technical pacemaker are 1. blocks within the atrio-ventricular conduction of the heart (AV-blocks) and 2. deficiencies of the rhythm generating system, e.g. the incompetence of the sinus node to adjust heart rate according to the demands of the cardiocirculatory strain due to physical exercise or emotional stress. AV-blocks can be compensated fairly easily by a technical pulse generator

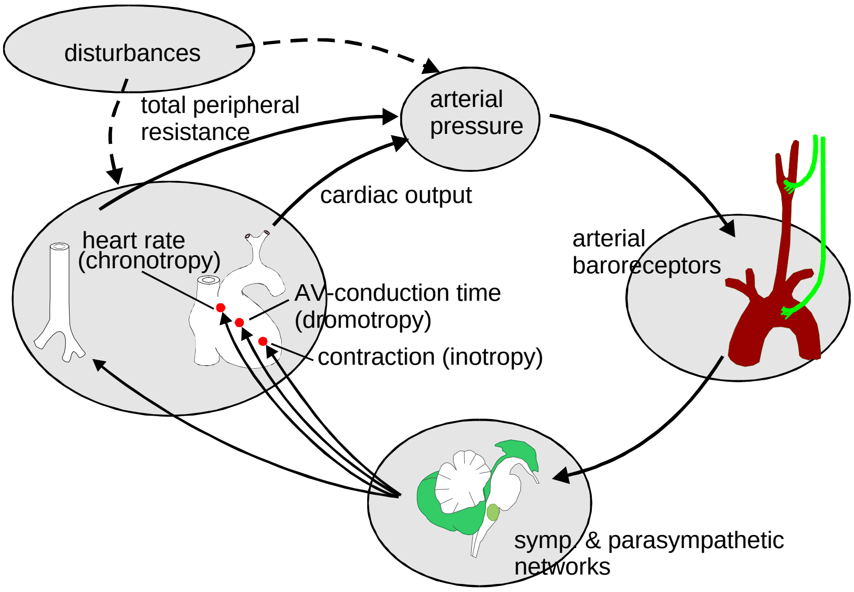

Fig.1: The blood pressure control loop with four actuators triggered by the autonomic nervous system

(pacemaker) stimulating those parts of the heart which are not triggered by the intrinsic rhythm. Sinus node incompetence needs a more sophisticated technical system which senses the status of cardiocirculatory strain.

2. THE INOTROPIC PACEMAKER CONCEPT: CLOSED-LOOP CONTROL

Historically the pacemaker industry looked for sensors the signals of which are well correlated with physical exercise. Hence the still most commonly implanted sensor-controlled pacemaker possesses an acceleration sensor within the pacemaker case which senses movements of the body. This obviously is an open-loop approach only, and does not sense the internal strain, but only an external parameter correlated with physical exercise, unfortunately often in an inadequate way. Further developments continued to ask the wrong question, namely: Which pacemaker is best correlated with physical exercise? However, the right question must be: Which sensor-controlled pacemaker restores the original physiological control-loop to the greatest extent? (Werner, et al., 1999 a). As the ideal concept, i.e. technical measurements of the signals from the autonomic nervous system (ANS), cannot be reality, the solution may be concluded from Fig. 2: Three types of ANS-signals normally control the heart action. When the chronotropic signal is not available (“sinus node incompetence“, SNI), the attempt should be made to measure a signal closely correlated either with the dromotropic signal or the inotropic signal and to stimulate the right atrium of the heart according to this information (Werner et al., 1999 b). Measuring the dromotropic information is possible by determining the shortening of atrio-ventricular conduction time due to cardiocirculatory strain, and increasing the pacing rate according to this shortening. This is the basis of the dromotropic

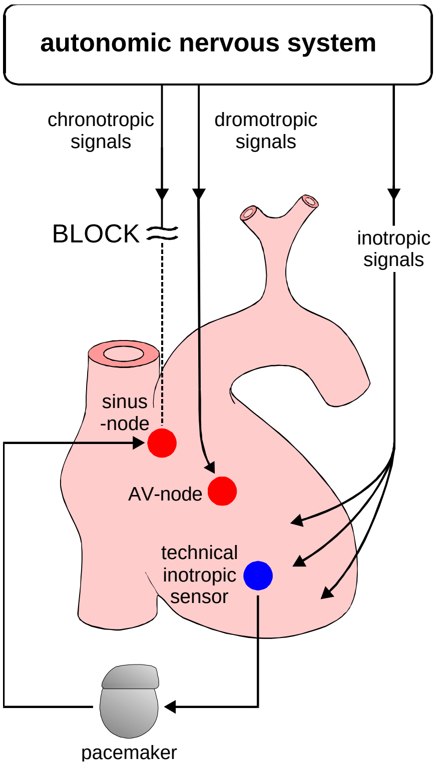

Fig. 2: The “inotropic” pacemaker uses inotropic signals to control the pacing frequency, as inherent chronotropic signals are not available. The control-loop is re-closed.

pacemaker (Hexamer, et al., 2000), which, of course, is restricted to SNI-patients with intact AV-conduction (only about 5 % are supposed to develop AV-problems). The second possibility is to measure a signal correlated with the inotropic information. Such concepts rely on a more indirect correlation with ANS-information than the dromotropic pacemaker. However, they re-establish closed-loop control. Systems recently put on the market measure either the electrical impedance (Zecchi, et al. 1999) or the acceleration of the heart (Clémenty, 1999). Problems might arise either from instability or sensitivity to disturbances of the sensor. Therefore, we developed a new inotropic pacemaker concept by measuring heart contraction by use of optic fibers, inserted within a pacemaker lead, which, implanted within the heart, follows all bending caused by cardiac contraction.

3. THE FIBEROPTIC INOTROPIC SENSOR

Fiber optics are commonly used for the transmission of light of high power density, for data transmission and for sensor techniques (Gowar, 1984; Lagakos, et al., 1987, Mignani and Baldini, 1997). The fiber consists of a cylindrical core with a refraction index n_1, a surrounding cladding with a refraction index n_2 and the outer coating (Fig. 3). If the angle between the beam and the border line between core and cladding is smaller than a critical value

$$(?_{\mathrm{lim}} = \text{arc cos}\ (n_2 / n_1),$$

total reflection is observed, meaning that the light is conducted within the fiber. Bending of the fiber caused changes of (in a way that those beams hitting the border of core and cladding with ?(> $(?_{\mathrm{lim}}$ disappear in the cladding. Taking wave theory into account, we have to realize that only discrete angles are possible for transmission of light within the fiber. The different discrete transmission processes are called “modes”. The intensity distribution of the modes, particularly of the higher modes, propagating near the cladding, extends into the cladding. Bending the fiber means that the propagating processes in the more peripheral parts must have a higher speed than those in the inner parts. Beyond a critical speed these modes lose energy causing an attenuation factor depending on the bending radius, the penetration depth into the cladding and the arc length of bending. To make use of this effect as a sensor technique (Hoeland, et al., 1999), the end of the fiber to be placed within the heart has to be polished and coated (“sputtered”) carefully with a material guaranteeing a high reflection (> 90 %). As we apply a source omitting light near the infrared (800 ... 900 nm), silver, gold and certain aluminum alloys may be used. The free inner diameter in a pacemaker lead (usually used for a guiding wire during the insertion of the lead) is 300 µm, meaning that the outer diameter of the optical fiber should be smaller. We use outer diameters from 155 to 250 µm. Further requirements for the fiber are flexibility, biocompatibility and possibility of sterilization. When the fiber is inserted into the pacemaker lead, it follows all bending processes of the pacemaker lead caused by cardiac contraction. The attenuation of the light has to be determined by a light receiver.

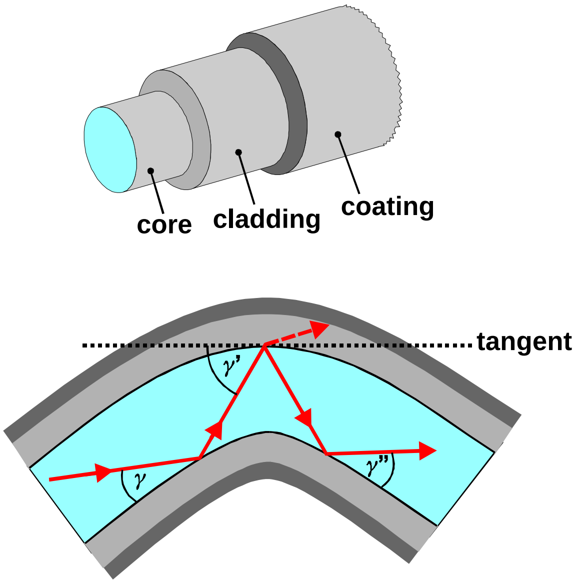

Fig. 3: Components of an optic fiber and the way of propagation of light within the fiber.

4. THE OPTO-ELECTRICAL UNIT

The essential components of the opto-electrical unit are a light emitter, two receivers (signal and reference) and a beam splitter (Fig. 4). As emitter an infrared light emitting diode (IR-LED) was chosen,

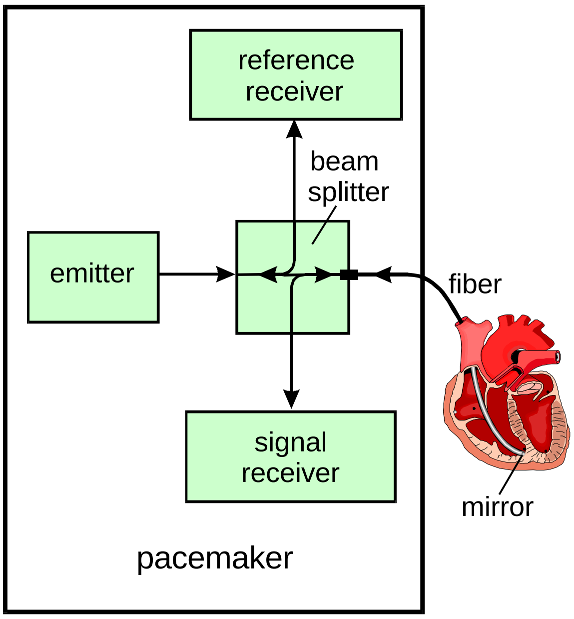

Fig. 4: Scheme of the opto-electrical unit and the sensing fiber.

as the coherence of laser light would evoke processes of interference. An additional control circuit was developed to stabilize the emitted optical power. The received signal due to the optical attenuation may be only 10 ‰ of the received power. From the photo current of the receiver (silicon photo diode) the offset is subtracted, before the signal is low pass filtered. The beam splitter is used 1) to send the emitted light both into the fiber and to the reference receiver for feedback control of the emitted light power, and 2) to send the reflected light to the receiver, and at the same time to the transmitter, where it is absorbed or reflected. The beam splitter is produced by polishing cladding and core of two fibers and sticking them together at theses sites (optical coupler).

5. TEST OF THE DEVICE

To test the sensing properties of the device we used a technical set-up where the fibers were wound around metal cylinders of different diameters. The change in photo current was recorded for each diameter (Fig. 5). The exponential course is congruent with theoretical considerations. From various fibers tested (fibers with stepwise changing or linearly changing refraction indices with outer diameters between 155 and 250 µm), the model TCL-105 from SpecTran with diameters 105, 125, 155 µm for core, cladding and coating was particularly suited. The value of the change in this photo current in Fig. 6 refers to the value measured at a bending diameter of 165 mm. One has to take into account that the optical attenuation is also dependent on the arc length wound around the bending cylinder. Greater arc lengths deliver a greater damping. The analysis of the parameters, bending diameters and arc lengths brought about adequate results for the values to be expected within the heart. Maximal sensitivity for measurements with the fibers used so far is estimated to be ~ 4 % / mm diameter. The noise signal corresponds to about 1 % of the diameter. To test the longevity of the fibers a test device was constructed bending the fibers about 200 times per minute. It has been working for one year without any problems in the measuring quality.

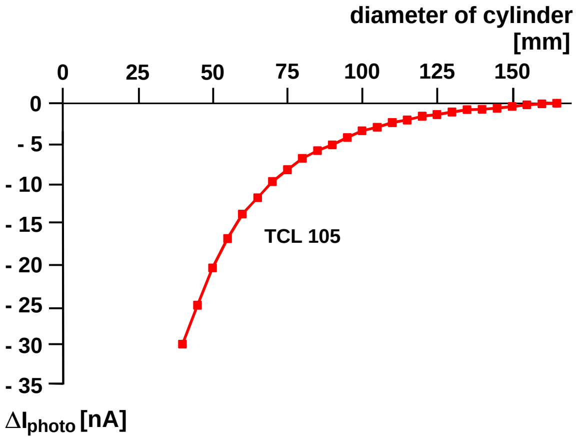

Fig. 5: Change of photo-current as a function of bending diameter for a TCL 105 fiber.

Moreover the complete system was tested in explanted, working pig hearts controlled under physiological conditions (Kloppe, et al., 1999), which means that they work under realistic hemodynamic conditions with right and left heart circulation and adequate pre- and afterloads. The heart may work according to the intrinsic rhythm or may be paced by the pacemaker. ECG, intracavitary pressures and blood flows are monitored, blood gases are controlled and adjusted via an oxygenator. Inotropic modification of heart action may be triggered by administration of dopamine. Fig. 6 demonstrates the fiber signal following the contractions and relaxations of the heart synchronously with right ventricular pressure.

This makes possible a relatively simple design of an algorithm adjusting the stimulation rate according to the inotropic status. However, the properties and the stability of the system, particularly under various pathophysiological conditions of the myocard has still to be tested in many additional series of experiments.

6. CONCLUSIONS

The fiberoptic technique is suited to measuring the inotropic status of the heart, thereby delivering a reliable physiological parameter to control the stimulation rate of a rate adaptive “inotropic” pacemaker, which re-closes to the greatest extent the physiological control-loop, interrupted in patients with sinus node incompetence. Moreover, we suggest an additional parameter for tachycardia detection and shock application in automatic defibrillation systems. However, extensive pre-clinical experiments and clinical tests have to be continued to elaborate all “pros” and “cons” of the new system.

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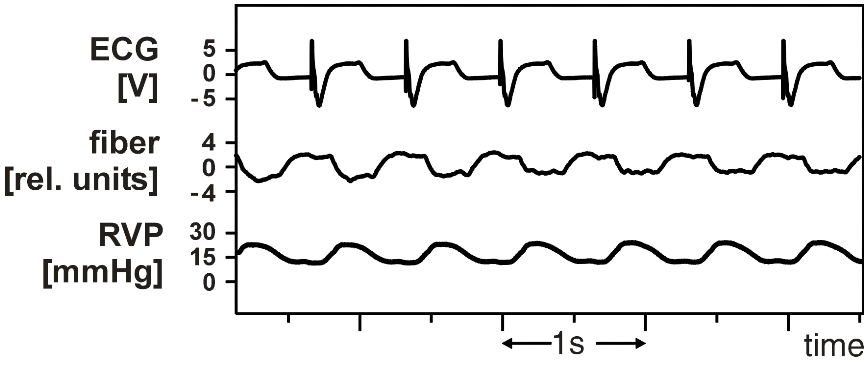

Fig. 6: The fiber signal following contractions and relaxations in a pig heart. EGG = intracardial electrocardiogram, RVP = right ventricular pressure.